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Band translation to short-wave infrared range: generalized mixer design for sensing
and communication applications

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy

in

Electrical Engineering (Photonics)

by

Faezeh Gholami

Committee in charge:

Professor Stojan Radic, Chair
Professor Prabhakar R. Bandaru
Professor Yeshaiahu Fainman
Professor Shayan Mookherjea
Professor Oleg Shpyrko

2013

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Chair

University of California, San Diego

2013

DEDICATION

To my parents

Fatemeh & Mohammad

who gave me wings

to fly my dreams.

EPIGRAPH

*"Just as life blazes within a body,
Knowledge brings light to the soul and spirit. "*

-Adib Pishavari

”چنان چون که تن زنده کردد به جان

به دانش فروزند جان و روان ”

- ادیب پشاورى



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LIST OF ABBREVIATIONS

AQN	Amplified quantum noise
3PA	Three photon absorption
BER	Bit-error-ratio
BERT	Bit-error-rate tester
CE	Conversion efficiency
CW	Continuous wave
DFB	Distributed feedback
DPSK	Differential phase-shift keying
ECL	External-cavity laser
EDFA	Erbium-doped amplifiers
FCA	Free-carrier absorption
FUT	Fiber under test
IR	Infrared
HNLF	Highly nonlinear fiber
FOM	Figure of merit
FWHM	Full width half maximum
FWM	Four-wave mixing
LIDAR	Light detection and ranging
LPF	Long-pass filter
mid-IR	Middle-infrared
MZM	Mach-zehnder intensity modulator
NIR	Near infrared

NRZ	Non return-to-zero
OPA	Optical parametric amplifier
OPO	Optical parametric oscillator
OSA	Optical spectrum analyzer
PC	Polarization controller
PD	Photodetector
PIC	Photonics integrated circuit
PM	Phase modulator
PRBS	Pseudo-random bit sequence
SBS	Stimulated Brillouin Scattering
Si	Silicon
SNR	Signal-to-noise ratio
SOA	Semiconductor optical amplifier
SOI	Silicon on insulator
SWIR	Short wavelength infrared
TPA	Two photon absorption
WDM	Wavelength division multiplexer
ZDW	Zero dispersion wavelength

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Faezeh Gholami, La Jolla, CA

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Chapter 4, in part is a reprint of the material as it appears in Optics Express in the article authored by Faezeh Gholami, Bill P.-P. Kuo, Sanja Zlatanovic, Nikola Alic, and Stojan Radic, “Phase-preserving parametric wavelength conversion to SWIR band in highly nonlinear dispersion stabilized fiber,” vol. 21, issue 9, pp. 11415-11424 (2013). Chapter 4, also contains in part material presented at the Optical Fiber Communication Conference in the article contributed by Faezeh Gholami, Sanja Zlatanovic, Evgeny Myslivets, Slaven Moro, Bill P.-P. Kuo, Camille-Sophie Brès, Andreas O. J. Wiberg, Nikola Alic, and Stojan Radic, “10Gbps Parametric Short-Wave Infrared Transmitter,” OThC6, Los Angeles, 2011. The dissertation author was the primary investigator and author/co-author of the journal paper and was the presenter of the conference presentation.

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ABSTRACT OF THE DISSERTATION

Band translation to short-wave infrared range: generalized mixer design for sensing
and communication applications

by

Faezeh Gholami

Doctor of Philosophy in Electrical Engineering (Photonics)

University of California, San Diego, 2013

Professor Stojan Radic, Chair

Both scientific and engineering endeavors in short-wave infrared and mid-infrared spectral bands suffer from a lack of fast high quality transmitters and receivers, which, if made available, would avail advanced sensing and high speed communication in these chiefly underutilized bands of high practical interest and potential. Motivated by the status quo, this dissertation focuses on spectral translation

as a powerful tool capable of successfully enabling application in these important spectral bands.

