Low Noise C-band Upconversion Detection for Demultiplexing Temporal Modes

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Abstract

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Quantum technologies have the capability of greatly increasing the security of communication systems. Many components are required for a full quantum network including memory, repeaters, routers, and detectors. The efficiencies of quantum communication technologies suffer greatly due to their inherent sensitivity to loss. Low-loss propagation and high detection efficiency can help create faster, more reliable quantum networks. Optical fibers are a convenient viable approach to low-loss propagation if the signals are in the range of 1530 to 1565 nm, the communications band (C-band). Efficient avalanche photodiode (APD) based single photon counters exist for the 400 to 900 nm wavelength range. Therefore, an efficient single photon detection system may employ both optical fibers and APDs. The issue then is converting a single photon from the low transmission loss C-band to the high efficiency visible range detection band.

Quantum frequency conversion (QFC) is a nonlinear optical process in which the frequency of a single photon is changed through an interaction with a strong optical pump in a nonlinear medium. Using QFC a signal photon can be transmitted in an optical fiber, upconverted in a nonlinear medium, and then detected on a high efficiency single photon counter.
A signal photon existing with a specific temporal mode shape has certain temporal pump profiles that will upconvert the signal photon with high efficiency. Given a set of photons in orthogonal temporal modes, different pumps can be designed that will upconvert them independently with high efficiency. By engineering these pumps to have high upconversion efficiency for one signal mode and low upconversion efficiency for other signal modes in the orthogonal set, we can selectively demultiplex single photons from a photon packet using QFC. Therefore, not only are the losses in the system greatly reduced by using QFC, but mode selectivity is also achieved which no other current technology is capable of. An up-conversion detection system utilizing QFC can accomplish both photon counting and mode resolution, which most other detection technologies do not achieve.

Using signal sets with \( d \) orthogonal temporal modes creates a \( d \)-dimensional Hilbert space, whereas most quantum communication techniques today use only a 2-dimensional space by encoding on polarization. These polarization-entangled photon schemes are one example of a quantum bit, qubit, technology. By increasing the Hilbert space to contain \( d \) modes a qudit technology is built. The experiments presented herein focus on temporal mode multiplexing but the Hilbert space can be further expanded by including polarization, spatial mode, and wavelength multiplexing technologies.

To demultiplex spatio-temporally overlapped orthogonal modes, multiple waveguides in series could provide multi-stage upconversions after which the signal photons could be detected on independent detectors. Due to the increased loss and complexity of such a system, it is desirable to use a single waveguide to upconvert independent temporal signals to different wavelengths which can then be separated into individual spatial paths for detection. This can be accomplished using a waveguide engineered to have multiple phase-matching peaks in its transfer function profile. Other research has demonstrated the ability to upconvert
signals in a waveguide with multiple phase-matching peaks but it has never been used for temporal mode demultiplexing.

Controlling the phase and amplitude of a frequency comb through optical arbitrary waveform generation (OAWG) allows fine tuned control over temporal pulse profiles. OAWG is essential for efficient QFC mode selection for a given signal mode set. Technological restrictions of OAWG devices are sometimes a bottleneck for system data rates. By implementing dynamic OAWG (DOAWG) new options for pulse rates and symbol switching in adjacent pulses is available. We propose a scheme which utilizes both OAWG and QFC to build a high data rate upconversion qudit system which can easily be adapted into a DOAWG system for improved performance.
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As I often use the phrase "my research" in this document, you may also encounter the terminology "our work" and "our research" as well. That is because no PhD, research, project, event, or anything really, is without the influence of others. Since this is an academic paper, I’d like to start with those who helped pave the intellectual path I have taken. But I won’t, because there’s another group of people who have emboldened me to pursue my every goal and wildest wish with fierce determination, so that is where I will begin.

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PROGRESS

To Progress. To all who pursue it.

To all who prevail, and all those who fail.

Only those who never try rue it.

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CHAPTER 1

Overview

1.1. Introduction

Quantum communications is a quickly growing research field due to the implications of improved security using methods such as quantum key distribution (QKD), quantum cryptography, and superdense coding. In such scenarios it is nearly impossible to eavesdrop on a channel without a high probability of being detected\[1,3\]. Modern QKD systems use few photons and can only transmit hundreds of kilometers at limited data rates due to the inherent sensitivity to loss. Demonstrated QKD secret key rates transmitted over 100 km currently only have tens of thousands of bits per second bandwidth\[4\]. Optical fibers are important for quantum communication technologies due to their low loss at communication band (C-band) wavelengths\[5,6\]. One problem with using optical fibers is that convenient avalanche photodiode (APD) based single photon detectors (SPDs) in the C-band have a number of drawbacks including low detection efficiencies and high dark count rates, while high efficiency C-band SPDs utilizing superconducting materials require cryogenic cooling. Silicon-based APDs, which are sensitive to <1 micron light, typically have higher detection efficiencies and lower dark count rates than III-V (c-band sensitive) based APDs. The problem with silicon-based technologies is that these detectors only work for visible and near visible wavelengths\[7,10\].
To reap the benefit from the low loss optical fiber transmission of C-band wavelengths and the high efficiency detection of silicon at near visible wavelengths, an upconversion detection system can be used. Upconversion is a nonlinear optical process that transfers energy from a field with a specific frequency to a field of a higher frequency. Moreover, quantum frequency conversion (QFC) has been demonstrated to preserve the quantum characteristics of single photons while converting them from one frequency to another \[11-13\]. Various noise processes should be considered in any system, but it should be noted that QFC itself is a noiseless process \[14\]. Upconversion systems have been demonstrated with high QFC efficiencies and overall detection efficiencies between 10 to 35%, whereas C-band APDs typically have detection efficiencies around 10\% \[2,15\]. In addition, nonclassical behaviors have been observed that confirm the preservation of the quantum information in these systems \[16-18\].

Many quantum information systems encode information on single photon signals using quantum bits (qubits) in a 2-dimensional Hilbert space. For example a qubit system can be developed using the polarization of a photon as its orthogonal basis \[19,20\]. Increasing the Hilbert space to include wavelength channels and spatiotemporal modes allows for much higher data transmission rates and has also been shown to be more secure \[21\]. A macroscopic state can be sent across a channel with photons spread across this high dimensional Hilbert space. At the detection side, QFC can be used to demultiplex these photons and send them to independent detectors, or serialize the process to one detector, as shown in Figure \[22\]. The signal set must be orthogonal to ensure that pumps can be designed that selectively upconvert only one of the signal modes. The work presented herein focuses on a low-noise single photon upconversion detection system that utilizes temporal modes of a higher dimensional Hilbert space, resulting in orthogonal time frequency division multiplexing (OTFDM) \[23\].
Figure 1.1. The basic QFC demultiplexing scheme with input signal set, shaped pump, waveguides, filters, and dichroic mirrors for filtering out the upconverted signals. SPCMs are then used to detect the QFC signal. The color of the arrows depicts the field or fields that exist in the specified path with red being pump, blue being signals, and purple being the upconverted modes. The left scheme shows that the residual signal set can be sent through additional waveguides and other signals can be selected and dropped from the set for detection. Filters between the waveguides can be used to filter out pumps used to upconvert signals in previous waveguides. The right shows a layout where the signal set is redirected back through the same waveguide to accomplish demultiplexing of multiple signals using a single waveguide. The more compact arrangement on the right can be implemented to make scalability much simpler. (Adapted from [22])

For the QFC process to select one of the photons in a specific polarization and spatiotemporal mode, a mode-tailored pump pulse must be introduced. The pump pulse is the driving energy for the frequency conversion process, and the polarization and spatiotemporal profile of the pump determines which signal photons will be upconverted [22]. Ideally, one pump would convert only photons in the desired signal mode while converting no photons in other spatiotemporal modes. In this fashion the QFC process acts as a demultiplexer or a drop device where the signal dropped is determined by the injected pump pulse [20,23]. The selected signal can then be separated from the rest of the set by means of prisms, dichroic mirrors, or a combination of any adequate filtering devices or techniques. Once the selected signal has been dropped from the set, it can then be detected on a single photon counting module (SPCM).
1.2. Overview of Chapter 2

Chapter 2 serves as an introduction to some of the basic concepts required for an understanding the material that follows. First, Maxwell’s equations for electromagnetic fields are presented. Maxwell’s equations are used in Section 2.1 to demonstrate how to derive a wave equation that governs the propagation of radiation through dispersive media. After the basic wave equation is derived, a field dependent polarization is incorporated and the nonlinear wave equation is derived in Section 2.2. The concept of nonlinear susceptibility is introduced and the second-order susceptibility, $\chi^{(2)}$, is further explored. In Section 2.3 an input field comprised of radiation with two independent frequencies is used in the nonlinear wave equation to derive the coupled wave equations for sum-frequency generation (SFG) and second-harmonic generation (SHG). Difference-frequency generation (DFG) and optical rectification are briefly discussed for completeness. The final section of Chapter 2 gives a basic overview of single-photon detector technologies. InGaAs and silicon technologies are discussed and the benefits and drawbacks of the current state of technologies are presented.

1.3. Overview of Chapter 3

Nonlinear materials are introduced and materials with high $\chi^{(2)}$ values are presented in this chapter. Lithium niobate (LN) and potassium titanyl phosphate (KTP) are selected for further discussion. The optical characteristics of each medium are presented and arguments are made for using one material over another when considering different nonlinear processes. The difference between bulk materials and waveguides is described and the choice to use waveguides for our experiments is made based on the characteristics of waveguides and the technical implementation of the technology.
Section 3.2 introduces the refractive indices of the materials and the wave vectors of fields traveling through a medium. Phase-matching requirements and engineering methods for maximizing the phase matching are presented. Limitations of mediums are explored and options for optimizing materials for nonlinear processes are considered. Quasi-phase matching is introduced and equations describing the field response to a periodically poled material are shown. Phase-matching profiles and the sine-squared dependence of conversion percent to power and waveguide length are discussed. Both periodically-poled lithium niobate (PPLN) and KTP are materials with developed poling technologies so the argument for using these two mediums for the nonlinear processes is further supported.

Section 3.3 considers two waveguide chips from different groups employing different fabrication technologies for use in our nonlinear experiments. Both chips are PPLN, one with 32 waveguides and the other with 72 waveguides. Across each chip the waveguides vary in phase-matching profiles, conversion efficiencies, coupling loss, and waveguide geometries. The phase-matching profiles for various waveguides are measured and the highest performing waveguides are found for each chip. A temperature tuning characterization for controlling the peak phase-matching wavelength is performed. The band of frequencies for SFG is determined by the specific measured phase-matching peaks and the temperature tuning capabilities of the chips. Based on the data presented from the waveguide characterizations, specific waveguides are chosen for the proposed experiments.

1.4. Overview of Chapter 4

Chapter 4 informs the reader of the requirements of a pump beam for efficient SFG in a medium. The concept of mode selectivity due to temporal field profile is also introduced. Generation of photon pairs in nonlinear mediums is described in Section 4.1. The
benefits of using second-order nonlinear materials over using third-order nonlinear materials are weighed, and using a second-order nonlinear medium for photon generation is selected. The equations for photon generation by means of spontaneous parametric down conversion (SPDC) in second-order nonlinear media are presented. Spectral factorability is discussed and various systems and schemes for generating single photons are considered. Joint spectral intensities are shown and used in simulations to determine the temporal fields for photons generated through SPDC.

Section 4.2 describes the code used to simulate the generation of single photons by means of SPDC. Various SPDC pump widths and filtering bandwidths are used in photon generation simulations to create different orthogonal signal sets for use in an SFG system. Next, Section 4.3 describes the split-step method used to apply the linear and nonlinear effects of waves traveling through PPLN. The iterative approach to the SFG pump optimization simulations is described and arguments for the assumptions made in the code are presented. Section 4.4 informs the reader of the specific statistics used in the SFG optimization process and the reasoning behind using those parameters.

The next section of Chapter 4 presents the results of the SFG pump optimizations. Using realizable parameters for pump shaping and measured nonlinear material efficiencies, the number of distinguishable modes for a given mode set is determined. This SFG selection optimization is performed for various SPDC generated mode sets. In this way, the ideal experimental SPDC pump and filter bandwidths are chosen and the temporal pump profiles for mode selectivity are derived. The final section explores the robustness of the SFG system by adding error to the pump shaping. Various amounts of error are added to the system and the efficiency and mode selectivity are found. The results are presented and the system’s
resistance to error is found to be robust with respect to a realizable system’s expected amounts of error.

1.5. Overview of Chapter 5

Upconversion detection systems are discussed as viable C-band single photon detection systems. The first section of Chapter 5 discusses the various possible sources of noise in an SFG single photon system. Other noise sources being mitigated, the Raman-generated photons in the system must be further investigated. An experiment looking into the Raman-generated photons in fiber coupled PPLN and PPKTP waveguides from AdvR is conducted. The results are reported and a low noise regime is found for use in SPDC single photon generation.

Section 5.2 describes an experimental setup to measure the SFG conversion of a signal and the number of generated Raman photons in the SFG signal band. Various pumps are implemented with continuous wave (CW) and pulsed configurations, and the distance of the input signal wavelength to the pump wavelength is varied. A filtering system to reduce noise in the SFG band is implemented and Section 5.3 presents the results. A low noise regime is found and the overall efficiency of the system is measured and reported. The results are promising and through the experiments and discussion in Chapter 5 an upconversion C-band system is deemed viable.

1.6. Overview of Chapter 6

Chapter 6 explores using a multi-phasematching peak waveguide to upconvert signals at different wavelengths into different SFG channels. Section 6.1 describes an SFG system where two pump-signal pairs are phasematched on adjacent phase-matching peaks in a waveguide
with phase-matching peaks separated by 5 nm. In this way, the two resulting SFG wavelengths are separated spatially using freespace wavelength tunable filters. The upconversion efficiency, pump generated noise, and crosstalk of the pump-signal pairs is investigated and reported in Section 6.2.

Due to lower phase-matching peak conversion efficiencies, the pump power required for high conversion efficiency is greater than in a single-peak waveguide. This results in more pump generated noise in the SFG channels. When both pumps are present in the waveguide, the pump generated noise is greater than the sum of pump generated noise measured from the independent pumps. This implied some interaction of pumps or upconversion of one pump Raman by the nearby neighbor pump. The results of this chapter show that a multichannel upconversion detection system with C-band pumps and signals is possible using a multi-phase-matching peak waveguide, and with careful selection of pump-signal pair wavelengths.

1.7. Overview of Chapter 7

Temporal mode-demultiplexing in multi-peak waveguides is explored in Chapter 7. Sections 7.1 and 7.2 describe the design and setup of a system that uses a 3-nm separated phase-matching peak multi-peak waveguide to upconvert temporal signal modes, where the signal modes all have the same wavelength. All pulses were shaped using a frequency comb and optical arbitrary waveform generator (OAWG). The pump-signal pairs were matched on neighboring phase-matching peaks of the waveguide resulting in upconverted signals that had different wavelengths in the visible spectrum. This allowed the upconverted signals to be separated into independent spatial paths using freespace optical filters. Section 7.3 reports the upconversion detection efficiencies, noise characteristics, and cross talk for the multi-peak system.
The results show that the pump generated noise in the upconverted signal paths is too high for use in single photon detection systems. A second OAWG was added to the pump path to allow arbitrary filtering of the pump spectrum before passing through the waveguide. This was used to determine the main sources of noise generated by the pump path. It was found that using pumps between upconversion phase-matching peaks caused too much noise in the neighboring upconverted signal channels. As previously demonstrated in Chapter 3, the pumps must have wavelengths a certain distance from the phase-matching peaks to reduce pump generated noise, which is also exacerbated in a multi-peak waveguide due to the higher pump powers required for high upconversion efficiencies.
CHAPTER 2

Background on Nonlinear Optics

This chapter gives the overarching equations and physical descriptions required to understand the work proposed and performed in later chapters. That is not to say that this chapter provides all of the necessary background for my work, as each chapter begins with a small section of information pertaining to the specific material covered in that chapter.

In this chapter we first introduce Maxwell’s equations, as a basic understanding of the electromagnetic field wave equation is necessary. Then, the non-linear wave equations are derived before specifically focusing on sum-frequency generation which is the most important non-linear effect for the presented work. The final section of this chapter discusses the basics of single photon generation and detection as it is used in the presented work.
2.1. Maxwell’s Equations

The following presentation of Maxwells equations and the non-linear version of the wave equation is found in a wide number of sources. Two sources, Boyd\[24\] and Agrawal\[25\], were used in the majority of this section and the next.

To obtain a wave equation that governs the propagation of electromagnetic waves through dispersive media, we begin with Maxwell’s equations.

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2.1a}
\]

\[
\nabla \times \mathbf{H} = \mathbf{J}_f + \frac{\partial \mathbf{D}}{\partial t} \tag{2.1b}
\]

\[
\nabla \cdot \mathbf{D} = \rho_f \tag{2.1c}
\]

\[
\nabla \cdot \mathbf{B} = 0 \tag{2.1d}
\]

Where \( \mathbf{E} \) and \( \mathbf{H} \) are the electric field (V/m) and magnetic field (A/m) vectors respectively, and \( \mathbf{D} \) and \( \mathbf{B} \) are the electric flux (C/m\(^2\)) and magnetic flux (Vs/m\(^2\)) densities respectively. \( \mathbf{J}_f \) and \( \rho_f \) are the free current density vector (V·s/m\(^2\)) and free charge density (C/m\(^2\)). There are no free charges for the nonlinear materials we are considering so \( \mathbf{J}_f = 0 \), and \( \rho_f = 0 \).\[25\]

When traveling through a medium, the propagating electromagnetic fields induce electric and magnetic polarizations, \( \mathbf{P} \) and \( \mathbf{M} \), in that medium. The flux densities \( \mathbf{D} \) and \( \mathbf{B} \) can then be derived through the relationships in Eqs. \((2.2a)\) and \((2.2b)\).
\[ D = \varepsilon E = \varepsilon_0 E + P \] (2.2a)

\[ B = \mu H = \mu_0 H + M \] (2.2b)

Where \( \varepsilon_0 \) is the permittivity of freespace (F/m) and \( \mu_0 \) is the permeability of freespace (H/m). The nonlinear materials used in the experiments are nonmagnetic mediums so \( M = 0 \), and for simplicity let us also assume \( P = 0 \) at this time\(^{20}\). Taking the curl of Eq. (2.1a) we get

\[ \nabla \times \nabla \times E = \nabla \times \left( -\frac{\partial B}{\partial t} \right) = -\frac{\partial}{\partial t} (\nabla \times B) \] (2.3)

Now using Eqs. (2.1c), (2.2a), and (2.2b) we can find Eq. (2.4) that only concerns the electric field \( E \).

\[ \nabla \times \nabla \times E = -\frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} \] (2.4)

Where \( c = \sqrt{1/\mu_0 \varepsilon_0} \) represents the speed of light in a vacuum. Finally, using the identity

\[ \nabla \times \nabla \times E = \nabla (\nabla E) - \nabla^2 E = 0 \] (2.5)

and using Eqs. (2.1d) and (2.1d) we can simplify Eq. (2.4) to

\[ \nabla^2 E - \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} = 0 \] (2.6)

Equation (2.6) is the electromagnetic wave equation in a nonmagnetic medium with no free charges and no induced polarization. The value \( c \) has the relation \( c = \nu/\lambda \) where \( \nu \) is the frequency (Hz) and \( \lambda \) is the wavelength (nm) of the electromagnetic radiation. For future reference the angular frequency is \( \omega = 2\pi \nu = 2\pi/\lambda \) (rads/s) and the wave vector
\[ |\mathbf{k}| = k = 2\pi \lambda \text{ (rads/m)}. \] In freespace this relation between the frequency, wavelength, and speed of light holds firm, but in a medium the speed of light slows down changing the wavelength of the radiation. This new speed is defined as \( v \) and \( c/v = n \) where \( n \) is the refractive index of the material. This index depends on the make up of the material and is the basis behind building waveguides, lenses, and many other optical devices and phenomenon. The index of refraction for a material can be different for different wavelengths leading to \( n(\omega_j) = n_j \). This definition of \( n_j \) and Eq. (2.6) will be used in formulating equations for the nonlinear effect of SFG \(^{24}\).

### 2.2. Nonlinear Equations

Nonlinear optical effects occur when the intensity of light in a medium is strong enough to alter the optical properties of the system. Any medium is a nonlinear medium in the presence of a strong enough optical intensity, but most materials do not exhibit any effects unless strong laser light is used \(^{26}\). Materials can be engineered that allow nonlinear effects to be observed and utilized in modern systems with readily obtainable optical powers. Chapter 3 discusses these materials in more detail. The optical output of a certain medium may demonstrate a quadratic, or higher order response to the input field which is why the term nonlinear is used for these interactions. We will be focusing on the second-order interactions since that is the regime for SFG, the nonlinear effect of interest. In the last section we examined the electromagnetic wave equation while not allowing an induced polarization, \( \mathbf{P} \), in the medium. In this section we require a value of \( \mathbf{P} \neq 0 \) to introduce the nonlinear response of a system.
An optical field propagating through a medium will induce a polarization dependent on the electric field given by

\[ P(t) = \epsilon_0 \chi E(t) \]  

(2.7)

where \( \chi \) is the susceptibility of the material \[24\]. For a nonlinear system \( \chi \) can be expressed as a power series expansion resulting in

\[ P(t) = \epsilon_0 \left[ \chi^{(1)} E(t) + \chi^{(2)} E^2(t) + \chi^{(3)} E^3(t) + \cdots \right] = P^{(1)}(t) + P^{(2)}(t) + P^{(3)}(t) + \cdots \]  

(2.8)

Now we see that \( P^{(1)} \) is the linearly induced polarization while \( P^{(2)} \) and higher terms represent the nonlinear contributions to the induced polarization of the material due to the electric field. The second term \( P^{(2)} \) is the second-order nonlinear contribution. Assuming the polarization response of the material is instantaneous, and the medium is lossless and dispersionless, we get the wave equation

\[ \nabla^2 E - \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 P}{\partial t} \]  

(2.9)

by following the same method laid out in Section \[2.1\] only with \( P \neq 0 \). This wave equation can be used to describe many nonlinear processes ranging from SFG and SHG to higher order processes like intensity-dependence of the refractive index \[24\]. The next section will specifically focus on using this wave equation to describe SFG.

### 2.3. Sum-Frequency Generation

When two electric fields of different frequencies co-propagate through a second-order nonlinear medium they can create radiation at new frequencies. Let us consider two fields
\( \mathbf{E}_1 \) and \( \mathbf{E}_2 \), of frequencies \( \omega_1 \) and \( \omega_2 \) respectively, represented by

\[
\mathbf{E}_1(t) = E_1 e^{-i\omega_1 t} + c.c., \quad \mathbf{E}_2(t) = E_2 e^{-i\omega_2 t} + c.c. \quad (2.10)
\]

for a combined total input electric field

\[
\mathbf{E}(t) = \mathbf{E}_1(t) + \mathbf{E}_2(t) = E_1 e^{-i\omega_1 t} + c.c. + E_2 e^{-i\omega_2 t} + c.c \quad (2.11)
\]

Using the relationship of \( \mathbf{E}(t) \) and \( \mathbf{P}^{(2)} \) from Eq. (2.8) and the field in Eq. (2.11) we find the second-order nonlinear polarization to be

\[
\mathbf{P}^{(2)}(t) = \epsilon_0 \chi^{(2)}[\mathbf{E}_1^2 e^{-2i\omega_1 t} + \mathbf{E}_2^2 e^{-2i\omega_2 t} + 2\mathbf{E}_1 \mathbf{E}_2 e^{-i(\omega_1 + \omega_2) t} + c.c.] + 2\epsilon_0 \chi^{(2)}[\mathbf{E}_1 \mathbf{E}_1^* + \mathbf{E}_2 \mathbf{E}_2^*] \quad (2.12)
\]

Where the various terms represent different nonlinear processes involving the combination of two fields to produce a third field with frequency dependence on the frequencies of the input fields. The first two terms lead to radiation generated at frequencies that is twice that of each input field, \( 2\omega_1 \) and \( 2\omega_2 \), known as second harmonic generation (SHG). The term of most importance for my research is the sum-frequency term which is the third term in the equation, involving the combination of two frequencies \( \omega_1 + \omega_2 \). We will not be considering difference frequency generation or optical rectification which are the other terms in Eq. (2.12).

Let us now consider the SFG output field at \( \omega_3 = \omega_1 + \omega_2 \), and that each frequency experiences a different index of refraction in the nonlinear medium \( n_i, i = 1, 2, 3 \). The three waves propagating through the nonlinear medium can be represented by

\[
\mathbf{E}(t)_j = \mathcal{E}_j e^{k_j z - i\omega_j t} + c.c. \quad j = 1, 2, 3 \quad (2.13)
\]

\[36\]
Where $\mathcal{E}_j$ is the amplitude of each field and $k_j = n_j \omega_j / c$ is the wavevector from Section 2.1. Using the vector identity from Eq. (2.5) the resulting nonlinear Helmholtz equation for the field at $\omega_3$ is

$$\nabla^2 \mathcal{E}_3(z) e^{i(k_3z)} + \frac{n_3^2 \omega_3^2}{c^2} \mathcal{E}_3(z) e^{i(k_3z)} = -\mu_0 \omega_3^2 P_3^{(2)}(z)$$

(2.14)

and since $\omega_3$ has been defined as the combination of the two frequencies $\omega_1$ and $\omega_2$ the only term in the polarization that contributes to the field generated at $\omega_3$ is the SFG term. Therefore the right side of Eq. (2.14) becomes.

$$P_3^{(2)}(z) = 2\epsilon_0 E_1(z) \cdot \chi^{(2)}(\omega_3 = \omega_1 + \omega_2) \cdot E_2(z)$$

(2.15)

Following the same process as above, the nonlinear Helmholtz equations for the other two fields at $\omega_1$ and $\omega_2$ can be found to be

$$\nabla^2 \mathcal{E}_3(z) e^{i(k_3z)} + \frac{n_3^2 \omega_3^2}{c^2} \mathcal{E}_3(z) e^{i(k_3z)} = -\mu_0 \omega_3^2 P_3^{(2)}(z)$$

(2.16a)

$$\nabla^2 \mathcal{E}_3(z) e^{i(k_3z)} + \frac{n_3^2 \omega_3^2}{c^2} \mathcal{E}_3(z) e^{i(k_3z)} = -\mu_0 \omega_3^2 P_3^{(2)}(z)$$

(2.16b)

with

$$P_1^{(2)}(z) = 2\epsilon_0 E_2^*(z) \cdot \chi^{(2)}(\omega_3 = \omega_1 + \omega_2) \cdot E_3(z)$$

(2.17a)

$$P_2^{(2)}(z) = 2\epsilon_0 E_3(z) \cdot \chi^{(2)}(\omega_3 = \omega_1 + \omega_2) \cdot E_1^*(z)$$

(2.17b)
The first term on the left hand side of the nonlinear Helmholtz equation for $E_3$, Eq. (2.14), can be written as

$$\nabla^2 E_3(z) e^{ik_3z} = \frac{d^2}{dz^2} E_3(z) e^{ik_3z}$$

(2.18a)

$$= \frac{d^2 E_3(z)}{dz^2} + 2ik_3 \frac{dE_3(z)}{dz} e^{ik_3z} - k_3^2 E_3(z) e^{ik_3z}$$

(2.18b)

The slowly-varying envelope approximation states that the second spatial derivative of a slowly varying field is much smaller than the first spatial derivative of that field and is therefore negligible in comparison. For the slowly varying amplitude $E_3$ that is

$$\frac{d^2 E_3}{dz^2} \ll k_3 \frac{dE_3}{dz}$$

(2.19)

Since the amplitudes $E_j$ of each field are slowly varying along the propagation direction $z$ we can apply this approximation to Eq. (2.14) and remove any second order spatial derivatives to get

$$\frac{dE_3(z)}{dz} = i\mu_0 \omega_3^2 \frac{2k_3}{P_3^{(2)}(z)} e^{-ik_3z}$$

(2.20a)

$$= i\frac{\omega_3 K_3}{n_3 c} E_1(z) E_2(z) e^{i\Delta k z}$$

(2.20b)

Where $\Delta k = (k_1 + k_2 - k_3)$ is the phase mismatch per unit length and the effective second-order susceptibility $K_3$ is

$$K_3 = \chi^{(2)}(\omega_3 = \omega_1 + \omega_2)$$

(2.21)
Following the same method as above we derive similar equations for $E_1$ and $E_2$.

\[
\frac{dE_1(z)}{dz} = i\frac{\omega_3 K_1}{n_3 c} E_2(z)^* E_3(z) e^{i\Delta k z} \tag{2.22a}
\]

\[
\frac{dE_2(z)}{dz} = i\frac{\omega_3 K_2}{n_3 c} E_1(z)^* E_3(z) e^{i\Delta k z} \tag{2.22b}
\]

with effective nonlinear second-order susceptibilities

\[
K_1 = \chi^{(2)}(\omega_1 = -\omega_2 + \omega_3)
\]

\[
K_2 = \chi^{(2)}(\omega_2 = \omega_3 - \omega_1) \tag{2.23a}
\]

The Eqs. (2.22a), (2.22b), and (2.20a) form a set of coupled equations called the equations of motion for the system. These equations show the flow of energy between the three fields $E_3$, $E_1$, and $E_2$.

Let us now consider these fields propagating through a medium of length $L$ and that the two input fields remain constant $E_1(z) = E_1$ and $E_2(z) = E_2$. There is now only one equation with dynamic interest

\[
\frac{dE_3}{dz} = i\frac{\omega_3 K}{n_3 c} E_1 E_2 e^{i\Delta k z} \tag{2.24}
\]

therefore solving over the length of the medium

\[
E_3(L) = i\frac{\omega_3 K}{n_3 c} E_1 E_2 \int_0^L e^{i\Delta k z} dz \tag{2.25}
\]

results in a field amplitude of
\[ E_3(L) = \frac{i\omega_3 K}{n_3 c} E_1 E_2 e^{i\Delta k L/2} L \text{sinc}(\Delta k L/2) \] (2.26)

Equation (2.26) shows that the amplitude of \( E_3 \) depends on the two input field amplitudes, material properties, and a sinc function of the length and wavevector mismatch of the waves in the material. This will be used in Chapter 3 when discussing phase matching and periodic poling which are essential to efficient SFG. Chapter 4 applies the above equations through a split-step algorithm to find optimized pump pulse shapes for single mode selection from a set of signals.

### 2.4. Propagation in a Dispersive Medium

The refractive index of a dispersive material depends on the frequency of light propagating in the material. Dispersion can be used for pulse compression, spectrometers, and is an important effect in building many other devices [27,28]. It can also have deleterious effects in a system and may require compensation for a system to function as desired [25,29]. For SFG using short pulses through dispersive-nonlinear mediums, the dispersion must be considered to ensure the highest conversion efficiency in the system.

The dependence of the refractive index on the optical frequency in a dispersive medium means that the wave vector of the propagating beam also depends on the optical frequency as shown in Eq. (2.27).

\[ k(\omega) = n(\omega) \frac{2\pi}{\lambda} \] (2.27)

where the frequency dependent wave vector can be expanded into the Taylor series
\[ k(\omega) = k(\omega_0) + k'(\omega_0)(\omega - \omega_0) + \frac{1}{2}k''(\omega_0)(\omega - \omega_0)^2 + \ldots \]  

(2.28)

with \( k' \) and \( k'' \) being the first and second derivatives of the wave vector with respect to frequency and \( \omega_0 \) is the optical carrier frequency. The first order dependence of the wave vector on frequency

\[ k' = \frac{\delta k}{\delta \omega} = \frac{1}{v_g} \]  

(2.29)

is the inverse of the group velocity and

\[ k'' = \frac{\delta^2 k}{\delta \omega^2} = \frac{\delta}{\delta \omega} \frac{1}{v_g} \]  

(2.30)

is the group velocity dispersion (GVD). The first order dispersion causes pulses of different frequencies to travel through the medium at different speeds. This is known as ‘walk off’ between pulses and means they may pass through each other changing the effective interaction length of the pulses in the medium. The GVD causes a pulse to spread or compress temporally as it propagates through the medium, changing the temporal profile of the pulse.

Incorporating the first and second order dispersion terms into Eqs.\((2.20a)\), \((2.22a)\), and \((2.22b)\) we get

\[
\left( \frac{d}{dz} + k'_3 \frac{\delta}{\delta t} - i \frac{k''_3}{2} \frac{\delta^2}{\delta t^2} \right) \mathcal{E}_3(z) = i \frac{\omega_3 K_3}{n_3 c} \mathcal{E}_1(z) \mathcal{E}_2(z) e^{i \Delta k z} \]  

(2.31a)

\[
\left( \frac{d}{dz} + k'_1 \frac{\delta}{\delta t} - i \frac{k''_1}{2} \frac{\delta^2}{\delta t^2} \right) \mathcal{E}_1(z) = i \frac{\omega_3 K_1}{n_3 c} \mathcal{E}_2(z) \mathcal{E}_3(z) e^{i \Delta k z} \]  

(2.31b)

\[
\left( \frac{d}{dz} + k'_1 \frac{\delta}{\delta t} - i \frac{k''_1}{2} \frac{\delta^2}{\delta t^2} \right) \mathcal{E}_2(z) = i \frac{\omega_3 K_2}{n_3 c} \mathcal{E}_1(z) \mathcal{E}_3(z) e^{i \Delta k z} \]  

(2.31c)
For short pulses the GVD and walk-off terms can effect the overall SFG efficiency depending on nonlinear medium parameters such as the material and length. Later chapters that consider nonlinear processes will include arguments as to why these dispersion terms are considered negligible or not, based on the specific waveguides and nonlinear process involved.

2.5. Single Photon Detection

The ability to efficiently detect single photons is key to implementing quantum technologies. Building a C-band quantum communication system is desirable as there is much developed technology at C-band wavelengths. Operating in the C-band allows systems to take advantage of the low loss of optical fibers used in transmission. Indium Galium Arsenide (InGaAs) detectors are used to detect photons in the C-band\(^7\). Current InGaAs technologies suffer from a number of drawbacks including low detection efficiencies and high dark count rates. Superconducting single-photon detectors (SSPDs) have been shown to work in the near IR range but are inconvenient because they require cryogenic temperatures. The efficiency of avalanche photodiodes (APDs) operated in Geiger mode can be increased by increasing the bias voltage, but that also raises the dark counts in the detector. Afterpulsing is also a major consideration with APDs as it adds false counts by releasing extra carriers that get trapped during the avalanche process in later time bins. It is desirable to increase the speed of the detector and therefore data rate of the communication system, but that causes higher afterpulsing counts which can ultimately limit the bandwidth of the system. Lowering the temperature of the APD reduces the dark counts but it also lowers the quantum efficiency and again increases the frequency of afterpulsing. The best performing C-band APDs on the market have efficiencies around 25%, with a dark count rate of 25 Hz, at temperatures in the -50 to -100 °C range.
The best commercially available single photon detectors (SPDs) have 70% quantum efficiency with dark count rates on the order of 10 counts per second. These SPDs are a silicon based technology which operates in the 600 to 900 nm wavelength band. To take advantage of the low loss regime in optical fibers and the high efficiency and low dark counts of the silicon SPDs, SFG can be used to convert transmitted C-band signals into the high detection efficiency band of the silicon SPDs. This kind of SFG detection system is know as an upconversion detector and has been built and characterized in a number of configurations for various experiments\cite{2,5,22}. The majority of the work presented in this dissertation focuses on various aspects of building high performance upconversion detection systems for demultiplexing of high dimensional Hilbert space photonic signals.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency (%)</th>
<th>DC Rate (1/s)</th>
<th>Operating Temp. (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photomultiplier tube</td>
<td>2@1550 nm</td>
<td>200000</td>
<td>200</td>
</tr>
<tr>
<td>Si-APD</td>
<td>65@650 nm</td>
<td>25</td>
<td>250</td>
</tr>
<tr>
<td>InGaAs APD</td>
<td>10@1550 nm</td>
<td>91</td>
<td>200</td>
</tr>
<tr>
<td>Transition edge sensor</td>
<td>95@1556 nm</td>
<td>NA</td>
<td>0.1</td>
</tr>
<tr>
<td>Superconduction nanowire SPD</td>
<td>57@1550 nm</td>
<td>NA</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 2.1. Comparison of detector technologies\cite{2}. 

The best commercially available single photon detectors (SPDs) have 70% quantum efficiency with dark count rates on the order of 10 counts per second. These SPDs are a silicon based technology which operates in the 600 to 900 nm wavelength band. To take advantage of the low loss regime in optical fibers and the high efficiency and low dark counts of the silicon SPDs, SFG can be used to convert transmitted C-band signals into the high detection efficiency band of the silicon SPDs. This kind of SFG detection system is know as an upconversion detector and has been built and characterized in a number of configurations for various experiments\cite{2,5,22}. The majority of the work presented in this dissertation focuses on various aspects of building high performance upconversion detection systems for demultiplexing of high dimensional Hilbert space photonic signals.
CHAPTER 3

Nonlinear Waveguides

3.1. Nonlinear Materials

Any medium exhibits nonlinear effects when a strong enough electric field is present. Depending on the application, a large pump power may not be desired due to excess noise generation or limited filtering capabilities. Therefore, nonlinear mediums with high $\chi^{(2)}$ values are required since these materials require lower powers to exhibit nonlinear behaviors. Major considerations for choosing a nonlinear material include the birefringent properties of the material, chromatic dispersion, strength of the nonlinear susceptibility, and absorption or transparency at the wavelengths of interest. LN and KTP are commonly used for visible and C-band operations since they are transparent at these frequencies and have $\chi^{(2)}$ values which allow the use of conventional laser sources and EDFAs to observe nonlinear effects\cite{6,10,18,22}. High optical powers can cause self-focusing and photorefractive damage which distorts the wavefronts in crystals. KTP has a fairly high damage threshold but LN can often be damaged when generating milliwatts of light in the visible band. Although LN has a low damage threshold it has a fairly large nonlinear susceptibility keeping it viable as a medium for nonlinear technologies. Also, it has been shown that if photorefractive damage does occur in LN it can be reversed by proper heating of the material\cite{30}.

The length of a nonlinear medium determines the phase-matching bandwidth as well as the amount of time or distance that the interaction can take place. Both LN and KTP can be fabricated with lengths over a few centimeters long and insertion losses of 3 dB
or less. Nonlinear media are often used as bulk crystals or as waveguides. Bulk media required that the interacting waves be focused into the crystal at a point allowing maximum interaction, which may not be the same for all of the wavelengths involved due to walk-off. Also bulk crystals require the entrance angles be matched for ideal conversion. Detunings of the entrance angles will cause reduced conversion and walkoff must be considered for exact temporal placement as well. With a waveguide, the beams only need to be coupled into the waveguide, which can be done in freespace or from optical fiber, and pulses need to be properly timed for maximum interaction length. Angular differences between the beams can be more easily tuned for waveguides as they can independently be coupled into the waveguide for lowest loss. Once in the waveguide, the radiation at the various wavelengths copropagates as long as single mode operation is confirmed. For our purposes we work with nonlinear waveguides since the fabrication technology is mature, phase-matching transfer functions can be engineered, and high conversion coupling schemes are potentially easier to accomplish.

### 3.2. Phase Matching and Periodic Poling

It was shown in Section 2.3 that the wave vector for electromagnetic radiation in a medium is \( k_j = n_j \omega_j / c \) where \( n \) is the refractive index in that medium. The desired SFG will

<table>
<thead>
<tr>
<th>Medium</th>
<th>Largest d Coefficient</th>
<th>Damage Threshold (MW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO₃</td>
<td>( d_{33} = 25 )</td>
<td>20</td>
</tr>
<tr>
<td>KTiOPO₄</td>
<td>( d_{33} = 16.9 )</td>
<td>20000</td>
</tr>
<tr>
<td>Ba₂Na₂Nb₅O₁₅</td>
<td>( d_{31} = 32 )</td>
<td>1</td>
</tr>
<tr>
<td>Urea</td>
<td>( d_{14} = 3 )</td>
<td>5000</td>
</tr>
</tbody>
</table>

Table 3.1. List of nonlinear mediums and optical properties. Subscripts denote crystal orientation and the chosen orientations report the highest nonlinear susceptibilities. The \( d_{ij} \) values are a contracted notation and are half of the \( \chi^{(2)} \) value for that orientation.
only occur with high efficiency if phase matching between the interacting waves occurs. That is

$$\omega_s + \omega_p = \omega_{SFG} \quad (3.1a)$$

$$k_s + k_p = k_{SFG} \quad (3.1b)$$

$$k_s + k_p - k_{SFG} = \Delta k \quad (3.1c)$$

Equation (3.1a) comes from the conservation of energy, the wave vector matching requirement Eq. (3.1b) comes from conservation of momentum, and the subscripts s, p, and SFG correspond to the signal, pump, and SFG accordingly. Equation 3.1c shows that if the sum of the wave vectors for the signal and pump do not equal the wave vector for the SFG then there is some phase mismatch represented by $\Delta k$. It is apparent from Eqs. (3.1a) and (3.1b) that the condition

$$n_s \omega_s + n_p \omega_p = n_{SFG} \cdot \omega_{SFG} \quad (3.2)$$

must also be satisfied. Where $n_i$ is the refractive index for the corresponding wave in the medium.