In particular, the method of choice consists of employing the four-wave mixing-based spectral translation from the telecom band to short-wave infrared in silica-based highly nonlinear fibers as a platform for construction of frequency and amplitude modulated optical transmitters that are ported to the longer bands by means of wavelength conversion. Furthermore, this approach is extended to developing a telecom-derived short-wave infrared *transceiver* taking advantage of a two-way spectral translation. The practical importance of the contribution is demonstrated by means of momentous signal-to-noise-ratio improvement through indirect detection of weak signals in the vicinity of 2 μ m wavelength that is not achievable by direct means. Finally, silicon as a complementary nonlinear platform, is considered expanding the concepts set forth above, to the mid-IR spectral range.

Chapter 1

Introduction

1.1. Motivation

In the electromagnetic spectrum, the infrared region, and more specifically the three subdivisions of near-infrared (0.8-1.6 μ m), short-wave-infrared (1.7-2.1 μ m) and mid-infrared (2.2-8 μ m) [1] have been of interest in a wide range of applications [2], [3]. The existence of strong absorption features of a variety of environmental pollutants [4], [5], industrial emission gases [6] and disease-related molecular compounds [7],[8] in the short-wave-infrared (SWIR) and mid-infrared (mid-IR) spectral regions has led to an explosion of applications in biological and chemical sensing and spectroscopy (in these portions of the electro-magnetic emission spectrum). Figure 1.1 illustrates a number of molecular compounds that exhibit pronounced spectral footprints in the SWIR and mid-IR bands. The specific range of wavelengths which are not associated with absorption by atmospheric gases such as water vapor, carbon dioxide and ozone identify the atmospheric transparency windows (marked by yellow-dotted lines in Fig. 1.1). Low atmospheric loss in these parts of the electromagnetic spectrum, suggests that operation in SWIR and mid-IR regions is inevitable for remote sensing and free-space communication applications [9], [10].

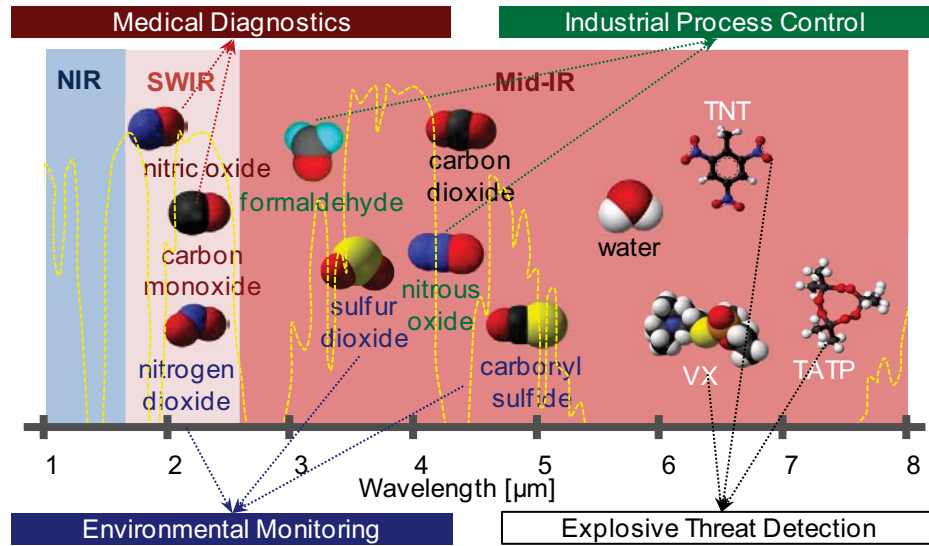


Figure 1. 1 Molecular compounds exhibiting absorption in SWIR and mid-IR spectral regions are associated with important sensing applications. Dotted yellow line shows the atmospheric transparency widows.