Many materials used in nonlinear applications are dispersive which means the refractive index in the medium depends on the wavelength propagating through it. If the crystal is also birefringent then two different wavelengths can be phase matched using orthogonal polarizations but there are a number of drawbacks: functional wavelengths are limited based on available materials, operating with birefringent phase matching does not often correspond to the highest nonlinear coefficient of the material, and interaction lengths can be limited due
to walk-off of the required orthogonal polarizations. These reasons all limit the conversion efficiencies of birefringent phase matching to a point that is not practical for use in up-conversion technologies.

![Figure 3.1](image)

**Figure 3.1.** Bulk materials or waveguides can be periodically poled for high nonlinear conversion efficiency due to quasi-phase matching. In this diagram the signal, blue arrow, is completely upconverted by the pump, red arrow, to the SFG wavelength, purple arrow.

A method of material engineering called periodic poling, illustrated in Fig. 3.1, can be implemented to compensate for phase mismatch between the waves. By adding a poling axis switch across the crystal nonlinear material with period $\Lambda$ a new term $k_g = 2\pi/\Lambda$, known as the grating vector, is introduced to the wave vector matching equation. The wave vector matching equation then becomes

$$k_s + k_p + k_g = k_{SFG}$$

or if there is imperfect matching then a mismatch of $\Delta k_Q$ where

$$\Delta k_Q = k_{SFG} - k_s - k_p - k_g = k_{SFG} - k_s - k_p - \frac{2\pi}{\Lambda}$$
Where $\Delta k_Q$ is the phase matching of a quasi-phase matched (QPM) system. Periodic poling is considered QPM because each period is not perfectly matched. The mismatch in one period has an equal and opposite phase mismatch in the next period. This balanced mismatch results in an overall positive transfer of energy from the signal and pump into the SFG band [37]. This allows all three beams to be copolarized reducing walkoff, and allowing the highest susceptibility nonlinear crystal orientation to be used.

Additionally, the efficiency of the phase-matching peaks in a QPM nonlinear waveguide is dependent on the phase matching as well, and takes the form of the sinc-squared function shown in Equation (3.5) [36].

$$\eta = \eta_0 \text{sinc}^2(\Delta k_Q L/2) \quad (3.5)$$

Where $\eta_0$ is the peak conversion efficiency and $L$ is the length of the waveguide.

Designing the poling period for given signal, pump, and SFG wavelengths is straightforward from Eq. 3.4 For the most basic case it can be seen that

$$\Lambda = \frac{2\pi}{k_o - k_s - k_p} \quad (3.6)$$

Now using a small signal regime and the undepleted pump approximation, the conversion efficiency of the waveguide has been shown to be

$$\eta = \frac{N_{SFG}(L)}{N_s(0)} = \sin^2((\eta_{nor} P_p)^{1/2} L) \quad (3.7)$$

where $N_i(z) = |E_i|^2/(\hbar \omega_i)$ is the number of photons existing in the state $i=s$, p, or SFG and depends on the position, $z$, in the waveguide. $P_p$ is the pump power in the waveguide which is invariant along the length of the waveguide, and $\eta_{nor}$ is a normalized efficiency
constant determined by the effective nonlinear coefficients and refractive indices of the wavelengths being considered. This relationship of upconversion efficiency dependence on pump power is illustrated in Fig. 3.2. The power required for maximum conversion can be calculated by setting the $\sin^2$ term in Eq. (3.7) to unity. This results in a power of

$$P_{\text{max}} = \frac{\pi^4}{4\eta_{\text{nor}} L^2}$$

(3.8)

Figure 3.2. Assuming a normalized efficiency of unity, the conversion efficiency has a sine squared relation with the pump-length factor. Here the length of the waveguide $L = 4.6$ cm and the conversion efficiency is 1000%/W which is taken from the Stanford waveguides in our laboratory. After a first maximum efficiency at pump power $P_{\text{max}}$ the efficiency decreases following a sine squared trend. Multiple high efficiency peaks exist at higher pump powers and are not considered for use in our system due to noise considerations.

It is apparent from the $\sin^2$ relation that the SFG upconversion efficiency oscillates as pump power is increased monotonically. Therefore, for practical use, the lowest $P_{\text{max}}$ is used to produce the least pump generated noise in the SFG band. Using the lowest $P_{\text{max}}$ also helps prevent any optical damage and photorefractive index changes in the medium.
Let us now consider the phase mismatch of the three waves in the waveguide, $\Delta k$, and its effect on the output intensity and phase-matching profile of the waveguide. Considering phase mismatch between waves in the SFG interaction, the intensity of the SFG is given by the square of Eq. (2.26)

$$I_{SFG} = 2n_3\varepsilon_0 c |E_{SFG}|^2$$

and if all of the constants and field values are set for maximum SFG conversion the equation becomes

$$I_{SFG} = I_{SFG}^{max}\text{sinc}^2(\Delta kL/2)$$

This dependence of the SFG intensity on a $\text{sinc}^2$ function describes the shape of the phase-matching profile of the waveguide. The width and null locations of the $\text{sinc}^2$ profile is based on the specific dispersion properties of the waveguide and the interacting wave vectors. As $\Delta k$ diverges from 0, the SFG intensity decreases. In waveguides, $\beta$ is often used for the phase mismatch, $\Delta k$, when describing the phase-matching profile. $\beta$ will be used when characterizing the waveguides in later sections of this chapter.

As shown above, periodic poling is effective for engineering devices with high conversion efficiencies, but fabrication variations in the poling period, duty cycle, and waveguide surfaces can cause parasitic effects. Imperfect poling periods and duty cycle cause decreased efficiency and undesired side peaks in the phase-matching curve. Waveguide channel imperfections can cause loss in the waveguide and alter phase-matching profiles. If wavelength restrictions on the pump, signal, and SFG in a system are tight then the index of refraction for the three waves must be accurately known as the correct poling period for phase matching depends on
all three wave vectors. For some materials even a refractive index error of one-thousandth can alter the behavior of the device\cite{31}.

KTP and LN are not only good candidates for nonlinear conversion due to their nonlinear susceptibilities, transparency window, and damage thresholds, but both materials have mature poling technologies as well. The basics of poling for a three wave interaction has been presented but more complex poling techniques, like chirped poling, can be used to engineer more complex phase-matching profiles and is not presented in this text. Multi-peak waveguides have been demonstrated for more complex SFG regimes with multiple pumps and signals and broad phase-matching peaks have been used for SPDC generation\cite{9,15}. Our experiments will take advantage of combinations of material engineering techniques to build complex systems utilizing SPDC and SFG for upconversion detection.

3.3. Characterization of Waveguides

Periodically poled LN (PPLN) and periodically poled KTP (PPKTP) are investigated for use in generating single photons via SPDC and for SFG conversion. Waveguide coupling and propagation losses, conversion efficiency, and phase-matching curves are very important for efficient detection systems. Temperature tuning of the phase-matching center wavelength also allows the periodically poled devices to operate across a band of frequencies\cite{11}. The following waveguide characterizations are focused on optimization for SFG. The analysis of the noise in the waveguides is combined with the analysis of other noise sources in the system and is reported in Chapter\cite{5}.

The first set of waveguides characterized are single and double peak PPLN waveguides from SRICO, chip number SR102214.2.C2. The chip is illustrated in Fig. 3.3 and contains 32 waveguides in groups of four, with the first four groups (16 waveguides) having single
phase-matching peaks, and the final four groups having double peaks in the phase-matching profile. Each group of four has one waveguide with no tapering, and the other three contain tapered inputs and outputs leading to varied channel widths. Varying the channel width changes the sensitivity to waveguide defects, the center wavelength, and peak conversion efficiency.

Figure 3.3. The layout of the waveguides on the SRICO PPLN chip. The top 4 groups labeled A-D have single phase-matching peaks, while the bottom four groups have two phase-matching peaks. Each group of four waveguides has tapered inputs and outputs leading to varied channel thicknesses that increases from waveguide to waveguide down the group. The waveguides are separated by 100 µm while the groups are separated by 250 µm. (Adapted from [39])
A simple freespace optical setup was used to couple a strong pump into the waveguide and the SHG and residual pump was observed on the back end. A SANTEC Tunable Semiconductor Laser (TSL-210) was used as a CW source out of which 160-ps pulses were carved using a simple amplitude modulator with a 50-MHz RF input. The pulses were then amplified using a homemade erbium-doped fiber amplifier (EDFA), passed through a fiber polarization controller, and filtered using a 3-nm bandpass tunable filter (Newport: TBF-1550-3) to remove any excess noise from the EDFA. The pump was then collimated into freespace and mirrors and a focusing lens were used to couple the pump radiation into the waveguide, Figure 3.4.

The SRICO chip was mounted on an aluminum oven that had an integrated 100-kOhm thermistor and a thermoelectric cooler (TEC) to monitor and control the temperature of the waveguide. The oven was mounted on a plate that was translatable in the x-axis, co-planar to the optical table and orthogonal to the direction of propagation. Once the pump was coupled into a waveguide, the oven fixture and waveguide chip could thus be shifted and the light could easily be coupled into a neighboring waveguide for the next characterization.

After the waveguide, a lens collimated the output beam and a dichroic mirror reflected the SHG band and transmitted the C-band radiation. An iris was used in the C-band path to get rid of any light scattered from the chip, so that only the fundamental mode guided by the waveguide was measured on the freespace detector (Thorlabs: PM100D). The reflected SHG band passed through a prism and another iris to further filter out any C-band light reflected off of the dichroic mirror. The SHG was then measured on a freespace detector (Newport: 818-SL) and the conversion percentage was calculated. The pump wavelength was tuned over a bandwidth of 20 to 30 nm around the peak conversion wavelength at room temperature to produce a phase-matching curve for each waveguide.
Figure 3.4. After pulse carving, amplification, and filtering, the pump was coupled into the waveguide using bulk optics. The waveguide was mounted in an oven to control its temperature and was translatable to simplify switching the coupling from one waveguide to the next.

Figure 3.5 presents samples from the conversion efficiency vs wavelength measurements. Overall the waveguides had peak SHG conversion efficiencies between 30 and 40%/$W$ with some higher than 70%/$W$. Most of the waveguides did not have a single clearly defined phase-matching peak due to appreciable SHG conversion at multiple wavelengths.

Across a group of four waveguides the peak upconversion wavelength for SHG increased from waveguide one to four and the conversion efficiency also increased across the four as well. This trend is expected as the waveguide channel widths are increased across a waveguide group which changes the phase-matching peak wavelength. Loss of between 5 to 6 dB was achieved through the waveguides, further alignment of the initial collimation lens and the focusing lens for the waveguide could yield better coupling into the waveguide, but the low conversion of the waveguides on this chip may render them useless for our experiments. Coupling to higher spatial modes is observed, but most of the power is in the fundamental mode. Due to the poor performance, $<100%$/W conversion, and noisy phase-matching curves of the SRICO waveguides, new waveguides were obtained from the Fejer group at Stanford.
Six PPLN nonlinear waveguide chips were received from Stanford and were AR coated to avoid back reflections at the output facet. Each chip consisted of 72 waveguides split into six groups of 12 waveguides each. Between each group is a multimode waveguide, or waveguide bookmark, used for alignment. When coupling to the waveguides, this bookmark can be used to track your location in the waveguide array. There are three different apodizations across the 6 groups of waveguides. The apodization is a gradual increasing and decreasing of
the nonlinear coefficient along the length of the waveguides. Apodization of the waveguides allows control of the parasitic side peaks in the phase-matching profile. The first and fourth groups have no apodization, $\chi^{(2)}$ is constant at its maximum value, while the second and fifth groups have 20% apodization meaning the first 10% and last 10% of the waveguide has a gradient $\chi^{(2)}$ which reduces side peaks in the phase-matching transfer function but also decreases the overall conversion efficiency. The third and sixth groups have 40% apodization, 20% of the first half and 20% of the second half which should further reduce side peaks but also further reduce the maximum conversion efficiency.

Each group of 12 waveguides is split into four sets of three waveguides, each set with different phase-matching curves. The first three waveguides in each group are single peak waveguides. Since they have a single peak the efficiency in these waveguides is generally higher than the waveguides with multiple peaks. These are useful for high output at the SFG wavelength making alignment of optics and thermal tuning easier since only one set of pump and signal wavelengths need to be considered. The following sets of waveguides all have five phase-matching peaks but are split into sets of three with 3, 4, and 5-nm separated peaks. Figure 3.6 illustrates the Stanford waveguide chip layout.

The Stanford chip was placed into the setup in Figure 3.4 and the loss, SHG phase-matching curve, and temperature tuning curves were recorded. The Stanford waveguides typically had total losses of 2.8 dB due to coupling and propagation through the PPLN. Figure 3.7 shows the SHG phase-matching wavelength vs temperature for a single peak waveguide on the chip. The peak phase-matching wavelength shifts at 0.138 nm/°C which is similar to other chips with PPLN waveguides[12].

The phase-matching curve for all of the single peak waveguides and two of the multi-peak waveguides were characterized. The phase-matching curves for the multi-peak waveguides
Figure 3.6. Each chip consists of 72 waveguides separated into six groups of 12. The first and third groups have no apodization, the second and fourth have 10% apodization on each end, and the third and sixth have 20% apodization on each end of the waveguides. The first three waveguides in each set, represented by dotted vertical lines, have single peak phase-matching curves, the other 9 in the set have five phase-matched peaks separated by 3, 4, and 5 nm in sets of three waveguides. *(Adapted from [40]*)

![Waveguide diagram](image)

Figure 3.7. SHG was observed on a single peak waveguide and the temperature of the chip was varied. The pump wavelength of peak SHG was tracked using a Santec tunable laser source. The waveguide exhibited a peak wavelength shift of 0.138 nm/°C which is similar to other reported PPLN devices.

![Graph](image)

were already recorded at Stanford so the tests we performed for the multi-peak waveguides was only to confirm the reproducibility of that data. None of the single peak waveguides
had been characterized so all of the phase-matching curves for the single peak waveguides were recorded.

![Graphs showing phase-matching curves for waveguides](image)

Figure 3.8. (a) Phase-matching curve for waveguide 3-2 on Stanford chip M21R1C2. The SHG efficiency reaches over 1000%/W. (b) Waveguide with higher parasitic side peaks. These two waveguides display the extreme differences between the single peak waveguides on the chip. All other characterized waveguides exhibit profiles with mixtures of lower conversion efficiency than (a) and less prominent side peaks than (b).

Single peak waveguides in group three had the highest conversion of around 1000 %/W compared to the other groups having 500 %/W and 300 %/W. For future references to waveguides, an address of the form #-# is used where the first number is the waveguide group and the second indicates which waveguide in that group. Waveguide 3-2 had the highest conversion and smallest side lobes in the phase-matching curve, so this waveguide was chosen for future experiments. The multi-peak waveguides generally had conversion efficiencies between 400 %/W and 500 %/W. Waveguide 2-12 had efficiencies greater than 500 %/W with only one appreciable side peak. Waveguide 2-12 was selected as the waveguide to use in future experiments where multi-peak waveguides are required.
<table>
<thead>
<tr>
<th>Waveguide ID</th>
<th>$\lambda_{\text{max}}$ (nm)</th>
<th>$\eta_{\text{max}}$ (%/W)</th>
</tr>
</thead>
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<td>1532.8</td>
<td>363</td>
</tr>
<tr>
<td>1-12</td>
<td>1532.2</td>
<td>398</td>
</tr>
<tr>
<td>1-11</td>
<td>1531.7</td>
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<td>1536.4</td>
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</tr>
<tr>
<td>6-11</td>
<td>1537.2</td>
<td>212</td>
</tr>
</tbody>
</table>

Table 3.2. Measured efficiencies span from 100 %/W to >500 %/W for the waveguides with multi-phasematched peaks at 54°C. Waveguide 2-12 has peak separations of 5 nm which displayed the highest conversion efficiency. This waveguide will be used in experiments that require media with multiple phase-matching peaks.

The observed conversion efficiencies, between 500 to 1000 %/W, and required peak pump powers of between 100 to 200 mW should be sufficient for peak SFG conversion with available optical sources. Amplifiers are readily available to amplify pumps within the required wavelength range, and many filtering technologies are available in the measured SFG wavelength bands for backend filtering. Moving forward, the Stanford chips should provide sufficient SFG for an upconversion detection system with low required pump powers.
Figure 3.9. The phase-matching transfer function for waveguide 2-4 on the Stanford chip. This waveguide is an example of a phase-matching profile with peaks separated by 3 nm. A 3-nm peak separated waveguide will be used for multichannel temporal mode demultiplexing in Chapter 7.
CHAPTER 4

SFG Pump Pulse Optimization

A system can be created that extracts single modes of a field while all other modes co-propagating in the same time bin are left unaffected by a strong pump pulse. Using SFG for this selection process is practical due to the fact that SFG is only efficient for certain polarizations, k-vectors, and wavelengths where QPM is satisfied. Therefore, by designing the phase-matching conditions of the waveguide, a single signal mode can be converted with high efficiency while all others are left in the C-band. This requires complicated fabrication techniques and has only been proven to work with a few materials \[41,42\]. Also, a waveguide engineered for a single temporal mode set will not necessarily perform efficient upconversion selection on a different mode set, and therefore is not robust. Instead of engineering a specific material profile and assuming given phase-matching conditions of a waveguide, the pump temporal profile can be engineered to select a single signal mode and leave all other orthogonal modes in the set unaffected \[20,22\]. This chapter presents simulations and a genetic optimization algorithm developed to generate an orthogonal set of signal modes, and determine corresponding pumps to selectively upconvert independent modes through SFG.

4.1. Introduction to Single Photon Generation

Single photons are essential for implementation of many quantum technologies and can be generated through various methods \[22,43–46\]. Photons from photon pairs with frequency or
space-time correlations may reveal distinguishing information about the state of the corre-
lated photon and therefore cause the photon to be useless in quantum experiments. Depend-
ing on the experiment, sensitive information could be encoded in the wavelength, temporal
position, polarization, or k-vector. That being understood, the single photon source must
be designed to preserve the sensitive information in the quantum experiment. Spectral cor-
relations between the photons often reveal such information. One way to prevent this is to
implement filtering on the system. Narrow band filtering can limit the amount of distin-
guishing information of a correlated photon pair, but due to the short coherence times of
some generated photons, many usable pairs are filtered out, lowering the generation rate of
the source significantly. Increasing the pump power can compensate for this but it raises
the background noise and can create undesired multi-pair emissions.

Many efforts have focused on generating single photons that are uncorrelated in frequency
space, called factorable states. These factorable states result in high purity pairs with
high production rates. This can be achieved through proper engineering of the system
considering factors such as pump wavelength, nonlinear medium, phase-matching bandwidth,
and crystal length. The key behind generating factorable photon states is a separable joint
spectral density function.

$$\Phi(\omega_s, \omega_i) = \phi_s(\omega_s) \cdot \phi_i(\omega_i)$$ (4.1)

Where $\Phi$ is the joint spectral density and $\phi_s$ and $\phi_i$ are the spectra for the signal and idler
generated photons. Factorable states are generated when the joint spectral density is the
product of two independent spectra as shown in Eq. (4.1). The shape of the joint spectral
intensity is controlled by the pump bandwidth and the waveguide length. It is desirable to
engineer the joint spectral density to be an ellipse, shown in Fig. 4.1 (b), when generating factorable states\textsuperscript{43,45}.

Figure 4.1. Joint spectral density plots generated by the SPDC mode set code. (a) The joint spectral density for a non-factorable state. (b) The joint spectral density of a factorable state. Both are ellipses but it is clear that the joint spectrum in (b) can be separated into two independent spectra along the x-axis, $\omega_s$, and the y-axis, $\omega_i$.

It has further been shown that factorable states are not necessary as long as the detection system does not reveal any distinguishing information of the heralded photon. Using a broadband rectangular filter of width $B$ in radians per second, and detector temporal resolution of length $T$ where

$$ BT < 4 $$

allows only the measurement of a single temporal mode resulting in no knowledge of when the photon arrived within the window time $T$. The resolution time $T$ can be controlled by putting a shutter in front of the detector or gating the detector. Therefore, narrow bandwidth filters are not required as long as the temporal resolution of the detector is compensated
accordingly. In this way the loss can be reduced and high-purity single photons can be produced at a high rate\textsuperscript{45}. At this point a specific method and material must be selected for photon generation since there are a number of media to choose and methods for creating them.

Nonlinear wave mixing in solid state media is commonly used to generate entangled photon pairs. In fact, entangled photons can be generated in any nonlinear medium as long as no distinguishable information is revealed about the generated photons. For a nonlinear waveguide this is accomplished when $B_{pm}T_p < 1$, where $B_{pm}$ is the phase-matching bandwidth of the material and $T_p$ is the temporal width of the pump pulse. The exact temporal location of the generated photon is not able to be determined when $B_{pm}T_p < 1$, and therefore no distinguishing information is revealed\textsuperscript{20}. With this restriction, photon pairs in a broad spectrum, over 100 nm, can be generated from a single source. PPKTP, PPLN, and dispersion-tailored optical fibers are commonly used as single-photon sources. Photon generation in PPKTP and PPLN is due to SPDC, a second-order nonlinear process, whereas in optical fibers, pairs are generated from four-wave mixing, a third-order nonlinear process\textsuperscript{22,48}. Using optical fibers to generate photons has many advantages including easy input coupling, low loss when coupling to other devices, compatibility with telecommunication technologies, and it is compact and conveniently portable. Theoretically, four-wave mixing in optical fibers can generate photon pairs at much higher rates than other current methods but the overwhelming issue with optical fibers is noise due to spontaneous Raman scattering\textsuperscript{44,49,50}. By choosing a signal polarization orthogonal to the pump, the Raman noise is reduced, but the four-wave mixing efficiency is also three times less efficient in this regime. The Raman process also effects the four-wave mixing efficiency by changing the refractive index of the material due to the Kramers-Kronig relations which creates further hurdles\textsuperscript{14}. After weighing the benefits
and drawbacks of using fiber for single photon generation, we chose to focus on using the second-order nonlinear process of SPDC for single photon generation in PPKTP and PPLN.

4.2. Generation of Signal Sets

MATLAB code was developed using SPDC as a model to simulate the generation of photons in an orthogonal temporal mode set. For the pump, a super-Gaussian pump profile represented by

\[ E_p = e^{-t^2M/2\sigma^2M} \] (4.3)

is used. Where \( E_p \) is the pump field, \( \sigma \) is the standard deviation of the pump in the time domain, and \( M \) is a positive integer representing the order of the super-Gaussian shape. When \( M = 1 \) the pump pulse is Gaussian, whereas with higher values of \( M \) the super-Gaussian becomes more square, as shown in Figure 4.2. When referring to the pulse width, I will use values twice that of the standard deviation so a 20-ps pulse has \( \sigma = 10 \). The width of the pump pulse controls the number of modes generated and their generation efficiency. The comb lines generated in our system are spaced at 20 GHz which corresponds to a 20-GHz repetition rate of the shaped pulses, or a pulse every 50 ps. Thus, the width of the pump for SPDC is limited to less than 50 ps. A filter is used to limit the spectral content of the pump and the generated signal and idler photons. Higher frequency content is filtered out by tightening this filter bandwidth which reduces the generation of higher-order modes.

The joint spectral intensity, \( \Psi \), is calculated to determine the temporal mode shapes of the SPDC generated signal and idler photons in Eqs. (4.4a), and (4.4b).
Figure 4.2. Super-Gaussian pump field shapes with $\sigma = 25$ and varied values of $M$. The pump becomes Gaussian when $M = 1$, and approaches a squared shape with increased values of $M$.

$$\Phi = c \times \text{sinc}\left(\frac{\mu_s \omega_s + \mu_i \omega_i}{2}\right) \quad (4.4a)$$

$$\Psi = \Phi^2 \quad (4.4b)$$

Where $c$ is the set of spectral values given by the Fourier transform of the pump field and $\mu_s$ and $\mu_i$ are the phase-matching coefficients for signal and idler fields. In our simulations phase matching is assumed so a value of 0 is used for $\mu_s$ and $\mu_i$. A singular-value decomposition is performed to find the orthonormal mode sets for the generated signal and idler photons in the frequency domain. The efficiency of generating a specific mode is also
recorded and the pump width and filter bandwidths are tuned to control the number of generated modes and spectral content allowed into the system. Higher spectral content requires more waveform generator frequency-comb bandwidth to resolve the signal pulses and generate high conversion pumps. Figure 4.3 displays various temporal mode shapes generated from an SPDC system along with the probability of generation, $\lambda_i$ for each mode number $i$.

Figure 4.3. The generated SPDC signal mode set with a 25-ps 5th order super-Gaussian pump and 2.4-nm spectral filter on the generated signal and idler. The plots contain the temporal profiles for the first three odd numbered modes (left), the first three even numbered modes (right), and the probability of generating the modes $\lambda_i$ for the first ten modes (bottom).
4.3. Split-Step Method

Now that the method of generating an orthonormal mode set has been established, a set of pump pulses must be determined to select a desired mode from this set. To derive these pump pulses, a split-step method is performed using the nonlinear coupled mode equations from Chapter 2. For a given signal mode, an initial pump guess is made. The initial pump is a copy of the temporal profile of the signal chosen for high conversion, only with greater amplitude. In the laboratory, these pumps will be shaped by our pulse-shaping system which has a limited bandwidth due to the number of available comb lines and comb line frequency spacing. These technical limitations are taken into account in these optimizations and the number of discernible modes, given various sets of frequency comb parameters, is determined. The pump and signal are propagated through the waveguide and the generated sum frequency field is calculated using a discretized split-step method. The same pump is then propagated through the waveguide with each other signal in the set and each signal’s corresponding SFG is found. Using the percent of SFG conversion for each signal under a given pump, the selectivity for a specified mode is calculated and recorded.

A random perturbation in phase and amplitude is then applied on one randomly chosen pump comb line. The pump is then propagated through the waveguide again with the set of signals and new SFG efficiencies and selectivity is calculated. If this selectivity is higher than the value obtained in the previous iteration, then the new pump comb line values are kept and the next iteration of this perturbative process continues. If the new selectivity is lower than that from the previous iteration, then the perturbed pump is discarded and another random perturbation is applied to the previous pump profile and passed through
the system. This iterative process continues until a specified SFG efficiency and selectivity are met, or alternatively, after a set number of iterations are completed.

Figure 4.4. Pump optimization process diagram. A signal from the orthogonal signal set is selected and an identical pump, with higher amplitude, is injected into the stepwise SFG algorithm with it. The SFG efficiency and selectivity are calculated and stored in memory. A perturbation is applied to the pump, the efficiency and selectivity are calculated and compared to the previous values. If the performance has degraded the new pump is discarded and the old pump is again randomly perturbed. If performance has improved the new pump is kept and a new perturbation is applied. This process continues until specified efficiencies and selectivities are met, or the number of iterations reaches a determined limit.

A split-step method is used to calculate the SFG conversion of the signals in the waveguide. For a nonlinear waveguide of length $L$, step sizes of $dz \ll L$ are used. Two processes occur in the waveguide, the linear effects including dispersion and phase change due to propagation, and the nonlinear effects of the strong pump acting on present signals. First, the linear effects are calculated over a distance $dz$, the output fields are then re-propagated through the same length $dz$ and the nonlinear effects are applied. In this way, the pump and signal are each propagated though small lengths $dz$ until the entire length of the waveguide has been traversed.
Figure 4.5. Split-step process for pump optimization. First the linear effects are calculated on the input pump (red arrow), input signal (blue arrow), and SFG waves over a distance $dz$ in the waveguide. Then the nonlinear effects are calculated over that same length. The green arrow represents the linear propagation while the orange arrow represents the nonlinear contribution. The output SFG is represented by the purple arrow.

Some important assumptions to note include that since we are using waveguides for the nonlinear medium, instead of bulk crystals, incoherence due to off axis SFG k-vectors can be ignored\cite{51}. Large nonlinear phase shifts can be caused by a strong pump but they are not considered in this analysis due to the materials and pump powers used\cite{52}. Group velocity dispersion of the three fields is negligible for the selected mediums and the length of the pulses in the system\cite{20}.

4.4. Statistics of Interest

The outputs of the split-step method code are the three field amplitudes in the time domain: the pump, the residual input signal, and the SFG. The initial input signals and the
SFG output of each mode are used to calculate the statistics of interest (SoI) used for the optimization process. The three SoI are presented in Eqs. (4.5a)-(4.5c).

\[ \eta_{jk} = \frac{E_{SFG}^{jk}}{E_j^{s}} \]  

(4.5a)

\[ D_{jk} = \eta_{jk} \times \left( \frac{E_{SFG}^{jk}}{\sum_{l=1}^{n} E_{SFG}^{lk}} \right)^2 \times \lambda_j \]  

(4.5b)

\[ M_{TN} = \sum_{j=k=1}^{n} D_{jk} \]  

(4.5c)

where \( E_{SFG} \) and \( E_s \) are the energy in the SFG and input signal fields respectively. The subscripts denote the signal and pump number so \( \eta_{jk} \) is the conversion percentage of the \( j^{th} \) signal mode under the influence of a pump optimized for conversion of the \( k^{th} \) signal mode.

The mode distinction (MD), \( D_{jk} \), is determined by multiplying this conversion percentage by the field generation efficiency, \( \lambda_j \), for the \( j^{th} \) mode. The ratio in the mode distinction compares the energy of the generated SFG for a given signal and pump mode interaction to the sum of the SFG generated by that pump acting on all the modes independently in the system. I will refer to this ratio as the SFG energy ratio. For perfect distinction, the only mode with energy converted to the SFG wavelength would be a single mode of interest and therefore this ratio would be unity. As energy of other modes is also converted to the SFG wavelength, this ratio decreases lowering the mode distinction parameter and showing that the system cannot perfectly extract a single temporal mode from the orthogonal mode set. \( M_{TN} \) is the total number of modes (TNM) and is a sum of the mode distinctions across the entire signal set and approximates the number of discernible modes in the system. If the generation of a mode is unity and the conversion efficiency of that mode under a given pump
is perfect, and the SFG energy ratio is near unity for a given pump and signal combination, then the TNM increases by 1. The mode distinction decreases for higher modes due to low conversion efficiency of the desired mode, or low generation of that mode, and therefore the mode distinction contribution to the TNM decreases until at some point it becomes completely negligible. So if the first four modes in an orthogonal mode set under designed pumps have high mode distinctions then the TNM will have a value close to, but not above, 4. In this way, an estimate of the number of modes the system can resolve is determined.

Using the defined SoIs and applying a range of bandwidth signal sets and OAWG resolution capabilities, system trends were explored. The results allow us to design an orthogonal signal set that provides good upconversion temporal mode distinction for a realizable system. The simulations also can provide valuable insight into what potential bottle necks in the realizable system might be, and how to improve such an upconversion mode-selective system.

4.5. Results of Simulations

SFG optimization is performed on the modes generated by the 30-ps SPDC pump pulse with a 2.4-nm filter. Initial values for the waveguide parameters are taken from waveguides obtained from characterizations of the AdvR waveguide chips. These waveguides have a $\beta$ value of 2.54 ps$^2$/cm and a length of 4 cm. The number of comb lines and the frequency spacing of the optical frequency comb determines the temporal resolution of the pulses that the OAWG can generate. We use values of 20, 30, and 40 comb lines at 20-GHz spacing to determine the maximum number of distinguishable modes for each scenario. Figure [4.6] shows a signal mode reconstructed by an OAWG with varied numbers of frequency comb lines.
Table 4.1. Mode distinction values for the first 10 modes of the orthogonal signal set after pump optimization. Systems with optical frequency combs containing 20, 30, and 40 comb lines are analyzed. The mode set is generated from a 30-ps pump pulse with 2.4-nm bandwidth filter through SPDC. Little difference is observed between the 30 and 40 comb line cases while the 20 comb line system shows degraded performance due to its smaller bandwidth.

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Table 4.1 shows the mode distinction values calculated for the signal modes generated by the 30-ps SPDC pump with a 2.4-nm filter with 20, 30, and 40 comb lines controlled by the wave shaper. The TNM is also reported for each optimization scenario. The 30 and 40 comb line cases both can support between 4 and 5 modes after which the MD values drop below 0.5. The fact that the 30 and 40 comb line systems perform similarly means that the 30 comb line system has enough bandwidth to properly resolve the modes of interest. The 20 comb line case has less temporal resolution and therefore can only distinguish up to mode 3.

A wider filter generates higher order SPDC modes with increased probability and provides broader bandwidth signals to the SFG stage. With broader bandwidth signal sets, the OAWG requires a broader comb bandwidth to optimize pumps that can achieve high mode distinction. Table 4.2 shows the MD values where a 4.8-nm filter is used on the signal set. The 20 and 30 comb line cases show low MD values before the 4th mode, whereas in the 2.4-nm filter case the lower spectral content signal set allows for the 20 and 30 comb line scenarios to have better performance, as shown in Table 4.1. For the 4.8nm filter case, the MD values are all below 0.2 by the 8th mode. Figure 4.7 shows the conversion efficiency of the mode set generated with the 4.8-nm filter case with optimized pumps in 20, 30, and 40
Figure 4.6. The number of comb lines and frequency spacing of the optical frequency comb determines the bandwidth of the OAWG. A broader OAWG bandwidth allows for greater temporal resolution of the reconstructed pulses. OAWGs with smaller bandwidths are unable to fully resolve the high frequency content of signal modes. Both reconstructions shown are for the sixth mode of the signal set.

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Table 4.2. Mode distinction values for the first 10 modes of the orthogonal signal set after pump optimization. Systems with optical frequency combs containing 20, 30, and 40 comb lines are analyzed. The mode set is generated from a 30-ps pump pulse with 4.8-nm bandwidth filter through SPDC.

In these plots, it is desirable to have high values along the diagonal with low values everywhere else. It is apparent that the 40 comb line case can resolve more modes than the 30 and 20 comb line cases due to the extent at which the diagonal pillars maintain larger values at higher mode numbers.

SFG optimization was performed for signal sets generated by super-Gaussian SPDC pump pulses with widths of 20 ps, 30 ps, and 40 ps. Two different spectral filters of 2.4 nm and 4.8
Figure 4.7. More modes are generated in the system when a 4.2-nm filter is used on the SPDC signal and idler spectra. This raises the generation probability of higher modes as well as the spectral content of all modes. For the various systems analyzed the 40 comb line case has a clear advantage over the 30 and 20 comb line systems. A mode is considered resolvable when a high value on the diagonal exists with all off diagonal values very low or ideally 0.

nm were used to limit the number of modes and spectral content in the system. Optical frequency combs with 20, 30, and 40 comb lines were generated with 20-GHz spacing. The MD values for each scenario were summed to characterize the number of distinguishable modes. Figure 4.8 shows the number of distinguishable modes against the ratio of waveshaper to pump-pulse bandwidth. The number of distinguishable modes increases to a point then levels out at a filter bandwidth about twice that of the SPDC pump bandwidth. The results show how the OAWG resolution capabilities, due to limited comb lines and bandwidth, and SFG selection perform with various bandwidth signal sets. As the number of comb lines increases, the technical complexity of the calibration and control of the optical frequency comb also increases. From Fig 4.8, it is apparent that the minimal optical frequency comb bandwidth
should be twice that of the SPDC pump bandwidth. This allows a simpler technical implementation using the OAWG while maintaining maximum conversion and distinction of the modes in the system.

![Graph showing the total number of distinguishable modes versus the ratio of OAWG bandwidth to SPDC pump bandwidth.](image)

Figure 4.8. The total number of distinguishable modes verses the ratio of OAWG bandwidth to SPDC pump bandwidth. An OAWG with bandwidth greater than twice the pump pulse bandwidth provides no extra benefit or increased performance for the 15 ps pump pulse scenarios.

The filter applied to the signal modes limits the bandwidth of the modes for SFG optimization. Figure 4.9 shows that in 10 and 20 comb line systems, the number of distinguishable modes decreases as the SPDC filter width to pump bandwidth ratio increases. This is because the wave-shaper bandwidth is too small to resolve the fast temporal fluctuations of the modes being passed through the filter. At 40 comb lines, the bandwidth is adequate to maintain a high level of distinguishability for a wide signal mode filter. As expected, the 40 comb line case can distinguish the highest number of modes but only when the filter
Bandwidth is wide enough to allow a large number of modes into the system. This delicate balancing act is important for generating the desired number of modes while limiting the frequency content of these modes to ensure high conversion and mode distinction.

Figure 4.9. The total number of distinguishable modes verses the ratio of filter bandwidth to SPDC pump bandwidth. Selecting a proper SPDC filter is important to generate the number of modes required in the system while limiting the bandwidth of the generated modes to ensure high performance.

Figure 4.10 shows the number of distinguishable modes with various OAWG bandwidths. As expected, the wider 4.8-nm filter allows more modes through and therefore has higher TNM when a system with enough OAWG bandwidth can resolve the modes. With the 4.8-nm filter, both the 20-ps and 30-ps SPDC pump modes perform worse than the 2.4-nm filter case due to insufficient resolution of the OAWG. By limiting the bandwidth of the signal modes to 2.4 nm, the 20 and 30 comb line waveshaper systems are able to distinguish between 3 and 4 modes due to decreased spectral content in the mode set. For the mode
sets with the 2.4-nm filter, having more than 20 comb lines provides no added performance benefit. By letting more modes into the system with higher spectral content, the 40 and 60 comb line systems can distinguish up to 6 modes. The 20 and 30 comb line systems perform worse with the 4.8-nm filter. The added spectral content is too much for the lower bandwidth OAWGs to resolve.

Figure 4.10. The total number of distinguishable modes versus the OAWG bandwidth. Mode sets with higher spectral content, orange circles and purple triangles, allow higher TNM due to the greater number of modes in the system while the lower bandwidth content sets are limited.

Best performance of the system is accomplished when the OAWG bandwidth, SPDC pump pulse bandwidth, and filters are chosen carefully. Different combinations of SPDC pump and OAWG bandwidths are required for a system with six modes versus one with only four. The reported trends above can guide the design of a system and assist in understanding the trade-offs between the pump, signal, filter, and OAWG bandwidths. It is also important
to note that more OAWG comb lines does not mean better performance. The TNM saturates after a certain optical frequency comb bandwidth is reached for a given mode set. Also, having more modes generated in the system allows the lower order modes to receive higher frequency content as well which can reduce the performance of the system given a set number of comb lines. All of these parameters must be considered carefully to ensure that the desired performance is achieved.

Pump optimization simulations were performed for multi-peak waveguides to support experiments. Due to experimental constraints, only 3-nm and 5-nm peak separated waveguides were considered. Tables 4.3 and ?? compare optimizations performed for the two multipeak waveguides with varied numbers of pumps, frequency comb lines, and number of optimization iterations.

4.6. Error and Robustness Analysis

In order to verify the robustness of the OAWG-enabled QFC technique, we performed simulations by adding intensity and phase-noise to the frequency combs of optimized pump pulses. In this way, the errors in the programmable OAWG technology were simulated and the effect on conversion efficiency and mode distinction were evaluated. The conversion efficiencies for the mode set in Figure 4.3 were calculated with normally-distributed random perturbations added to each optimized pump comb line. Both the amplitude and phase were given error for each comb line. The mean of the random amplitude perturbation distribution was equal to that comb lines amplitude, $c_i$ for $0 < i < N$, where $N$ was the total number of comb lines, and had a standard deviation $\sigma = 0.05 \cdot c_i$. Similarly, random phase perturbations were applied to each comb line with a standard deviation $\sigma = 0.05 \cdot 2\pi$ (18 degrees). We performed 99 trials using the noisy pumps and the conversion efficiencies for each mode were calculated
Table 4.3. Conversion percentage and mode distinction for two and three mode systems using 3-nm and 5-nm peak separated waveguides. Two different frequency combs, 17 and 25 lines, are used to compare the ability of a given frequency comb to resolve two or three signal modes with 250 iterations of the perturbation algorithm.

and recorded. The mean and standard deviation of each modes conversion efficiency were calculated for the set of 99 trials. We show the effects of the amplitude and phase noise on lower- and higher-modes in Fig. 4.11. For the third mode, the optimized conversion efficiency was 93.5%, which reduced to $85 \pm 0.91\%$ when the noise was added to the pump. Similarly, the eighth mode had an optimized conversion efficiency of 92.4% which reduced to $83 \pm 0.9\%$ with the presence of noise. With 5% noise added to each comb line phase and amplitude, the mean conversion for the selected modes reduced by 8 to 10%. Despite the decrease in conversion efficiency for individual modes, the mode-selectivity remained robust to these perturbations, and stayed above 10 for modes 1 through 8, 9.8 for mode 9, and 9.7 for mode 10. Furthermore, comparing the noisy pump pulse shape to the optimized pump
Table 4.4. Conversion percentage and mode distinction for 2 and three mode systems using 3-nm and 5-nm peak separated waveguides. Two different frequency combs, 17 and 25 lines, are used to compare the ability of a given frequency comb to resolve two or three signal modes with 500 iterations of the perturbation algorithm.