The aforementioned sensing and communication applications urge for advanced transceiver systems operating in SWIR and mid-IR bands. Current systems fail to exhibit adequate performance to fully facilitate these advanced applications; on the transmit side, the traditionally employed optical transmitters suffer from a lack of modulation-capable sources, and at the receiver end, the available SWIR and Mid-IR detectors are extremely limited in terms of noise performance, speed and operation condition (associated with burdensome of cooling requirements) [11]. Indeed, a high-speed modulation capable solution enabling low-noise detection in the mid-IR portions of the electromagnetic spectrum is on demand [12],[13].

In sharp contrast to SWIR- and mid-IR bands, near-infrared (NIR) spectral region has primarily remained the operating spectral band of the communication network interconnects constituting the global transport infrastructure for broadband data services as well as for internet applications[14]. The demand for higher per-fiber

transport capacities and the drive for lower costs per end-to-end transmitted information bit, in the telecommunication industry, have led to development of optical sources, modulators and detectors with superior performances operating in the NIR band [15],[16]. In this dissertation, we aim to bridge the gap between the application demand in the mid-IR band and the technological capabilities in the telecommunication band by introducing a new transceiver design based on spectral band translation.

The proposed transceiver system relies on two-way (i.e. forward-backward) wavelength conversion through efficient four-wave mixing (FWM). The nature of the FWM parametric process in theory preserves the optical phase, amplitude, and/or quantum state of the original source, thus allowing for the translation of advanced modulation formats. Consequently, the FWM-based optical wavelength translation can extend the functionality of telecom-specific devices to applications beyond their original purpose, that will be exemplified in this dissertation by constructing modulation-capable mid-IR sources [17],[18] for spectroscopy as well as for detection of weak SWIR signals.

Additionally, the two-way wavelength conversion represents a potential path to a successful migration of silicon photonics from the telecom wavelength region to longer wavelengths. Current trends in silicon photonics are aiming to integrate telecom optical amplifiers and wavelength converters [19] by employing the mature silicon fabrication process [20]. The existence (and ubiquity) of these fundamental building blocks of data communication networks have been responsible for availing wavelength division multiplexing (WDM) which is a key enabling feature improving

the efficiency of data transport in the telecom band. However, a major hurdle in creating practical nonlinear devices based on the silicon platform rests an intrinsic (nonlinear) loss mechanism at high powers in the NIR [21]. The silicon nonlinear loss in theory reduces dramatically in the mid-IR spectral range, thus presenting mid-IR band as a particularly promising region for nonlinear optical processing in silicon[22],[23],[24]. In this respect, investigation into the efficiency of silicon as a nonlinear mixing platform in the mid-IR is of prime importance.

1.2. Outline of the Dissertation

This dissertation commences with an introduction in Chapter 2, intended to provide an overview of the physical phenomena important for understanding of the optical systems discussed in remainder of the presented material. In Chapter 2, a brief description of $\chi^{(3)}$ nonlinear media and a number of nonlinear optical processes that have an impact on the construction and performance of optical parametric translators is presented. Additionally, different operating regimes for an optical parametric wavelength converter are discussed, as well.

In Chapter 3 we investigate the feasibility of silicon, an important $\chi^{(3)}$ nonlinear medium, as a parametric platform in the mid-IR band. A description of nonlinear loss mechanism in silicon is provided, followed by experimental measurements of Kerr nonlinearity and multi-photon absorption coefficients in silicon in a portion of the mid-IR spectral region in which no experimental data had previously existed.

Another widely used parametric $\chi^{(3)}$ nonlinear medium, silica glass fiber, is employed for demonstration of modulation-capable SWIR sources in Chapter 4. In that respect, the theoretical background of the physical phenomena imposing the performance limitations to fiber wide-band parametric translators is presented first. The theoretical discussion is then followed by experimental demonstrations of two distinct SWIR source architectures with arbitrary amplitude and phase modulation capability. The subsequent discussion includes consideration of techniques for suppression of deteriorating effects and fiber fabrication limitations on wide-band optical translators.