In conclusion, SFG can successfully be used to convert a single mode of an orthogonal set with high distinction. By varying the SPDC generated signal modes, signal filter bandwidth, and OAWG bandwidth, the number of discernible modes can be engineered for a given waveguide. A four mode system can be realized with a 30-ps SPDC pump and 2.4-nm signal filter which is implementable in our lab with the Srico or Stanford waveguides and OAWG currently in use. Increasing the bandwidth of the OAWG increases the number of discernible modes until its bandwidth is about twice that of the pump bandwidth. A wider filter allows
more modes into the signal set but also requires greater OAWG bandwidth to generate SFG pumps that are able to resolve the faster temporal mode fluctuations. The robustness of the system to OAWG error is promising for stable, repeatable measurements and a realizable SFG-based mode selection system.
CHAPTER 5

SFG and Single Photon Detection

5.1. Noise Sources

Single-photon level measurements require that potential noise sources be identified and reduced as much as possible. Three noise generating process are of concern for quantum sum-frequency generation (QSFG) which are SPDC, second harmonic generation (SHG), and Raman scattering, illustrated in Figure 5.1. The first of these three, SPDC, can be avoided by selecting a pump wavelength that is longer than the signal wavelength. In this regime, the SPDC cannot produce noise photons in the signal band. The second noise source is second harmonic generation due to the strong pump. Most upconversion systems avoid this by placing the pump and signal wavelengths far apart and further detuned from the phase-matching peak than in our regime. For example, in a system with a signal near 1550 nm and a pump near 1800 nm, any SHG due to the pump is further from the SFG wavelength and is therefore easier to reduce through filtering. Prisms and multiple bandpass filters can be used to reduce the SHG in the signal channel to produce an acceptable signal to noise ratio (SNR) for our upconversion system. Due to both our pump and signal being in the C-band, the SHG and SFG will only be separated by a few nanometers which requires tighter filtering and could cause some leakage of nearby SHG into the upconverted signal path. The C-band is convenient to work in due to highly-developed low-cost technologies which make implementation and scalability very easy. Also, commercial OAWG waveshaping technologies are available in the C-band.
The final noise source, Raman scattering, is reduced by placing the signal wavelength in the anti-Stokes region of the pump and making sure that the waveguide has high conversion efficiency. Since Raman noise generation is linearly proportional to the optical power, using a waveguide with high conversion efficiency allows lower pump powers for efficient SFG, therefore reducing Raman emissions. Most Raman measurements are taken with large differences in the signal and pump wavelengths, for example with a pump at 1550 nm and the signal in the 1310-nm band. This reduces the Raman greatly, but for signals in the 1550-nm band pumps would need to be above 1800 nm which is inconvenient with current OAWG technologies. A temporal mode upconversion selection system with both the pump and signal wavelengths in the C-band is more compatible with modern technologies so an investigation into near-band Raman generated noise is conducted.

![Figure 5.1. Spectrum of pump, signal, SFG, SPDC, and Raman noise. The pump should have a frequency lower than the signal to prevent any SPDC from being generated in the signal band. Signals are typically chosen that are far from the pump to reduce the Raman noise at the signal wavelength. (Adapted from [12].)](image)

The Raman noise generated in PPLN and PPKTP waveguides from AdvR was investigated. A 1533-nm pump with a 160-ps FWHM at a 50-MHz repetition rate was injected
into the fiber-coupled input, freespace output (FIFSO) waveguide. The peak pump power was set at a level that would achieve maximum SFG conversion in the waveguide. After the waveguide, a 1-nm bandwidth tunable filtering system was used to measure the Raman generation at wavelengths from 0 to 26 nm away from the pump. The selected band was then sent to a single-photon detector (Nucrypt, CPDS-2000-4-C) where the counts were recorded. Filtering was performed before the waveguide to reduce any Raman noise generated in the fiber before the waveguide. To quantify the input background noise, the waveguide was removed from the system and the noise counts at the wavelength bands of interest were recorded. A fiber was added before the 1-nm filtering system that was the same length as the fiber pigtail on the AdvR device to generate an estimate for the amount of noise generated in the filter pigtail of the waveguide. In this way the background was subtracted from the measured counts with the waveguide in the system, and the Raman noise generated in the waveguide was calculated. Raman noise can be generated copolarized with the pump or in the orthogonal polarization. The PPLN waveguide only guides polarizations parallel to the input field so only one polarization was investigated for the PPLN waveguide, while both polarizations were investigated for the PPKTP waveguide. Figure 5.2 shows the system layout and results of the measurements.

Both the PPLN and PPKTP exhibit the lowest Raman generation around 10 nm away from the pump. In the PPLN waveguide the lowest Raman counts was 8e-5 counts per pulse. The PPKTP had overall higher Raman generated noise with a peak 16 nm away from the pump which resulted in 3e-3 counts per pulse. The results show that a low Raman noise regime can be designed with the signal and pump wavelengths in the C-band as long as an investigation into the location of the Raman noise trough is conducted. For these waveguides that trough was at wavelengths between 10 and 15 nm away from the pump as shown in
Figure 5.2. (a) The experimental setup for the Raman measurement. A strong pump was injected into a waveguide after Raman from the fibers was filtered out. Two tunable bandpass filters were used to measure Raman generated from 6 to 26 nm away from the pump. (b) Raman generated at various wavelength distances from the pump. The lowest Raman generation was measured to be 8e-5 counts per pulse at a distance of 10 nm from the pump in the PPLN waveguide.

Figure 5.2b. It is likely that the increased noise when the pump-signal wavelength distance was <10 nm was due to pump leakage into the signal band rather than pump generated Raman.

5.2. SFG Experimental Setup

Using the results from Section 5.1 a low noise upconversion detection system was built. Two tunable lasers were used for the pump and signal sources. For the pump, a Pure Photonics laser (PPCL200) supplied 1550.2-nm continuous wave (CW) radiation while a Santec Tunable Semiconductor Laser (TSL-210) supplied CW radiation for the signal. The pump and signal were combined using a WDM and sent to a pulse shaping system. Two different pulse shapers were used in the experiments. The first was comprised of an amplitude modulator that carved out 160-ps pulses at a 50-MHz repetition rate. The second shaping system consisted of a frequency comb generator and a commercially available OAWG device.
The frequency comb generator consisted of a cascaded configuration of phase and amplitude modulators strongly driven by 20-GHz RF signals. The optical frequency comb generated 17 comb lines with peaks typically within 5 dB of the maximum comb line amplitude. After the waveshaper the pulses were amplified by a Lightwaves 2020 EDFA and pulse picked to reduce the repetition rate to 1.25 GHz. The side peaks of the temporal pulses in Figure 5.3 are due to imperfect pulse picking and are not expected to contribute significantly to the noise in the SFG band due to the nonlinear dependence of SFG on pump power. Since Raman noise has a linear relationship with power, the Raman noise generated by the side peaks can be approximated by taking the ratio of the power in the side peaks and comparing it to the power in the main peak.

After pulse shaping, the pump and signal were then separated using an in-line 5-nm bandpass filter centered at 1550 nm. The pump was further amplified using an IPG EDFA (EAD-100-C) and passed through a polarization controller and two WDMs to filter out any Raman generated photons or EDFA noise in the signal band. The pump was coupled to freespace and passed through two Semrock filters. First a 3-nm bandpass filter centered at 1550 nm (NIR01-1550/3-25) and then an angle tunable bandpass filter centered at 1570 nm (NIR01-1570/3-25) to further reduce any signal band noise in the pump path. The 1570-nm filter was angle tuned to transmit the pump wavelength. After the filters, two mirrors and a lens were used to couple the pump into the waveguide. The waveguide used for these experiments was the second waveguide in the third group on the Stanford PPLN chip (M21R2C2 #3-2), whose phase-matching profile is shown in Figure 5.4.

After the pump and signal were pulse shaped and separated by the WDM, the signal passed through a tunable delay line (General Photonics: VDL-001-35-60-FC/PC-55), a tunable attenuator module (JDS Uniphase: HA11), a fiber polarization controller, and then
Figure 5.3. (a) Output pulse from the amplitude modulator with a 160-ps width and a 50-MHz repetition rate. (b) Pump pulse output from the waveshaper which is a 5th order super-Gaussian with a 20-ps width at 1.25 GHz. (c) Signal pulse from the waveshaper which is a Gaussian with 15-ps FWHM. The side pulses 20 ps away from the main pulses in (b) and (c) are due to imperfect pulse picking.

was coupled to freespace. The signal was then directed onto the output face of the 1570-nm centered Semrock filter that the pump was transmitted through. The signal was incident on the Semrock filter at the point at which the pump emerged from the filter, and the signal was reflected at an angle that caused the pump and signal to copropagate and couple into the waveguide. In this way, the 1570-nm bandpass filter functioned as both a filter for the
strong pump and a beam combiner for the pump and signal. Figure 5.5 shows the freespace setup for the waveguide coupling and SFG conversion vs noise measurements.

SFG phase-matched wavelengths are approximately symmetric around the SHG phase-matching wavelength at a given temperature. After a phase-matched SHG wavelength was found at room temperature, the temperature of the waveguide chip was increased until an ideal center phase matching wavelength for SFG was found. This was achieved by tracking the phase-matching peak using a tunable laser and observing the peak SHG generation wavelength as the temperature was increased. The pump and signal wavelengths were then chosen symmetrically around the SHG wavelength and efficient SFG was observed. After the waveguide, the SFG was separated from the residual pump and signal, and filtered to ensure that no pump, signal, or SHG from the pump was present in the SFG path. To properly align the backend system, the pulse carving was removed so that the pump and signal were
The pump and signal were combined on a freespace filter and coupled into the waveguide. The SFG was separated using a dichroic mirror and a prism. The residual pump and signal were coupled into a fiber to be observed on the OSO. The detector D1 was inserted into the SFG path to maximize the pump and signal coupling to the waveguide and find the peak phase-matching temperature. After the maximum SFG was achieved, the detector was removed and the SFG was allowed to propagate into the single-photon detection system.

After the waveguide, a dichroic mirror passed the C-band and reflected the SFG signal. The residual C-band pump and signal were then fiber coupled and separated using WDMs so that the signal depletion could be observed on a fast sampling oscilloscope called a digital communications analyzer (DCA), as shown in Figure 5.6. The SFG was reflected off of the dichroic mirror and passed through a system of prisms, mirrors, irises, and narrowband filters before being detected on the SPCMs. The prism dispersed the C-band radiation and SFG radiation at different angles allowing the irises to act as frequency filters due to the 

both CW. This removed any pulse overlap timing complications and allowed the SFG to be easily observed with the naked eye.

After the waveguide, a dichroic mirror passed the C-band and reflected the SFG signal. The residual C-band pump and signal were then fiber coupled and separated using WDMs so that the signal depletion could be observed on a fast sampling oscilloscope called a digital communications analyzer (DCA), as shown in Figure 5.6. The SFG was reflected off of the dichroic mirror and passed through a system of prisms, mirrors, irises, and narrowband filters before being detected on the SPCMs. The prism dispersed the C-band radiation and SFG radiation at different angles allowing the irises to act as frequency filters due to the
Figure 5.6. (a) The residual unconverted CW signal at the output of the waveguide. A 160-ps pump pulse is used to carve out the 160-ps wide trough shown. The pump was set to a power that coincides with maximum upconversion. (b) The pump power was increased to a power higher than required for maximum upconversion. As described by the coupled equations, power is being returned to the CW signal resulting in less radiation in the SFG band. These traces were captured on a DCA with limited resolution which results in the undershoot and overshoot in the plots.

spatial separation of the two wavelength bands. The narrowband filters were 3-nm wide Semrock filters centered at 780 nm, (LL01-780-25), that were angle tuned to pass the SFG while blocking the nearby SHG. A lens then focused the SFG band and a flip mirror was used to either pass the focused SFG to the SPCM (Excelitas: SPCM-AQRH-14) or fiber couple the SFG to be observed on an OSA (Ando: AQ6317). The spectrum observed on the OSA was used to tune the 3-nm wide, 780-nm Semrock filters to block nearby SHG. With a pump-signal separation of 10 nm, the SFG was generated at 772.01 nm and the SHG was generated at 774.87 nm as shown in Figure 5.7. Each filter was tuned so the SFG wavelength was at the upper edge of the filter wavelength passband. This provided the highest possible attenuation of the nearby SHG. After tuning the filters, the signal power was reduced to
single photon levels using the tunable attenuator. The SPCM was then aligned so that the SFG was focused onto the center of the detector.

Figure 5.7. The spectral output of the waveguide after a series of optics were used to filter out the C-band radiation. The spectrum was observed while 3-nm bandpass filters were tuned to reduce the SHG in the spectrum. SFG was present at 772.01 nm while pump SHG was observed at 774.87 nm.

Once the back-end filters were aligned, the signal and pump were carved into 160-ps pulses at a 50-MHz repetition rate. The residual signal was observed on an optical sampling oscilloscope (EXFO: PSO-101) and the extinction of the signal was recorded to determine the SFG upconversion percentage. For the 160-ps pulses, the peak pump power required for maximum conversion was found to be 110 mW which yielded a conversion efficiency, $\eta$, of 909%/W. At this pump power, the SHG generated by the pump was -49.7 dBm. At signal input powers of 1 photon per pulse, the SFG power generated is -78.9 dBm. To achieve an SNR of 10 between the SFG and SHG, 47 dB of SHG attenuation was required. A single
Figure 5.8. The backend filtering on the SFG band. A flip mirror was used to couple the beam to fiber to be viewed on the OSA. The 3-nm filters were tuned by observing the spectrum on the OSA, and the maximum extinction of the nearby SHG was achieved.

tuned Semrock filter provided >15 dB of attenuation on the SHG while causing only 0.5-dB loss at the SFG wavelength. To ensure that the SHG was sufficiently filtered out of the SFG band, four of the Semrock 780-nm bandpass filters were used. Upconversion and noise measurements were taken by setting a pump power, recording the signal depletion on the optical sampling oscilloscope (OSO), then blocking the signal and measuring the noise counts on the SPCM. The percent of signal upconversion and noise counts per pulse were then calculated.

5.3. Results

The Raman noise in the signal band was investigated using pump and signal pulses with roughly a 3rd order super-Gaussian shape, 160-ps FWHM, and at a 50-MHz repetition rate. The pump power was increased until back-conversion of the SFG into the C-band was observed. Measurements were recorded with the signal wavelength 8, 10, and 12 nm away
Table 5.1. SFG conversion and noise counts at different pump-signal wavelength distances. Conversion efficiency and noise counts were measured for 160-ps and 20-ps pulses with the pump to signal wavelength separation varied from 8 to 27 nm.

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<th>Noise Counts Per Pulse</th>
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<td>90 (73)</td>
<td>9.5e-3 (9.5e-4)</td>
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<tr>
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<td>88 (71)</td>
<td>1.3e-3 (2.8e-4)</td>
</tr>
<tr>
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<td>1.5e-3 (3.6e-4)</td>
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<tr>
<td>10 nm</td>
<td>20 ps</td>
<td>88 (74)</td>
<td>6.3e-4 (2.4e-4)</td>
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<tr>
<td>15 nm</td>
<td>20 ps</td>
<td>84 (65)</td>
<td>1e-4 (6.5e-5)</td>
</tr>
<tr>
<td>20 nm</td>
<td>20 ps</td>
<td>86 (71)</td>
<td>2e-4 (7.7e-5)</td>
</tr>
<tr>
<td>27 nm</td>
<td>20 ps</td>
<td>84 (70)</td>
<td>5.7e-4 (1.e-4)</td>
</tr>
</tbody>
</table>

from the pump. The measurements were then repeated using the waveshaping system to shape the signal and pump to produce a super-Gaussian pump pulse with a 20-ps width, and a 15-ps wide Gaussian signal pulse at a 1.25-GHz repetition rate. By reducing the pump width, the number of temporal modes that the Raman noise was generated in was decreased. Measurements using the super-Gaussian pump pulse were performed with signal wavelengths 10, 15, 20, and 27 nm away from the pump.

To measure the loss of the backend filtering system, the pump power was set to maximum conversion for each of the cases in Table 5.1, the signal was reduced to single photon levels, and the SFG counts were observed. The loss through the backend system included 2 dB due to the Semrock 780-nm filters, 1.8 dB due to imperfect detector efficiency, and another 2 dB due to imperfect SFG and stray reflections off of interfaces and the SPCM glass cover. With a signal power of -89.4 dB at the input to the waveguide, 4 dB coupling and propagation loss through the waveguide, and using an SPCM correction factor provided by Excelitas, the expected counts came to 9.2e5 counts/sec\[^{56}\]. The measured counts was 8.8e5 counts/sec which is 0.11 dB less than the expected value.
Figure 5.9. The residual 15-ps wide Gaussian C-band signal was observed on the OSO after passing through the waveguide. (a) Residual signal after the waveguide with no pump present. No depletion is observed. (b) Residual signal with a pump applied with power less than that required for maximum conversion. 45% depletion is observed. (c) The residual signal with the pump power increased to observe maximum conversion at 86% conversion efficiency. (d) The pump power applied was greater than that required for maximum depletion. The C-band residual signal shows back conversion resulting in 81% conversion.

The noise counts were measured on the SPCM and the loss through the back-end optics was taken into account to calculate the noise counts per pulse generated at the output of the waveguide. Table 5.1 summarizes all of the results for the various pump to signal
Figure 5.10. For each given conversion percentage the 20-ps super-Gaussian pump pulse resulted in less noise counts than the 160-ps pump pulse.

wavelength separations and two pump pulse widths. The noise generated by the 160-ps pump is compared to the noise generated by the 20-ps pump in Figure 5.10. Since Raman noise generation is a linear process, the noise was expected to decrease by a factor comparable to that of the temporal pump difference. The pump width was reduced by a factor of eight, whereas the noise decreased by a factor of only two to three. One contributor to this extra noise was that the pump power required for maximum upconversion using the 20-ps pump was 1.4 times greater than that required for full upconversion using the 160-ps pump. This could potentially increase the amount of generated Raman noise, and increase the amount of Raman noise upconverted into the SFG band. Figure 5.11 shows the conversion percentage versus the noise counts for the four scenarios that exhibit the lowest noise counts with conversion percentages greater than 80%.
Figure 5.11. The noise counts per pulse vs the upconversion percentage for the four lowest-noise scenarios which all use 20-ps wide 5th order super-Gaussian pump pulses and 15-ps wide Gaussian signal pulses with a repetition rate of 1.25 GHz. The best scenario is at a pump to signal distance of 15 nm which resulted in 1e-4 noise counts per pulse at a maximum conversion efficiency of 84%.

At signal wavelengths >10 nm from the pump there was a noticeable noise increase. This could be due to higher Raman, or the inability of the backend filters to adequately attenuate the pump SHG since the pump SHG wavelength approaches the SFG wavelength as the pump-signal distance decreases. The lowest noise in the SFG band was achieved when the signal wavelength was between 10 and 20 nm away from the pump, and with pump pulse widths that occupy only a single temporal mode of the waveguide. The temporal width of a single mode in the system is determined by the phase-matching bandwidth of the nonlinear waveguide used in the system. It should be noted that if 1e-4 noise counts per pulse is too
high for a given system, a lower pump power can be applied which reduces the overall system efficiency, but also reduces the pump generated noise counts.
CHAPTER 6

Multi-Channel SFG Upconversion Detection

6.1. Experimental Overview

A multi-channel experiment was performed to demonstrate the ability to upconvert two signals with different wavelengths by phase-matching them with pumps on adjacent phase-matching peaks. The two upconverted signals were then observed on two independent SPCMs. Using a single waveguide with multiple peaks to upconvert multiple signals simultaneously simplifies system scalability and greatly reduces the loss of the system compared to using multiple single-peak waveguides. The goal of this experiment is to show that a low noise multichannel upconversion detection system can be implemented using a single waveguide. A 5-nm separated phase-matching peak waveguide was chosen so that the longer wavelength SFG was 2.7 nm shorter than the SHG of the shortest wavelength pump. Using a 5-nm peak separated waveguide made filtering out the SHG easier, and also separated the two SFG signal wavelengths further than if the 3 or 4-nm waveguide had been used. This allowed for better SFG filtering and higher channel isolation of the two SFG channels. Figure 6.1 demonstrates how the SHG and SFG wavelengths are affected by the pump-signal distance, and the distance of adjacent phase-matching peaks.

The 5-nm separated peak waveguide with the highest conversion efficiency relative to side peaks was chosen. The phase-matching profile of the multi-peak waveguide used in the 5-nm separated multi-channel experiments is shown in Figure 6.2. The signal wavelengths $S_1 = 1533.54$ nm and $S_2 = 1537.51$ nm were phase-matched with pumps 15 nm away at...
Figure 6.1. The SHG due to pump 1 increases in wavelength as the pump and signal wavelength distance is increased (dots). By increasing the phase-matching peak distance (colors) the SFG due to P1S1 (solid) and SFG due to P2S2 (dashes) can be further separated. It is notable to observe that as the pump to signal wavelength distance decreases to 0, the SFG and SHG wavelengths converge.

$P_1 = 1549.23 \text{ nm}$ and $P_2 = 1554.34 \text{ nm}$. The phase-matching peaks had efficiencies of $\eta_1 = 141\% / W$ and $\eta_2 = 144\% / W$.

Table 6.1 shows the various pump, signal, SHG, and SFG wavelengths in the two wavelength signal-pump system. Optimization simulations were performed for the multi-peak waveguide and it was found that using 5th-order super-Gaussian pump pulses with a FWHM of $\tau = 20 \text{ ps}$ and Gaussian signal pulses with a FWHM of $\tau = 15 \text{ ps}$ could achieve SFG efficiencies $>80\%$. Figure 6.4 shows the fiber-based front end used for frequency comb and pulse generation. The polarization of each pump and signal source is independently controlled using a fiber polarization controller (FPC), and the four wavelengths are combined using 50/50
Figure 6.2. The phase-matching profile for the multi-peak waveguide used in the multi-wavelength signal upconversion experiment. The pumps (red) and signals (blue) are phase-matched on adjacent phase-matching peaks. Pump 1 and signal 1 (P1S1) are phase-matched on the center peak near 1542 nm, and pump 2 and signal 2 (P2S2) are matched on the peak near 1547 nm.

splitters. After the four combs are generated and pulses are shaped in the OAWG, the signals and pumps are separated using a WDM. The signal is then passed through a digital attenuator, an FPC, and a tunable time delay before being coupled to free-space. The pumps are further amplified, passed through a digital attenuator, an FPC, and two WDM’s are used to filter out amplified spontaneous emission of the amplifier and out-of-band Raman noise before being coupled into freespace. The final FPCs in the pump and signal paths are necessary because of the polarization dependent guiding of the PPLN waveguide.

Once collimated to freespace, the pump passes through two 3-nm wide wavelength-tunable filters centered at 1570 nm (Semrock: NIR01-1570/3-25). The filters are spatially angled to shift the center wavelength to 1550 nm which allows the two pumps through with
minimal attenuation. The signals, whose wavelengths are outside the bandwidth of the filters, are incident on and reflected off of the second filter. In this way the second filter acts as both a noise filter for the pumps, and beam combiner for the pumps and signals.

The four wavelengths are then coupled into the waveguide where upconversion occurred. After the waveguide, the upconverted light and residual pump and signal are collimated and the upconverted light is reflected off of a dichroic mirror, while the residual C-band pumps and signals are transmitted. The C-band pumps and signals are then coupled to a fiber, separated using a WDM, and observed on either the OSO or an OSA. The visible-band/SFG-band light is filtered using multiple prisms, irises, and free-space filters before being coupled to fiber and observed on an OSA.

Table 6.1. Wavelengths for all pumps, signals, and expected SHG and SFG in the two wavelength signal system.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>P1</th>
<th>P2</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 SHG</td>
<td>1549.23</td>
<td>1554.34</td>
<td>1533.54</td>
<td>1537.51</td>
</tr>
<tr>
<td>P2 SHG</td>
<td>774.62</td>
<td>777.17</td>
<td>766.77</td>
<td>768.76</td>
</tr>
<tr>
<td>S1 SHG</td>
<td>770.67</td>
<td>772.93</td>
<td>770.67</td>
<td>772.93</td>
</tr>
<tr>
<td>S2 SHG</td>
<td>770.67</td>
<td>772.93</td>
<td>770.67</td>
<td>772.93</td>
</tr>
</tbody>
</table>

Figure 6.5 shows the experimental setup for the waveguide coupling, post-waveguide filtering, and upconversion detection for the multi-peak experiment. The SFG1 and SFG2 signals are separated into two spatially independent paths using tunable 3-nm bandwidth filters centered at 770 nm (Semrock: LL01-780-25). The SFG band is coupled to fiber and all SFG and SHG wavelengths are observed on an OSA. Figure 6.6 shows all observed SFG-band radiation. To separate the two SFG signals into two spatial paths, a 770 nm filter is placed in the optical path and tuned so that it is centered on SFG2's wavelength, 772.9 nm. This filter then reflects SFG1, 770.67-nm, radiation and any other noise, including SHG, present
Figure 6.3. Pump and signal pulse generation for the 5-nm peak separated multi-peak experiment. Tunable lasers inject four source radiations with different wavelengths into 50/50 splitters where they are combined and passed through phase and amplitude modulators to generate the frequency combs. The OAWG then shapes each comb, which are then amplified, and then the pumps and signals are separated. The pumps are further amplified and filtered, and both the pumps and signals are passed through tunable attenuators and polarization controllers before being collimated into free space.

in the SFG band. Two more filters are put in each spatial channel, one channel passing SFG1 and one channel passing SFG2, and are centered to pass the corresponding SFG wavelength while filtering out any nearby SHG or residual SFG of the other channel. The total loss through the back-end system includes 2 dB due to filtering, 1.8 dB due to imperfect detector efficiency, and another 2 dB due to imperfect SFG conversion and stray reflections from the
Figure 6.4. The pump and signal pulse shapes used in the two wavelength signal set experiment. The pump (a) has a full-width at half-max of $\tau = 20$ ps and the signal (b) has a $\tau = 15$ ps.

SPCM window. After tuning the back-end filtering and spatially aligning the SPCMs, the pump noise and conversion efficiencies for the system were recorded.

Figure 6.5. (A) Front-end free-space setup for combining the pumps and signals, and coupling them to the waveguide. The residual C-band radiation is then passed through a dichroic mirror while the SFG band radiation is reflected and sent to a filtering and single-photon detection area. (B) The SFG band is observed on an OSA and filters are tuned to pass SFG2 and reflect SFG1 and all other radiation. Then both of the SFG1 and SFG2 channels are further filtered before being focused onto independent SPCMs.
Figure 6.6. The SFG and SHG measured on the OSA without any filtering in the two wavelength signal set experiment. The pumps and signals were independently turned on and off to confirm the peaks in the SFG band were due to the expected nonlinear interactions of SHG or SFG. 3-nm bandpass filters were tuned while observing the spectrum on an OSA to filter out SHG, and to separate SFG1 and SFG2 into two independent spatial channels.

6.2. Results

As in Chapter 5, the maximum conversion was found which required a peak pump power of \( P_{\text{max}} \approx 566 \text{ mW} \). This peak power is approximately five times greater than that required for the single-peak waveguide, which is expected. The pump power required for maximum conversion in a waveguide depends on the efficiency of the phase-matching peaks. For a single chip, the multi-peak waveguides can be expected to have peak efficiencies inversely proportional to the number of peaks \[^{36}\]. Therefore, the five-peak waveguide should exhibit peak SFG efficiencies reduced by a factor of five compared to that of the single-peak waveguides.
on the same chip. Which means, to achieve peak conversion efficiencies in the multi-peak waveguides, the pump powers must be around five times greater than that required by the single-peak waveguides.

To confirm that maximum upconversion was reached, pump powers were increased until back conversion was observed in the multi-peak waveguide. The input pump power was varied to observe a range of conversion efficiencies, and pump induced noise counts in both SFG channels was recorded. While tuning the wavelengths of the pumps, it was found that the pump generated noise counts could vary as much as $\simeq 10$ dB when the pump wavelength was changed by as little as $\simeq 0.2$ nm. This wavelength-dependent noise variation may be due to parasitic side peaks and waveguide transfer function fluctuations between phase-matching peaks of the multi-peak waveguide. To mitigate this, an iterative tuning of waveguide temperature and pump wavelength was used to minimize noise while maximizing SFG efficiency.

Noise counts were recorded in both SFG channels with pump 1-signal 1 (P1S1) into the system and pump 2-signal 2 (P2S2) into the system. Greater noise counts than in the single phase-matching peak waveguide were expected due to the higher pump powers required for equivalent SFG upconversion percentages. The results in Figure 6.7 show that the pump generated noise photons approach $10^{-4}$ photons/pulse with an internal conversion efficiency (overall system efficiency) of 54%(11%) for both channels when signals are upconverted using the corresponding pumps. The highest efficiencies observed were $> 80\%(15\%)$ with pump generated noise photons on the order of $10^{-3}$ photons/pulse.

Next, crosstalk between the channels was measured. The noise equivalent power (NEP) for a quantum detection system is defined by Eq. 6.1 where $h$ is Plank’s constant, $\nu$ is the
Figure 6.7. The noise counts per pulse vs upconversion efficiency for the two pump, two signal system using a 5-nm separated phase-matching peak waveguide. Noise counts for both channel 1 (solid) and channel 2 (dashes) are shown with both P1S1 and P2S2 into the system. Noise counts of $10^{-3}$ were observed at peak conversion efficiencies $> 80\%$.

The crosstalk was measured by injecting P1S1 into the system, varying the input signal power, and finding where the detected upconversion power equaled the NEP of channel 1. P1S2 was then injected into the waveguide and the signal power was varied to find where the upconverted counts crossed the NEP for channel 1. The difference of two signal powers required to reach the NEP defines the crosstalk, or robustness, of the channel. It was found that the power of S2 had to be 18 dB greater than that of S1 to reach the NEP of channel 1. That means the upconversion efficiency of P1S2 into channel 1 is 61 times less than that of

\[
NEP = \frac{h\nu}{\eta} (\sqrt{2R})
\]  

(6.1)

frequency of the photon, $\eta$ is the detector efficiency, and $R$ is the noise at the input pump power required to achieve a given conversion efficiency.
upconverting P1S1 into channel 1. For channel 2 it was found that S1 power needed to be 21 dB greater than that of S2 to reach the channel’s NEP, which means that the upconversion efficiency of P2S1 into channel 2 is 124 times less than that of upconverting P2S2 in channel 2. Figure 6.8 shows the results of the crosstalk measurement for each channel, and the detection counts as the signal power was increased for P1S1, P1S2, P2S1, and P2S2.

![Figure 6.8. The measured SFG counts vs. the input signal power for channel 1 (left) and channel 2 (right). The NEP for each channel is denoted by the horizontal green line. (left) The required power of signal 2 to achieve the NEP of channel 1 is 18 dB higher than signal 1. (right) In channel 2, signal 1 requires 21 dB more power than signal 2 to reach the NEP of channel 2.]

The noise was measured while the combinations P1P2S1 and P1P2S2 were injected into the system with all three pulses temporally overlapped. The noise and conversion efficiencies were measured for different pump powers, as shown in Figure 6.9. If no extra noise was contributed by having both pumps on simultaneously, the observed noise should be the sum of the noises for each channel when the pumps are on independently. The measurement showed that the noise measured with both pumps on is 3-5 dB higher than the sum of their independent contributions, which suggests some sort of pump interaction.
Figure 6.9. The expected noise when both pumps are on is the summation of noise counts of each independent pump contribution. The measured noise was 3-5 dB higher than when the pumps were on independently. The extra noise could be due to pump-pump interactions, one pump upconverting the Raman noise of the other pump, or some other cascaded nonlinear process.

To test if the extra noise was due to an interaction between the two pumps, a tunable fiber delay line was introduced into one pump’s path and the pump pulses were temporally walked through each other. Figure 6.10 shows that when the pumps were not temporally overlapped the extra 3-5 dB of noise was not present and the noise level reaches the expected summation of the noises of the two pumps when independently injected into the waveguide.

The extra noise when the pumps are overlapped is possibly due to cascaded interactions between the pumps. One possibility is pump 2 interacting with the SHG of pump 1, creating new C-band radiation that is then upconverted into the SFG bands. One way to reduce the extra noise would be to use a two peak waveguide since the other three peaks in our waveguide were not used for upconversion. Having two peaks, instead of five, would increase each peaks upconversion efficiency thereby reducing the pump powers required to achieve maximum upconversion. Minimizing the maximum pump powers reduces the amount of
Figure 6.10. Noise vs. pump delay as one pump is temporally walked through the other. The extra noise is present when the pumps are perfectly overlapped but disappears when the pumps are sufficiently separated. Three different pump powers are shown and the added noise due to pump overlap is more significant in channel 1 (left) than channel 2 (right).

Figure 6.11. The amount of added noise above the expected noise level increases as the input pump power is increased. This demonstrates how added noise can be mitigated by reducing the required pump powers for high upconversion efficiencies.
Raman generated noise and would also reduce the amount of noise due to the pump-pump interactions, as evidenced in Figure 6.11. Also, as Figure 6.10 shows, the extra noise due to simultaneous pumping, could be eliminated by offsetting the two pumps temporally into two different time bins and interleaving upconversion signals. While this would decrease the noise in the system it would also decrease the bandwidth capabilities of each channel by a factor of two.
CHAPTER 7

Temporal Mode Demultiplexing to Multiple Upconversion Wavelengths

Temporal mode demultiplexing of signals at the same wavelength can be implemented by upconverting signals using pumps matched at different phase-matching peaks in a multi-peak waveguide. In this way, a single wavelength temporal-mode signal set can be upconverted to different wavelengths, separated into different spatial paths, and detected on independent SPCMs. By selectively upconverting different spatio-temporally overlapped modes the bandwidth of the system can be increased without adding more waveguides which would significantly increase the loss and complexity of the system. These experiments are the first demonstration of selective upconversion on spatio-temporally overlapped modes using multiple phase-matching peaks to demultiplex upconverted signals.

Pump optimization simulations were performed for the experiments in this chapter according to the methods described in Chapter 4. Due to filtering limitations, a 3-nm phase-matching peak waveguide was used for a 3 signal mode set, instead of the 5-nm separated peak waveguide used in previous chapters. The temporally orthogonal signal set was generated using the SPDC mode generation simulations described in Chapter 4 and then pumps were optimized for both the 5-nm and 3-nm waveguides. The SPDC pump bandwidth was varied to find a three mode signal set that the 17 comb line shaping system could resolve. Pump noise and conversion efficiencies were measured and mode selectivity was determined for each pump.
A system with three pump-signal pairs is implemented with each pump-signal pair phase-matched on a different phase-matching peak. To demonstrate selectivity of a temporally orthogonal mode set, the signals are all at the same wavelength and the pumps are phase matched on different phase-matching peaks of a waveguide. In this way the resultant SFG of each pump-signal pair is at a different wavelength allowing them to be separated into independent spatial paths. Due to limitations of available filters and laser sources, a 3-nm peak separated waveguide is chosen so that the pumps only have to span 12 nm rather than using a 5-nm peak separated waveguide which would required pump filter widths of 20 nm. The signals are placed at 1533.57 nm with pumps between 8 and 20 nm longer than the signals to keep the pump generated Raman noise low. The pumps are placed at 1542.42, 1548.42, and 1554.57 nm, which are between and outside of the phase-matching peaks of the waveguide shown in Figure 7.1. All system wavelengths including pumps, signals, expected SHG, and SFG are reported in Table 7.1.

### Table 7.1

<table>
<thead>
<tr>
<th>SFG from P1S1</th>
<th>P2S2</th>
<th>P3S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>768.99</td>
<td>770.48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SHG from P1</th>
<th>P2</th>
<th>P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>771.21</td>
<td>774.21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SFG from P1P2</th>
<th>P1P3</th>
<th>P2P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>772.71</td>
<td>774.23</td>
</tr>
</tbody>
</table>

Table 7.1. Expected wavelengths in the three signal mode system with all signals at the same wavelength. Two noise sources are within the upconverted signal wavelength band which are the SHG of Pump 1 and Pump 1 - Pump 2 SFG.
The wavelengths of the SFG radiation from each corresponding pump-signal pairing lies between 768 and 772 nm. In addition, two noise sources are within that wavelength range, pump 1’s SHG and the potential upconversion interaction of pump 1 and pump 2 (P1P2). The back-end filters used to reduce noise in the SFG band cannot remove any in-band noise meaning that the pump 3-signal 3 (P3S3) SFG channel at 771.99 nm will have added noise due to these in band SHG and upconversion interactions.

The three signal system was simulated and the peak SFG upconversion, channel selectivities, and optimized upconversion pumps were found. Table 7.2 reports the results of the optimization simulation, and Figure 7.2 shows the resulting pumps and signals in the time and frequency domain. For a 17 comb line system, selectivities are 0.89, 0.73 and 0.66 for pumps 1 through 3 respectively. The decreased selectivity of the higher modes is due
Table 7.2. Results of pump optimization simulations for a signal set with three temporally orthogonal signals at the same wavelength. Conversion percentage for each pump-signal combination and pump selectivities are reported. The optimization was performed for a waveguide with five phase-matching peaks separated by 3 nm, 20% apodization on either end of the waveguide, and both 17 and 25 comb line frequency combs with lines separated by 20 GHz.

<table>
<thead>
<tr>
<th>Comb Lines</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>Selectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>81.1%</td>
<td>5.4%</td>
<td>2.4%</td>
<td>0.91</td>
</tr>
<tr>
<td>P2</td>
<td>9.6%</td>
<td>72.7%</td>
<td>8.5%</td>
<td>0.80</td>
</tr>
<tr>
<td>P3</td>
<td>1.46%</td>
<td>19.7%</td>
<td>64.2%</td>
<td>0.75</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>76.9%</td>
<td>5.07%</td>
<td>2.01%</td>
<td>0.92</td>
</tr>
<tr>
<td>P2</td>
<td>11.07%</td>
<td>69.78%</td>
<td>5.35%</td>
<td>0.81</td>
</tr>
<tr>
<td>P3</td>
<td>3.24%</td>
<td>18.91%</td>
<td>75.96%</td>
<td>0.77</td>
</tr>
</tbody>
</table>

to the bandwidth limitations of the system, as it is unable to resolve the faster temporal fluctuations of the higher signal modes. Simulated results of a three signal system with 1.5 times comb bandwidth (25 comb lines) is simulated and the results show that the separability improves as the number of comb lines, and therefore bandwidth, of the shaping system increases. A 25-line frequency comb with 20-GHz spacing spans 4 nm which, in the 3-nm waveguide, would allow for the overlap of pump energy with nearby phase-matching peaks causing significant SHG noise in the SFG band. To prevent this added noise in the SFG band, a 17 line comb system is used for the 3-mode signal set in the 3-nm phase-matching peak separated waveguide.

7.2. Experimental Setup

A PPLN waveguide with 3-nm separated phase-matching peaks is used as the upconversion medium. Figure 7.1 shows the SHG small signal transfer function of the waveguide which exhibits peak efficiencies of ≈110 %/W. A frequency comb centered at 1533 nm is used for the signals, and pump combs are centered at 1542, 1548, and 1554 nm. The pump
Figure 7.2. The pump (bottom) and signal (top) temporal mode profiles for the three-mode system using a 17-line frequency comb.

...wavelengths are placed between phase-matching peaks as to reduce pump generated SHG. To determine the exact wavelengths of the pumps, the temperature of the waveguide is tuned to maximize the SFG upconversion efficiency of P1S1. The other pump wavelengths are then determined by injecting the signal wavelength into the waveguide and turning on one pump at a time and tuning the wavelength of that pump to achieve the highest conversion efficiency possible. This ensures the maximum conversion efficiency for each pump-signal pairing, but could place the 2nd and 3rd pumps at wavelengths that induce higher than minimal noise due to overlap with nearby phase-matching peaks. This could generate more noise in the second and third mode SFG channels. It is noted though that pump 3’s wavelength is long enough that it is outside of the phase-matching peak region, and therefore will not overlap with any nearby peaks. This was not a problem for the previously performed 2-pump experiments since the pumps and signals were all independent wavelengths and could therefore be...
tuned independently. For this experiment though, the signals are all the same wavelength and the pumps must all be tuned to phase-match with that same signal wavelength.

The frequency combs are each 17 lines with 20-GHz spacing, which results in a total bandwidth of 2.7 nm for each pump comb. This requires that the pumps be nearly centered between two adjacent phase-matching peaks for minimal pump generated SHG. The pumps are matched to the signals on adjacent peaks of the multi-peak waveguide and the pumps are not phase-matched with each other. The phase-matching peaks that are use have conversion efficiencies of 110%/W . The pump and signal combs are generated using the same method as in Chapter 6 and pulses are shaped using the Finisar OAWG.

Figure 7.3. (A) The front-end free-space filtering and coupling to the waveguide. A 12-nm wide filter combines the pump and signal. After the waveguide the sum frequency generation SFG and C-band residual pump and signal are separated. (B) Filtering and detection of the upconverted SFG signals for the three-mode system. DCA, digital communications analyzer; OSA, optical spectrum analyzer.