In Chapter 5 we aim to eliminate the necessity for pursuing construction of optical transmitter and receiver devices operational in SWIR band and to, instead, benefit from the mature technology developed in the NIR band. We propose and experimentally demonstrate a two-way spectral translation scheme between telecom- and SWIR band, constructed only from telecom components. We show the compatibility of the proposed concept to a range of applications in sensing and communication by using the bi-directional translator to perform sensing of carbon dioxide and detect weak signals in the SWIR band. Finally, we conclude the dissertation in Chapter 6 with a summary of the work presented, alongside with pointing to the future directions.

Chapter 2

Parametric Spectral Translation Concepts

Wide-band spectral translation making use of four-wave mixing optical effect in nonlinear $\chi^{(3)}$ media forms the foundation of the approach pursued in this work to construction of sensing and communication systems in the wavelength region beyond $1.8\mu\text{m}$. This chapter covers a review of the nonlinear processes critical to analysis, design and performance of the architectures and approaches presented in the subsequent chapters.

The chapter starts out with a qualitative description of the media characterized by the third order nonlinear response. Following that, we introduce concepts that have significant impact on the efficiency of wide-band translators. The FWM parametric interaction, i.e. the main effect enabling spectral translation, is discussed in Section 2.2, followed by Section 2.3 focusing on the aspects of the FWM processes engineering requiring phase matching condition covering very wide bandwidths.

2.1. Third-order Nonlinear Media

Nonlinear optical effects occur when the response of a material to an applied optical field depends on the strength of the optical field in a nonlinear manner. To describe optical nonlinearity more specifically, we first consider the linear case. In a

linear system, the induced polarization $P(t)$, or dipole per unit volume, of the material depends linearly on the optical field, $E(t)$ [25]:

$$P(t) = \varepsilon_0 \chi^{(1)} E(t) \quad (2.1)$$

where ε_0 is the permittivity of free space and $\chi^{(1)}$ represents the linear susceptibility of the medium. A generalization of equation (2.1) leads to the nonlinear case, where $P(t)$ is expressed as a power series in the field strength $E(t)$:

$$P(t) = \varepsilon_0 [\chi^{(1)} E(t) + \chi^{(2)} E^2(t) + \chi^{(3)} E^3(t) + \dots] \quad (2.2)$$

$\chi^{(2)}$, known as the second-order non-linear optical susceptibility only occurs in non-centrosymmetric materials, which does not apply to the materials of interest in this dissertation, i.e. silica glass fiber and silicon. Centrosymmetry corresponds to perfect symmetry in the lattice structure, which, actually, results in an odd- (i.e. skew-) symmetry in material response. In this dissertation we are interested in the nonlinear interaction arising from the third-order non-linear optical susceptibility coefficient, $\chi^{(3)}$. The $\chi^{(3)}$ is responsible for phenomena such as third-harmonic generation, four-wave mixing, and nonlinear refraction [26].

In the presence of Kerr (i.e. $\chi^{(3)}$) nonlinearity, the refractive index can be presented as:

$$n = n_0 + n_2 I \quad (2.3)$$

where I is the intensity of the incident wave, n_0 is the linear refractive index and n_2 is the nonlinear contribution to the refractive index of the material arising from the

third-order term in the induced polarization ($\epsilon_0 \chi^{(3)} E^3(t)$). The Kerr coefficient n_2 is related to the real part of $\chi^{(3)}$ by:

$$n_2 = \frac{3}{4\epsilon_0 c n_0^2} \chi_{eff}^{(3)} \quad (2.4)$$

where $\chi_{eff}^{(3)}$ is the effective third-order nonlinearity, n_0 is the linear refractive index, ϵ_0 is the vacuum permittivity, and c is the speed of light in vacuum. The specifics of this relations depend upon the crystallographic orientation [21].

The Kerr coefficient, n_2 , is an optical constant that characterizes the strength of the optical nonlinearity. Another nonlinear parameter, defined as

$$\gamma = \frac{n_2 \omega_0}{c A_{eff}} \quad (2.5)$$

, is also widely used in design of nonlinear waveguides where A_{eff} is the effective cross-section area of the waveguide mode, c is the speed of light, and ω_0 its (angular) frequency. The nonlinear parameter along with the length of the waveguide and the medium loss dictate viability of a nonlinear medium as a platform for third-order nonlinear processes such as FWM. The fundamentals of FWM interaction is reviewed later in this dissertation. For the time being, Table 2.1 presents a comparison between various nonlinear platforms employed for wide-band spectral translation through FWM.

Table 2. 1 Nonlinear optical parameters. Comparison of platforms used for wide-band spectral translation through FWM third-order nonlinear process.

Citation	Material	Nonlinear parameter γ (W ⁻¹ km ⁻¹)	Linear loss (dB/m)
Jiang et. al. [27]	photonic crystal fiber	70	0.05
Yeom et. al.[28]	chalcogenide waveguide	93.4×10^3	<1
Boggio et. al. [29]	silica HNLF	11.5	<0.001
Zlatanovic et. al.[30]	silicon nanowires	97.3×10^3	280

Among $\chi^{(3)}$ nonlinear platforms, silicon (Si) waveguides and silica highly nonlinear fibers (HNLF) benefit from a well developed fabrication processes. Recent developments in the silica-based HNLF fabrication process offer remarkably low loss as well as precise dispersion engineering and phase matching control of the fiber [31],[32], which, despite the low nonlinear Kerr index of silica, still provide highly-efficient nonlinear interaction. A competing platform of the engineered nanoscale silicon waveguides enhances the optical nonlinearities by up to five orders of magnitude and enables integrated chip-scale devices. Despite these advantages, however, the higher propagation losses in Si imply higher power requirements and present a fundamental obstacle, limiting the parametric gain in the FWM process. The following section will provide a theoretical background to the FWM parametric interaction.

2.2. FWM Parametric Interaction

The third order contribution to the nonlinear polarization presented in Eq. (2.2) leads to the third-order parametric processes involving nonlinear interaction among four optical waves. A parametric process is defined as a process in which the energy

and momentum of the interacting waves of the system are conserved [25]. The parametric interaction between four co-polarized waves in a $\chi^{(3)}$ nonlinear optical medium is governed by a set of coupled mode equations as [16]:

$$\begin{aligned} \frac{dA_{p1}}{dz} + \frac{1}{2}\alpha_{p1}A_{p1} &= i\gamma_{p1} \left[|A_{p1}|^2 + 2|A_{p2}|^2 + 2|A_s|^2 + 2|A_i|^2 \right] A_{p1} \\ &+ 2i\gamma_{p1}A_s^*A_{p2}A_i e^{(i\Delta\beta z)} \end{aligned} \quad (2.6a)$$

$$\begin{aligned} \frac{dA_{p2}}{dz} + \frac{1}{2}\alpha_{p2}A_{p2} &= i\gamma_{p2} \left[|A_{p2}|^2 + 2|A_{p1}|^2 + 2|A_s|^2 + 2|A_i|^2 \right] A_{p2} \\ &+ 2i\gamma_{p2}A_{p1}A_s^*A_i e^{(-i\Delta\beta z)} \end{aligned} \quad (2.6b)$$

$$\begin{aligned} \frac{dA_s}{dz} + \frac{1}{2}\alpha_sA_s &= i\gamma_s \left[|A_s|^2 + 2|A_{p1}|^2 + 2|A_{p2}|^2 + 2|A_i|^2 \right] A_s \\ &+ 2i\gamma_sA_{p1}^*A_{p2}A_i e^{(i\Delta\beta z)} \end{aligned} \quad (2.6c)$$

$$\begin{aligned} \frac{dA_i}{dz} + \frac{1}{2}\alpha_iA_i &= i\gamma_i \left[|A_i|^2 + 2|A_{p1}|^2 + 2|A_{p2}|^2 + 2|A_s|^2 \right] A_i \\ &+ 2i\gamma_iA_{p1}A_{p2}^*A_s e^{(-i\Delta\beta z)} \end{aligned} \quad (2.6d)$$

where α_n and γ_n ($n = p1, p2, s, i$) are the propagation loss and nonlinear coefficients of the pumps, signal and idler, respectively, with A_n being the optical field amplitude.