Figure 7.3 shows the freespace experimental setup for the three-mode system. Two freespace filters in the pump path are used to filter out Raman noise in the signal band. First, a filter centered at 1533 nm with a 3-nm bandwidth (Semrock: NIR01-1535/3-25) is angle tuned to transmit 1533 and reflect the pumps. The 1535-nm filter has ≃95% transmission of in-band radiation and >90% reflection of out of band wavelengths, and has a very flat transmission/reflection profile. A second filter centered at 1550 nm with a 12-nm bandwidth
(Thorlabs: FB1550-12-1”) is used to pass the three pumps and reflect the signal so that the pumps and signals are combined into the same spatial path. The 12-nm wide combining filter has a wide but uneven passband profile that distorts the pumps and signals appreciably. Figure [7.4] shows the passband profile of the combining filter. To observe the pump and signal pulses entering the waveguide, a freespace flip mirror is placed after the distorting 12-nm wide filter, and before coupling into the waveguide. The beam is then coupled into fiber and an OSA is used to adjust the amplitudes of the pump and signal comb lines. The phase distortion for each pump and signal comb is also observed and corrected by using a CSA. Once the pumps and signals are reshaped, new distortion compensated comb values are recorded. The freespace flip mirror is then removed, and the pumps and signals are allowed to propagate through the waveguide.

After the pumps and signals pass through the waveguide, a dichroic mirror and prism are used to separate the SFG from the residual C-band radiation and higher order nonlinear byproducts of the high power pump, like third-harmonic generation. Freespace 3-nm bandwidth angle tunable filters (Semrock: LL01-780-23) are tuned to block wavelengths longer than 772 nm, block wavelengths shorter than 769 nm, and separate the three SFG wavelengths into independent spatial channels. The SFG is then measured using a bulk silicon detector, and the residual signal is measured using a bulk C-band detector. Figure [7.3] shows the backend filtering for the three signal upconversion experiment. A digital time delay is used to walk the signals through the pumps, and SFG conversion percentages are recorded for each pump-signal combination, at three pump powers.
7.3. Results

7.3.1. Upconversion Efficiencies

All pump-signal combinations were independently injected into the waveguide, the upconversion percent for each pairing was recorded, and the selectivity of each pump was calculated. Figure 7.5 shows the conversion efficiencies vs. time delay for all nine of the pump-signal combinations, and Table 7.3 compares the experimentally measured values with the simulation results. For modes 1 and 2, the measured efficiencies for the optimized pump-signal pairings are below the simulated values, but the selectivities are still close to the expected values. For mode three, the system does not perform as well. This could be due to the fact that the mode three pump has the most complex phase profile, so any phase drifts...
<table>
<thead>
<tr>
<th>Simulation</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>Selectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>81.1%</td>
<td>5.4%</td>
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<td>0.91</td>
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<tr>
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</tr>
<tr>
<td>P3</td>
<td>1.46%</td>
<td>19.7%</td>
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<td>Experiment</td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>Selectivity</td>
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<tr>
<td>P3</td>
<td>19.8%</td>
<td>12.8%</td>
<td>58.9%</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Table 7.3. Results of pump optimization simulations and measured upconversion values for a signal set with three temporally orthogonal signals. Selectivity of each pump is also reported. The optimization was performed for a waveguide with five phase-matched peaks separated by 3 nm. The pump and signal combs contained 17 comb lines separated by 20 GHz.

due to temperature or the pulse picker can effect the pulse significantly. It should also be noted that the optimization simulations assume the phase-matching peaks are identical, but measurements have shown that significant differences in peak efficiencies and side-lobes can exist from peak to peak in a single waveguide, which may also contribute to disagreements between experimental and simulated results.

7.3.2. Optical Spectrum Analysis

Mitigating noise in the SFG band is important for single photon measurements, and it lowers the noise equivalent power of a detection system. The most obvious source of in-band upconverted noise is any 1533-nm radiation in the pump path that is upconverted whether a signal is present or not. The 12-nm filter used to combine the signals and pumps in freespace allows appreciable 1533-nm radiation into the pump path. This signal band noise in the pump path is likely due to ASE from the multiple EDFAs used to achieve high peak pump powers. A WDM and an added 1533-nm centered freespace filter are used in the pump
Figure 7.5. The normalized conversion efficiencies for all pump-signal combinations for the three signal set. Pumps are displayed in rows while signals are down each column. Plots on the main diagonal are corresponding pump-signal pairs which have high conversion efficiency, while the off diagonal plots are mismatched pump-signal pairs which exhibit low conversion efficiency. Each plot shows three pump powers: maximum power (black), 1 dB attenuation (red), and 2 dB attenuation (blue).

path to reduce noise radiation in the signal band. Figure 7.6 shows the pump spectrum at signal band wavelengths with and without the added 1533-nm freespace filter.

After the waveguide, the residual C-band radiation was filtered out and the SFG band was observed. Freespace filters were tuned to separate the three SFG wavelengths into
Figure 7.6. (left) 1533-nm noise in the pump path that contributes to noise in the SFG band. (right) The 1533-nm band in the pump after adding an add-drop multiplexer and a freespace filter tuned to pass 1533 nm.

independent spatial channels where they were measured on the OSA. Figure 7.7 shows the SFG spectra with and without filtering. The three SFG peaks are observed at 768.99, 770.48, 771.99 nm. Peaks at other wavelengths around the SFG are from pump SHG, SHG from C-band noise at the phase-matching peaks, and pumps phase-matching with and upconverting nearby C-band noise. The plots in the right column of Figure 7.7 show the SFG spectra after the filters have been tuned for the three SFG channels. After filtering, each SFG path has over 30-dB attenuation of out of band noise. With pump powers set to maximum achievable upconversions, noise photons of \( \sim 10^{-1} \) SPD counts/pulse were measured in the channels.

Noise levels of \( 10^{-1} \) counts/pulse are high compared to the results of Chapter 6 and other single photon counting technologies. By using 2.7-nm bandwidth combs for the pumps it is possible they partially overlap with nearby phase-matching peaks causing significant pump SHG in the SFG band.
Figure 7.7. SFG band spectra for inputs P1S1, P2S2, and P3S3 are shown in each row from top to bottom. Non-filtered (left) and filtered (right) SFG spectra are presented.
7.3.3. Superposition Modes

Mutually orthogonal bases (MUBs) are important for quantum information processes such as quantum key distribution. To demonstrate that our system can operate on MUBs, upconversion pumps were optimized for the 1+2 and 1-2 superposition signal modes generated from adding and subtracting orthogonal signal modes 1 and 2. The resulting superposition modes are presented in Figure 7.8. The two superposition signal modes have the same wavelength, and as in the previous experiments, the pumps are phase-matched to the signal wavelength on different phase-matching peaks. The upconverted signals are separated into independent spatial channels, using freespace filters, before being observed. The signal pulses are temporally walked through the pump pulses and the upconversion of each pump-signal combination is measured. The results of the superposition experimental results are presented in Figure 7.9 and compared to simulated values in Table 7.4.

At the maximum pump power the upconversion efficiency of signal 1+2 (1-2) by pump 1+2 (1-2) was 82% (18%). The upconversion of signal 1+2 (1-2) due to pump 1-2 (1+2) was 18% (23%). This resulted in mode selectivities of 0.824 (0.777) for pump 1+2 (1-2). The maximum measured conversion efficiencies are 10% less than the simulated values. This discrepancy could be due to the simulations being based on identical phase-matching peak profiles whereas across the five peaks in the 3-nm waveguide there are fluctuations in efficiency and sidepeaks. The mode selectivity for pump 1+2 was 0.824 which is slightly higher than the simulated value of 0.781. One reason for this may be that as a given pump was attenuated, the upconversion of undesired signal modes decreased at a faster rate than that of the corresponding signal mode. This, in turn, increases the mode selectivity at attenuated pump powers. Since the upconversion efficiency of pump 1+2 on signal 1+2 is
10% less than the expected value, the peak upconversion may not have been achieved, which results in a higher mode selectivity. The mode selectivity for pump 1-2, 0.777, agrees well with the simulated value of 0.782.

The upconversion of non-superposition signals 1 and 2 due to pump 1+2 or pump 1-2 is expected to be in the 40-50% range. The upconversions of signal 1 and signal 2 under pump 1+2 and 1-2 were recorded as the signal pulse was temporally walked through the pump.
Figure 7.9. The normalized SFG upconversion efficiency vs. pulse time delay between pump and signal superposition pulses. The rows denote what signal is upconverted while each column represents the upconversion pump. Three pump powers are presented for each pump-signal combination.

...pulse, and results are presented in Figure 7.10. At maximum pump powers the experimental upconversion of signals 1 and 2 were all between 40-50%, just as predicted by the simulations.

7.3.4. 5-nm Separated Peaks Noise Investigation

A 5-nm separated peak waveguide was used to reduce potential pump overlap with nearby phase-matching peaks, and thus help control one mechanism that may be generating noise.
Table 7.4. Results of pump optimization simulations and measured upconversion values for a signal set with two temporally orthogonal signals. The two signals are superpositions of the first two signal modes from the orthogonal modeset used in the 3-nm waveguide experiment. The selectivity of each pump is calculated and reported. The optimization was performed for a waveguide with five phase-matching peaks separated by 3 nm. The pump and signal combs contained 17 comb lines separated by 20 GHz.

<table>
<thead>
<tr>
<th>Simulation</th>
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<th>S1-2</th>
<th>Selectivity</th>
</tr>
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<tbody>
<tr>
<td>P1+2</td>
<td>95%</td>
<td>26%</td>
<td>0.78</td>
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<tr>
<td>P1-2</td>
<td>9.61%</td>
<td>72.7%</td>
<td>0.78</td>
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</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>S1+2</th>
<th>S1-2</th>
<th>Selectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1-1</td>
<td>82%</td>
<td>18%</td>
<td>0.82</td>
</tr>
<tr>
<td>P1+2</td>
<td>23%</td>
<td>80%</td>
<td>0.78</td>
</tr>
</tbody>
</table>

photons due to pump SHG. Placing the pumps at 1546 nm and 1556 nm and the signal at 1532 nm phase-matches the pump-signal pairs, and roughly centers the pumps between phase-matching peaks. An OAWG is used to generate 15-ps wide Gaussian signal pulses and 20-ps wide super-Gaussian pump pulses at a 1.25-GHz repetition rate.

Figure 7.11 shows the SFG band noise and pump 1-signal 1 SFG with no back-end filtering. Three noise peaks were observed in the pump noise spectrum with one being SHG due to the strong pump. The 12-nm wide free-space filter used to combine the pumps and signals allows C-band ASE into the waveguide which may be upconverted by phase-matching with the strong pump on a nearby phase-matching peak, or through SHG by coupling directly with one of the phase-matching peaks.

To investigate the source of the extra noise in the SFG band, radiation outside of the 2.7-nm wide pump comb was blocked by a 3-nm wide tunable fiber coupled filter. Figure 7.12 shows the C-band pump spectrum and the SFG band noise, both with and without the 3-nm tunable filter in the pump path. In the filtered spectrum, only one noise peak is
observed which is the SHG of the strong pump. This suggests that the ASE noise, around and between the pumps, is being upconverted into the SFG band.

The source of the noise was investigated by using a second OAWG (Finisar: Waveshaper 4000S) in the pump path after the final EDFA and before being collimated into freespace. Three tests were performed using an OSA to observe the SFG-band spectrum noise. The first measurement applies a filter centered at the pump wavelength, and the SFG spectrum noise
Figure 7.11. SFG band spectra for pump 1-signal 1 (left) and only pump 1 (right) into the waveguide. The shortest wavelength peak in the P1S1 pairing is SHG of the 1546-nm signal, and the peak at 769.75 nm is the P1S1 SFG. Other noise observed is the SHG of the pump, at 773 nm, and noise sidebands due to unknown interactions.

is observed as the filter bandwidth is widened. Next, the SFG band noise is observed as the center wavelength of a 3-nm band filter is swept through the pump wavelength band. The third SFG band noise measurement uses multiple bandpass filters. One filter is centered at the pump wavelength while the other 3-nm bandpass filters are placed at various wavelengths in the C-band to see if any nearby C-band noise is being upconverted by the strong pump. A 3-nm bandpass filter was used for these measurements because of the 2.7-nm pump comb width.

Figure 7.13 shows the SFG-band noise when a 3-nm filter centered on pump 1, 1546.22 nm, was applied with varying bandwidths. When a 3-nm wide filter was applied, SHG due to the pump was observed at 776 nm. As the filter bandwidth was increased, prominent noise bands slightly longer and shorter than the pump SHG were observed. The full noise spectrum in the SFG band was present when the filter was 15-nm wide.
A single 3-nm filter was applied with center wavelengths varied from 1535 to 1556 nm in 1.5-nm increments. This was used to determine if any SFG-band noise was generated by C-band radiation undergoing SHG by matching with nearby phase-matching peaks. As expected, SHG due to the pump was observed when the filter was centered near the pump wavelength, at 1547 nm. Figure 7.14 shows that noise was also observed with filters centered at 1544 and 1550 nm, which was C-band noise being upconverted through SHG by the nearby
Figure 7.13. The SFG-band noise observed on an OSA as a passband filter bandwidth was increased from 3-nm to 17-nm. Only pump SHG was observed when the filter was 3-nm wide. Noise side bands appear as the filter bandwidth was increased to 7-nm, and the full noise spectrum is present with a 15-nm wide filter.

phase-matching peaks around \(\approx 1544\) and \(\approx 1549\) nm. The high noise side-bands observed in the previous test, with varied filter widths, was not observed as the center wavelength of the filter was passed through the 21-nm spectrum in this measurement.

To determine if the pump was interacts with nearby C-band noise radiation through SFG on adjacent phase-matching peaks, a 3-nm bandpass filter was centered at 1546.22 nm. A second 3-nm bandpass filter was centered at wavelengths varied from 1535 to 1556 nm, at 1.5 nm intervals. It was found that significant noise was generated when the second filter was centered at either 1542.5 or 1553 nm. Two filtering profiles were then generated: one with
Figure 7.14. The SFG band noise spectrum observed on an OSA with 3-nm bandpass filters applied at various center wavelengths. SHG from the pump is present with a filter centered at 1547 nm. SHG due to upconverted C-band noise is observed with filters centered at 1544 and 1550 nm. No noise is observed with filters centered at 1542.5 and 1553 nm.

The three C-band filtering experiments presented show that tight, low loss filters in the pump path must be implemented with very specific center wavelengths and passbands for a low noise upconversion system. Without such stringent filtering, the in-band noise in the SFG channels can be greater than $10^2$ counts per pulse. One drawback is that tight filtering can also be lossy which reduces the overall system efficiency. The current system using an OAWG
Figure 7.15. SFG (bottom) and C-band (top) spectra observed on an OSA with 3-nm bandpass filters centered at 1542.5, 1547, and 1553 nm (left), and 1542.5 and 1553 nm (right). The SHG and sideband noise is only present when the pump is also present in conjunction with the other two wavelengths.

to apply arbitrary filtering adds over 3 dB of loss to the pump causing the upconversion efficiency to degrade to <50%. Higher input powers to the OAWG, or a lower loss filtering system, is required to achieve high conversion efficiency while simultaneously preventing the upconversion of nearby C-band radiation into the SFG band. A low loss filtering system could be implemented by purchasing custom freespace filters from a high quality filter vendor like Semrock, or by designing fiber-based filters from Sagnac interferometers.\textsuperscript{57}
CHAPTER 8

Conclusions and Discussion

We demonstrated the use of PPLN waveguides in upconversion detection systems that exhibit noise characteristics and efficiencies comparable to other single photon detection technologies. Multi-peak waveguides were used to demonstrate the ability to upconvert various signals at different wavelengths simultaneously using a single waveguide. Multi-peak waveguides were also used to upconvert temporally orthogonal signals at the same wavelength, and demultiplex them into independent spatial paths. Since mutually orthogonal bases are important for quantum information processes, the superpositions of modes were also determined and upconversion detection of those modes was performed as well.

8.1. Optimization Simulations

Chapter 4 demonstrated upconversion pump optimization simulations for SPDC generated signal sets. The results show that using the parameters of realizable PPLN waveguides, a 3-mode upconversion system can perform with conversion efficiencies >60% and selectivities above 0.65. This is accomplished with a multi-phasematching peak waveguide with either 5 or 3-nm separated phase-matching peaks. A two mode system has improved performance with upconversion efficiencies near 80% and selectivities above 0.8.

The simulations also explored trends of input signal mode bandwidth to resolvability and selectivity of modes, which were used to determine the abilities of a realizable system. Our pulse-shaping system was limited to a frequency comb with 17-comb lines separated by
20 GHz, which spanned 2.7 nm in the wavelength domain. This limited the bandwidth of the signals and pumps that were able to be generated and also effected the decision of how far the phase-matching peaks should be from each other. Table 8.1 summarizes the results that were used in the multi-mode upconversion experiments, and extrapolates on potential improvements to the system that a 25 comb line system could provide, which is particularly noticeable for the higher modes 2 and 3.

Chapter 4 also explored using pump pulse frequency combs with added error to determine the robustness of the optimized upconversion pulses. It was found that adding 5% error to each comb line’s amplitude and phase reduces the efficiencies for up to eight modes in a system by less than 10%, while the selectivity remains above 10 for all eight modes. For the OAWG system we were using, we expected less than 5% error per comb line due to our constant feedback system that checked and updated the combs continuously during measurements.
<table>
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<tr>
<th>3-nm Waveguide with 3 Pumps</th>
<th>5-nm Waveguide with 3 Pumps</th>
<th>5-nm Waveguide with 2 Pumps</th>
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<td><strong>17 Comb Lines</strong></td>
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<td><strong>17 Comb Lines</strong></td>
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<tr>
<td><strong>25 Comb Lines</strong></td>
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<tr>
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<td>9.88 74.40 9.00</td>
<td>P2</td>
</tr>
<tr>
<td>S3</td>
<td>1.61 18.29 64.34</td>
<td>P3</td>
</tr>
</tbody>
</table>

Table 8.1. Conversion percentage and mode distinction for 2 and three mode systems using 3-nm and 5-nm peak separated waveguides. Two different frequency combs, 17 and 25 lines, are used to compare the ability of a given frequency comb to resolve two or three signal modes with 500 iterations of the perturbation algorithm.

### 8.2. C-band Pump-Signal Pair SFG and Noise Measurements

Operating with both pumps and signals in the C-band is valuable for systems because of highly developed technologies at those wavelengths. Also, commercial OAWGs are not readily available at longer wavelengths which are required for temporal mode upconversion selection.

With upconverted Raman noise being the dominant noise source in the upconverted SFG channel, it was found that a Raman noise trough exists at wavelengths between 10 to 20 nm shorter than a strong pump in PPLN. It was also confirmed that using pump pulses with shorter FWHM temporal profiles creates less time bins, or modes, for the Raman noise to be generated in. These Raman measurements showed that 20-ps pump pulses could be used...
instead of 160-ps pump pulses, and that pump-signal wavelength distances should be within the 10 to 20-nm range to reduce pump generated Raman noise. Figure 8.1 shows the systems that exhibited the four lowest pump generated noise counts at efficiencies above 80%. It was found that noise counts of $10^{-4}$ per pulse are achievable at upconversion efficiencies of 84%.

Figure 8.1. The noise counts per pulse vs the conversion percentage for the four lowest-noise scenarios. All four systems implement 20-ps wide 5th order super-Gaussian pump pulses and 15-ps wide Gaussian signal pulses with a repetition rate of 1.25 GHz. The lowest noise system has a pump to signal distance of 15 nm which resulted in $10^{-4}$ noise counts per pulse at a maximum conversion efficiency of 84%.

8.3. Multi-Channel SFG Upconversion

Using a multi-phaseshifting peak waveguide, two signals at different wavelengths were upconverted by independent pumps phase-matched on adjacent phase-matching peaks. This was performed to demonstrated the capability of upconverting multiple wavelength signals
into independent SFG wavelengths and filtering them into different spatial channels for detection on independent SPCMs. The results on Chapter 6 show that two separate wavelength signals can be upconverted in a single waveguide with upconversion percentages >80%. The upconverted SFG signals are readily separable using tunable freespace filtering, and nearby SHG is able to be removed using the same filtering technique. The noise was in the range of $10^{-3}$ counts per pulse with upconversion efficiencies > 80%. A summary of the two channel upconversion vs noise is shown in Figure 8.2.

![Figure 8.2](image)

Figure 8.2. The noise counts per pulse vs upconversion efficiency for the two pump, two signal system using a 5-nm separated phase-matching peak waveguide. Noise counts for both channel 1 (solid) and channel 2 (dashes) are shown with both P1S1 and P2S2 into the system. Noise counts of $10^{-3}$ were observed at peak conversion efficiencies > 80%.

The crosstalk between the channels was also investigated and the system was found to be rather robust. Both channels exhibited over 10 dB of isolation of upconverting an adjacent channel’s signal into a given channel. Finally, there was additional noise observed in the system when both pumps were injected simultaneously. Using various power and time delay
measurements, it was determined that the pumps were interacting and generating added noise in the SFG channels. This could be mitigated by using waveguides with less phase-matching peaks, therefore requiring less input pump power, or interleaving the pumps to reduce their temporal overlap.