Assuming the fields' phases to be aligned at the origin ($z = 0$), the linear phase mismatch factor $\Delta\beta$ in Eq. 2.6 is defined as:

$$\Delta\beta = \beta_i - \left[\beta_s + (\beta_{p1} - \beta_{p2}) \right] \quad (2.7)$$

with β_n ($n = p1, p2, s, i$), the propagation constants of the waves in the transmission medium, becoming frequency dependent due to the frequency dependency of the refractive index. As a result, waves travel with different velocities as they propagate along the medium. Mathematically, the effects of this property, referred to as chromatic dispersion, are accounted for by expanding the mode-propagation constant, β , in a Taylor series about the frequency ω_0 at which the spectrum is centered:

$$\beta(\omega) = n(\omega) \frac{\omega}{c} = \sum_m \beta_m (\omega - \omega_0)^m / m! \quad \text{for } m = 0, 1, 2, \dots \quad (2.8)$$

Parameter β_1 is related to the group velocity, while the parameter β_2 represents the group velocity dispersion. Another parameter of practical importance is dispersion parameter, D , capturing the dispersive properties with respect to wavelength, which is related to the first and second order dispersion coefficient as,

$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta_2 \quad (2.9)$$

One possible third order parametric process in $\chi^{(3)}$ material is the degenerate (i.e. single-pump) FWM process in which two pump photons $p1$ and $p2$ in Eq. 2.6 are supplied by a single pump wave. The parametric interaction between an optical pump, centered at ω_P , and a spectrally distinct signal wave, with frequency ω_S , leads to the amplification of the signal and the creation of a new idler wave at a frequency ω_I (equal to $2\omega_P - \omega_S$, owing to the energy conservation). An illustration of the FWM process is given in Fig. 2.1.

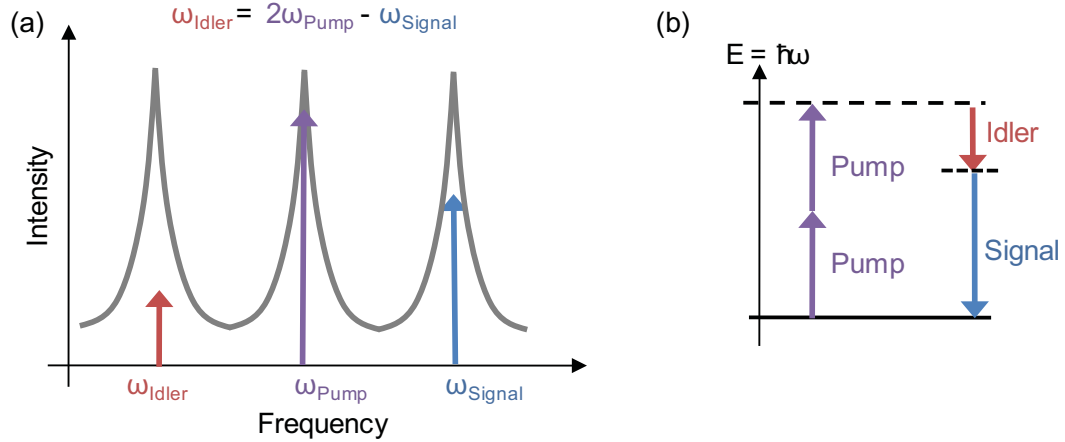


Figure 2. 1 Four-wave mixing. (a) frequency domain diagram, (b) Energy-level description showing two pump photon giving energy to an idler and a signal photon.

Nonlinear processes such as FWM that involve generation of new frequencies, are efficient only if, in addition to a low material loss at the frequencies of interest, special efforts are made to achieve phase matching between the interacting waves. In the following section we elaborate on the techniques utilized to achieve efficient FWM specifically for wide-band spectral translation.