8.4. Temporal Mode Demultiplexing in a Multi-Peak Waveguide

The final experiments showed that a multi-peak waveguide can be used for upconversion demultiplexing of a temporal signal mode set with all signals at the same wavelength. A three signal mode set was used with optimized upconversion pumps matched on adjacent phase-matching peaks. A 3-nm separated phase-matching peak waveguide was used for the experiments, and pulses were shaped using a 17 line frequency comb and an OAWG. The results showed that the experiment agreed with theory well for the first two modes, but the upconversion of signal 1 under pump 3 deviated from the expected values. This could have been due to the fact that the simulations assume uniform phase-matching peaks in the waveguide, which when measured, is simply not the case. It could also be due to the fact that the third mode has the broadest bandwidth and most complex phase profile, and therefore fluctuations in the pulse profiles could have greater effects on the outcome of the upconversion process. Another reason may be that experimental tuning of the pulses was performed using nearest neighbors as references. These three reasons combined may provide enough error for the margin between the experimental and simulated outcomes for pump mode 3. Table 8.2 summarizes the results of the three-mode upconversion experiment.

To demonstrate the ability of our system to act on MUBs, the superposition modes 1+2 and 1-2 were also selectively upconverted. The optimized superposition pumps were able to upconvert the superposition modes with selectivities $>0.78$, which is what was expected
based on simulations. The superposition pumps also upconverted the non-superposition signals 1 and 2 with near 45% conversion, which was also predicted.

The pump generated noise counts for the three mode system in the 3-nm waveguide were much higher than the 5-nm waveguide due to the fact that pump combs were 2.7-nm wide. Pump 1 was positioned between the phase-matching peaks used for upconversion of signals 2 and 3, resulting in significant noise in channels 2 and 3 when pump 1 was injected into the waveguide. This rendered channels 2 and 3 useless for single photon measurements in the systems current design. To mitigate this problem a mode selective upconversion system using multiple peaks could be designed with peaks further apart, pulse combs that take up a smaller portion of the phase-matching peak distance, and with a reduced number of phase-matching peaks. Also, custom filters in the pump path could be implemented to greatly reduce noise in the multiple SFG channels.

<table>
<thead>
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<th>Simulation</th>
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<th>S2</th>
<th>S3</th>
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<td>2.4%</td>
<td>0.91</td>
</tr>
<tr>
<td>P2</td>
<td>9.6%</td>
<td>72.7%</td>
<td>8.5%</td>
<td>0.80</td>
</tr>
<tr>
<td>P3</td>
<td>1.46%</td>
<td>19.7%</td>
<td>64.2%</td>
<td>0.75</td>
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<th>Experiment</th>
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<th>S2</th>
<th>S3</th>
<th>Selectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>72.4%</td>
<td>3.1%</td>
<td>5.4%</td>
<td>0.89</td>
</tr>
<tr>
<td>P2</td>
<td>12.5%</td>
<td>63.9%</td>
<td>9.4%</td>
<td>0.75</td>
</tr>
<tr>
<td>P3</td>
<td>19.8%</td>
<td>12.8%</td>
<td>58.9%</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Table 8.2. Results of pump optimization simulations and measured upconversion values for a signal set with three temporally orthogonal signals. The selectivity of each pump is also reported. The optimization was performed for a waveguide with five phase-matched peaks separated by 3 nm. The pump and signal combs contained 17 comb lines separated by 20 GHz.
8.5. Conclusion

This research successfully demonstrates novel approaches and implementations of all C-band upconversion systems using PPLN waveguides. Extensive simulations were performed which determined the trends and trade-offs of the various bandwidths of the pumps, signals, and OAWG capabilities given upconversion waveguide parameters. It is here reported, for the first time, a Raman noise trough within 10 to 20 nm from a strong pump in PPLN waveguides, where an upconversion detection system could operate. Also, the first multi-wavelength channel system using multiple phase-matching peak waveguides was demonstrated with two signal wavelengths matched with two pumps on adjacent phase-matching peaks. And finally, the first temporal-mode upconversion detection system with signals at the same wavelength was demonstrated, which can demultiplex spatiotemporally overlapped signals into independent spatial channels using a multi-peak waveguide.
References


[40] Langrock, Stanford Carsten. *M21 nwu/uta quiness project multi-mode waveguides - device layout*.


[55] Corzo-Trejo, Neil V., Silver, Michael, Hwang, Yuping, & Kanter, G. S. *Comparison of raman scattering with small detuning in ktp and linbo3 waveguides for applications in up-conversion single photon detection.*


APPENDIX A

Simulation and Optimization Matlab Code

The MATLAB scripts and functions in this Appendix are examples of codes that were written to perform various simulations presented in this document as well as for support on other experiments performed in our lab. The codes below are simply examples of one of the iterations that the code went through over the years. The codes presented below were not entirely generated by me but have been written and edited by many people over the years including Yu-Ping Huang, Vesselin Velev, Paritosh Manurkar, myself, and others in our lab. The inclusion of these scripts and functions is not to claim these codes as solely my work but to provide a more complete understanding of the approaches taken for the simulations presented in this document. The scripts and functions below were used to generate SPDC signal mode sets and optimize upconversion pumps for temporal mode upconversion selection, and other upconversion simulations.

A.0.1. Temporal Signal Mode Set Generation

An orthogonal mode signal set was generated through SPDC using a super-Gaussian pump pulse. The joint spectral density was constructed and a Schmitt decomposition was used to determine the signal and idler mode spectra, along with the probability of generation for independent modes in the orthogonal set.
%v5 has filter on output spectrum for more fine tuning of output pulse
%bandwidth and number of modes generated

clear all

dw = .05; %frequency resolution
sig = 25; %change width of time signal super-gaussian in ps
filt = 3; %filter width, value times 1/sigma
outFiltRat = .7; sigFilt = .06; MFil = 5; %generate frequency of S and I
%within filter spectrum
wi = -filt:dw:filt; wi=wi/sig; %offset frequency of idler
ws = -filt:dw:filt; ws=ws/sig; %offset frequency of signal
BandWidth = 1/(2*sig*(10^-12))*(sig*wi(end)-wi(1)*sig) %report bandwidth of
%S&I in freq
Bandwidth_nm=(3*10^8)/((1.93*10^14)^2)*BandWidth %report BW of S&I in
%wavelength
FilFrac = 1; %optional fraction

%bandwidth of pump
us = 0*20/sig; ui = 0*50/sig; %us, ui are phase matching coeffs
N = 1; k = 1;
M = 5; % Super Gaussian order

dt = dw; %set time resolution to same as freq
t = -50:dt:50; %time in ps
t0 = t;
Ap=t*0; %initialize pump field
Ao = \exp\left(-t^{(2*M)}/(2*(\text{sig.}^{(2*M)})\right); \text{\%construct super gaussian in time}

\textbf{for} ii=1:length(wi)

\quad c(ii) = 1/(2*\pi) \cdot dt \cdot \text{sum}(Ao \cdot \exp(1i \cdot 2 \cdot \pi \cdot wi(ii) \cdot t)); \text{\%FT of Super Gaussian to retrieve spectral coeffs}

\textbf{end}

\%display time and spectral representations of input pump

\textbf{figure}(9)

\textbf{subplot}(2,2,1)

\textbf{plot}(t, Ao)

\textbf{title}('Temporal SPDC Input Pulse')

\textbf{xlabel}('Time (ps)')

\textbf{ylabel}('Amplitude')

\textbf{drawnow}

\textbf{subplot}(2,2,2)

\textbf{plot}(wi/sig, c)

\textbf{xlabel}('Frequency (THz)')

\textbf{ylabel}('Amplitude')

\textbf{title}('SPDC Input Pulse Spectrum')

\textbf{drawnow}

\% Construct joint spectral density in PHI

\textbf{for} ii=1:length(wi)

\quad \textbf{for} jj=1:length(ws)

\quad \quad \text{PHI}(ii, jj) = c(floor((ii+jj)/2)) \cdot \text{sinc}(\text{us} \cdot \text{ws}(jj) + \text{ui} \cdot \text{wi}(ii)/2);

\quad \textbf{end}

\textbf{end}
end
end

% calculate and display the Joint Spectral Density Intensity
TPS = PHI.^2;
nor1=sum(sum(TPS))*dw^2;
PHI=PHI/sqrt(nor1);

figure(1) %plot the 2 photon spectrum
mesh(real(ws),real(wi),real(TPS))
title('Two Photon Spectrum')

figure(2) %plot spectral density
surf(ws,wi,real(PHI))
title('Joint Spectral Density')

%Schmidt decomposition of the Joint Spectral Density to extract Signal
% modes in Sig
[Sig S Idl] = svd(PHI(1:end/FilFrac,1:end/FilFrac));
norm2 = sum(Sig(:,1).^2)*dw;

%display mode generation efficiencies
lambda = (norm2*diag(S)).^2;

%filter output spectrum with a supergaussian filter shape
outFilt = exp(-(wi.(2*MFil))./(2.*(sigFilt.(2*M))))';
for jj = 1:length(Sig);
    SigFil(:,jj) = Sig(:,jj).*outFilt;
end

%plot spectral domain modes 1 through 3
wi0=wi;
wi=wi(1:end/FilFrac);
figure(3)
pplot(1/(sig*10^-12)*wi, abs(Sig(1:length(wi),1)), 1/(sig*10^-12)*wi,...
    abs(Sig(1:length(wi),2)), 1/(sig*10^-12)*wi, abs(Sig(1:length(wi),3)))
title('Frequency Representation of 1st 3 Modes')
ylabel('Amplitude')
xlabel('Frequency Offset (Hz)')

figure(30)
pplot((3*10^8)/((1.93*10^14)^2)*wi*1/(sig*10^-12),abs(Sig(:,1)))
title('Bandwidth of First Mode at 1550nm')
xlabel('Bandwidth (m)')
ylabel('Amplitude')

figure(31)
pplot(wi,abs(Sig(:,1)))
title('Bandwidth of First Mode at 1550nm')
xlabel('Bandwidth (Hz)')
ylabel('Amplitude')
A.0.2. Control Code

The highest level code that controls the input parameters to the pump optimization simulations. The waveguide phase-matching profile, dispersion, number of comb lines, pumps, signals, and number of iterations are set by a user in this script. The code calls on another script in a loop to perform the pump optimization. Once the set number of iterations, or a predetermined target value has been met, the optimization moves on to the next input pump. After all pumps have been optimized the code saves a file containing all input parameters and optimized parameters such as pump temporal profiles and upconverted signal energies.

```matlab
1 clear all
2 % Highest level control code for the pump optimization simulations.
3 % V6: Expects pumps to be inserted that are not a copy of the
4 % input signal mode, pumps are in P(:,ii) and records M2 values during
5 % optimization, reports back with energy values for upconverted modes for
6 % further processing.
7
8 addpath('./');
9
10 chi = 0.5;
```
L = 4; % length in cm

beta = 2.54; % ps/cm

number_com = 40; % number of comb lines

comb_space = 0.020; % comb spacing in THz


R = 0.005; %This is a good compromise, compare with 0.001 or 0.01 to see

zCalcm = [0:dz:L];

d_z_cal = ones(size(zCalcm)); %This assumes no quasi-phase matching

Target = 0.99;

t = [-25:0.1:25]'; %time, and dt set here

load('ModesIn')

A = Am;

load('optPump40CL', 'PumpOpt')

P = PumpOpt;

n = 14; % how many pumps you want,

steps = 1; % how many accepted iterations to take

mod_num =1; %record energy values every __ iterations

PumpOpt = zeros(length(t),n); %set input pumps as results of lower CL opt

Eo_Set = zeros(floor(steps/mod_num),n,n);

randStep = [0.20,0.20]; % how far to walk in the solver, per iteration

M2All = zeros(steps,n,n);
for ii=1:n
    [PumpOpt(:,(ii)),a,b,c_opt,Ei_Set(:, :, ii)] = ... opt_plsM_v6_mod(chi, t, A(:,1:n), beta, zCalcM, d_z_cal, 0, number_com, ii, Target, steps, randStep, P(:,ii), comb_space);
end

% Store idler fields for all steps, time vals, modes, mode opts
% Store Energy values for all steps, modes, and mode opts

converge(:,ii) = a; % check convergence with this
solT(:,ii) = b; % solution times here
save('optPump.mat'); % save at each pump step.
end

Appendix/optPumpMikeV6.m

A.0.3. Perturbation Code

The code performs the genetic algorithm process to converge on an optimized pump. Two statistics of interest (SoIs) are used: upconversion efficiency and mode selectivity. Initial pumps are taken as inputs and a phase and amplitude perturbation is applied to a randomly chosen comb line of the pump. The perturbation code then calls on another script to calculate the upconversion of the pump acting on each signal and the two SoIs are calculated. If the SoIs show improvement from the previous iteration the new pump is passed on to the next iteration. Otherwise, the pump is discarded and the old pump is used for the next iteration. After a specified number of iterations, or a target value has been met the code returns optimized parameters such as pump temporal profiles and upconverted signal energies.

% chi - chi
% t - t-vector, check shape, if error, may need to transpose
% A - Signal mode vectors, A(n,m), where n is the size of t, and m is the # of signals
% beta - beta, ps/cm
% z_QPM - z-grid for propagation down waveguide
% c_QPM - quasi-phase match grating, set to 1 for uniform, same size as z_QPM
% dk - phase-mismatch
% number_com - number of comb lines
% pN - for which signal do you want a pump optimized?
% TargetN - stop when conversion hits how much?
% steps - or if that doesn't work, go how many (accepted) steps?
% randStep - how far can I go each iteration?
% Ap - Initial guess for the pump, usually a multiple of the target mode
% combSpace - spacing of comb lines in THz
% <<---------------------------------------->>
% V6: Records M2 parameter with each step

dt = t(2)-t(1);

mod_num = 1; %set to record idler energy values every 10 iterations
Ei_All = zeros(floor(steps/mod_num),size(A,2)); %Declare energy output matrix
w=zeros(number_com,1);

21 mod_num = 1; %set to record idler energy values every 10 iterations
22 Ei_All = zeros(floor(steps/mod_num),size(A,2)); %Declare energy output matrix
23 w=zeros(number_com,1);
% Comb line spacing, angular THz

for jj=1:number_com
    w(jj)=(jj-(number_com+1)/2)*dw; % offsets in THz of comb lines
end

c = zeros(number_com,1);

for ii=1:number_com
    c(ii) = 1/(max(t)-min(t)) * dt * sum(Ap.*exp(1i*w(ii)*t));
end

Ap_recon = t*0;

for ii=1:number_com
    Ap_recon = Ap_recon+c(ii).*exp(-1i*w(ii)*t);
end

X = [];
Y = [];
Z = [];
sA = size(A);

fprintf(1, '<<--------------- Target Prob %d = %1.4f
 +--------------->>\n', pN, TargetN(1));
fprintf(1,'| P%2.0d ',[1:1:sA(2)]);
fprintf(1,'| Dist | G# | S# |
');

j = 0;
k = 0;
c_opt = c;
CPU_core = feature('numCores'); % Max per computer
CPU_core = 12;
sqrtC = 10;
accept = 0;

while sqrtC > 0.001 && k < steps

    accept = 0;

    k = k+1;
tic;

    for jj=1:CPU_core
        rk=randi(number_com);
        c2_tp(:,jj)=c_opt;
        c2_tp(rk,jj) = c2_tp(rk,jj)*(1+randStep(1)*(rand-0.5)*exp(1i*2*pi*randStep(2)*(rand-0.5)));

    end

    Ai_temp = zeros(length(t),sA(2),CPU_core);

parfor jj=1:CPU_core

    Ai_temp_in = zeros(length(t),size(A,2));
    Ap_tp(:,jj)=0.*t;

    for ii=1:number_com
        Ap_tp(:,jj) = Ap_tp(:,jj) + c2_tp(ii,jj).*exp(-1i*w(ii)*t);
    end

    [Amp,~] = QFC_QPM_SolverFmulti(chi,t,Ap_tp(:,jj),A,beta,z_QPM,c_QPM,dk);
    Ploop = zeros(5,1);
    dP = zeros(5,1);

    for ii=1:sA(2)
        Ploop(ii) = sum(abs(Amp(:,1,ii).^2))/sum(abs(A(:,ii).^2));
        Ai_temp_in(:,ii) = Amp(:,1,ii);
        if ii == pN
            dP(ii) = (Ploop(ii)-TargetN).^2;
        else
            dP(ii) = Ploop(ii).^2;
        end
    end
    Ai_temp(:,:,jj) = Ai_temp_in;
    P(jj,:) = Ploop;
    sqrtC_tp(jj) = sqrt(sum(dP));
end
\[ [-, i] = \min(\sqrt{C_{tp}}); \]
\[ Z = [Z, \sqrt{C_{tp}}(i)]; \]

\textbf{if} \ \sqrt{C_{tp}}(i) < \sqrt{C} \ 
\textbf{accept} = 1;
\textbf{end}

\textbf{if} \ \text{mod}(k, \text{mod}_num) == 0 \ \%\textit{store idler energy values every 10 iterations} \n\textbf{for} \ l = 1:sa(2) \n\quad Ei\_All(k/\text{mod}_num, l) = \text{sum}(|\text{abs}(A_{i\_temp(:, l, i) \cdot 2})| \cdot dt); 
\textbf{end}
\textbf{end}

\textbf{if} \ \sqrt{C_{tp}}(i) > \sqrt{C} \n\quad \text{randNum} = \text{rand}; \n\quad \text{ratio} = \sqrt{C}/\sqrt{C_{tp}}(i); \n\quad \textbf{if} \ \text{randNum} > \text{ratio} \n\quad \quad \text{accept} = 1; \n\quad \textbf{end}
\textbf{end}

\textbf{if} \ \text{accept} == 1; \n\quad j = j+1; \n\quad \textbf{for} \ l = 1:sa(2)
\quad \quad \textbf{fprintf}(1, '| %1.4f ', P(i, l));
\textbf{end}
A.0.4. Split-step Calculation of Fields

The linear and nonlinear effects on the pump and signal pair are separated into two functions in the split-step upconversion calculation script. Linear dispersion of the pump and signal is calculated and returned, then the nonlinear upconversion calculation is made. The code returns the upconverted and residual signal fields.
function [Ar,As] = QFC_QPM_SolverFmulti(chi,t,Ap,As,beta,z_QPM,c_QPM,dk)

% distances are in cm, times are in ps!, QPM vector has to be equally
% spaced
% chi - chi
% t - t-vector, check shape, if error, may need to transpose
% Ap - Pump for the solving
% A - Signal mode vectors, A(n,m), where n is the size of t, and m is the
% # of signals
% beta - beta, ps/cm
% z_QPM - z-grid for propagation down waveguide
% c_QPM - quasi-phase match grating, set to 1 for uniform, same size as
% z_QPM
% dk - phase-mismatch

% <<---------------------------------------->>

nu=0;
mu=beta;
eta=chi;

Trange = max(t)-min(t);

Nms = length(t);

for j=1:Nms
    zx(j,1)=Trange*(j-1)/Nms;
    kx(j,1)=2*pi*(j-1-0.5*Nms)/Trange;
end
hjx(j,1)=(-1)^{j-1};

end

sAp = size(Ap);
sAs = size(As);

az = zeros(sAp(1),sAp(2),sAs(2));
bz = As;

dz = z_QPM(2) - z_QPM(1);

for ii = 1:length(c_QPM);
    c = c_QPM(ii);
    [az,bz] = solvL(az,bz,hjx,mu,nu,kx,dz,dk);
    [az,bz] = solvNL(az,bz,Ap,eta,dz,c);
end
Ar = az;
As = bz;
end

function [azl, bzl] = solvL(Az,Bz,hjx,mu,nu,kx,dz,dk)
    azl = zeros(size(Az));
bzl = zeros(size(Bz));

for ii=1:size(Az,2)
for jj=1:size(Az,3)
    ak = ifft(Az(:,ii,jj).*hjx).*exp(li*mu*kx*dz+li*dk(ii)*dz);
    az1(:,ii,jj) = fft(ak).*hjx;
end
end

for jj=1:size(Bz,2)
    bk = ifft(Bz(:,jj).*hjx).*exp(li*nu*kx*dz);
    bz1(:,jj) = fft(bk).*hjx;
end
end

function [azl, bz1] = solvNL(Az,Bz,Ap,eta,dz,c)
    azl = zeros(size(Az));
    bz1 = zeros(size(Bz));
    for ii=1:size(Az,2)
        for jj=1:size(Az,3)
            azl(:,ii,jj) = Az(:,ii,jj)+li*eta*Ap(:,ii).*Bz(:,jj)*dz*c;
        end
    end

    for ii=1:size(Az,3)
        for jj=1:size(Az,2)
            pNL = 0;
        end
    end
pNL = pNL + 1i * eta * \texttt{conj}(Ap(:, jj)) * \texttt{conj}(Az(:, jj, ii)) * dz * \texttt{conj}(c);

end

bz1(:, ii) = Bz(:, ii) + pNL;

end

end