2.3. Phase-matching Schemes

In the specific FWM parametric interaction case when the total power acquired by the signal wave, with frequency ω_s , and idler wave, at a frequency ω_I constitutes an insignificant fraction of the power of the optical pump, centered at ω_P , the approximate solution to the coupled-mode equations (presented in Eq. 2.6) to the signal and idler evolution along a medium longitudinal section of length z (in the single transversal mode case), is given by

$$B_s(z) = (a_s e^{gz} + b_s e^{-gz}) \exp(-i\Delta kz / 2) \quad (2.10a)$$

$$B_i^*(z) = (a_i e^{gz} + b_i e^{-gz}) \exp(-i\Delta kz / 2) \quad \text{.....}(2.10b)$$

, here $B_k(z) = A_k \exp(-4i\gamma P_0 z)$, with A_k being the amplitude of the wave with k equal to s and i for signal and idler, respectively. γ is the nonlinear parameter and P_0 stands for the incident power at the waveguide input. The coefficients, a_s , b_s , a_i and b_i are determined from the boundary conditions.

From Eq. 2.10 the signal gain, G_s , and the idler generation efficiency, G_i , can be represented by the following expressions [16]:

$$G_s = 1 + \frac{(\gamma P_p)^2}{2g^2} [\cosh(2gL) - 1] \quad (2.11a)$$

$$G_i = \frac{(\gamma P_p)^2}{2g^2} [\cosh(2gL) - 1] = G_s - 1 \quad (2.11b)$$

$$g = \sqrt{(\gamma P_p)^2 - (\Delta k)^2} \quad (2.11c)$$

The length of the nonlinear waveguide, L , the nonlinear parameter, γ , the incident pump power, P_p and a frequency-dependent factor Δk , denoted as the total phase mismatch, affect the efficiency of the nonlinear interaction.

The spectral response of the parametric amplification (conversion) is determined by the total phase mismatch factor Δk :

$$\Delta k = \Delta\beta + 2\gamma P_p \quad (2.12)$$

For silica fibers and silicon waveguides, the phase mismatch for pump at λ_p and signal at λ_s can be described accurately by taking into account only the second, β_2 , and fourth-order, β_4 , dispersion coefficients and neglecting higher order dispersion terms [16]. Then, Eq. 2.8 can be approximated as:

$$\Delta\beta \approx \beta_2(\omega_p - \omega_s)^2 + \frac{1}{12}\beta_4(\omega_p - \omega_s)^4 \quad (2.13)$$

A phase-matching condition ($\Delta\beta = -2\gamma P_p$) must be satisfied to achieve high efficiency in the FWM process. Several conclusion can be drawn from this phase matching condition depending on the sign of dispersion coefficients β_2 and β_4 .

If we consider parametric amplification close to the pump, the fourth-order term can be neglected, and phase matching is therefore obtained if $\beta_2 < 0$ (anomalous group velocity dispersion). However, if we are operating in distant bands away from the pump, the fourth-order dispersion term has significant impact in phase matching and should be considered. To achieve phase-matching at the frequencies far away from the pump (i.e. when the pump-signal frequency difference ($\Delta\omega = \omega_p - \omega_s$) is large), β_2 and β_4 must be of opposite signs. If $\beta_2 < 0$ and $\beta_4 > 0$ a wavelength band close to the pump (broadband modulation instability) and far away from the pump (narrowband modulation instability) will experience parametric amplification, while in the opposite case ($\beta_2 > 0$ and $\beta_4 < 0$) only narrow band modulation instability far away from the pump will be observed. The frequency-detuning-dependent linear phase-mismatch for all of the four combinations of signs for β_2 and β_4 are schematically illustrated in Fig. 2.2. Only the solutions on the $\Delta\omega > 0$ side of the pump are shown in order to simplify the illustration. Within a phase detuning tolerance of $\pm 2\pi/L$, originating from the finite length L of the medium, efficient FWM can be achieved and is depicted by shaded area in Fig. 2.2.

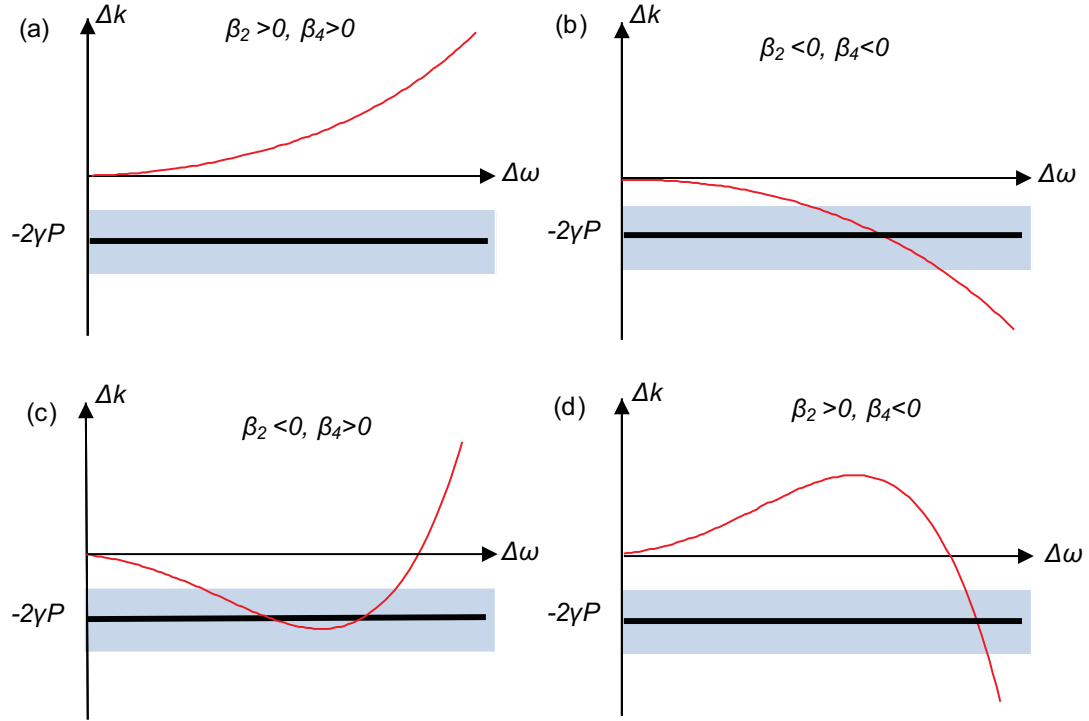


Figure 2. 2 Solutions to the phase-matching condition for various combinations of the signs of dispersion coefficients β_2 and β_4 . Solutions exist where the frequency detuning phase mismatch overlaps with the shaded area.

In the case when both the second and fourth order dispersion coefficients are positive no solution exists, while for both negative signs, there is only one phase-matching point. When β_2 remains negative and β_4 is positive, a flat negative phase mismatch over a wide spectral band is obtained, which is typically used for parametric amplification and wide-band frequency translation in optical parametric amplifiers (OPAs) and OPOs. For positive β_2 if β_4 is small, the contribution of the two dispersion terms can balance each other and we can achieve a broad frequency-detuning range where the peak of the linear phase-mismatch curve lies entirely within the shaded grey region. Later in Chapter 4 of in this dissertation, we discuss SWIR

sources, operating under the phase matching regime depicted in Fig. 2.2(c) and (d) where we further describe the characteristics of these modes of operation.

Chapter 3

Third Order Nonlinearity in Silicon

The mid-infrared spectral range has been identified as a promising region for silicon photonics, particularly for building nonlinear optical devices that operate at high powers [33] such as silicon Raman lasers [34]. At high intensities, the high third-order nonlinearity, combined with a large index-contrast of silicon on insulator (SOI) waveguides has allowed for parametric generation [30] and amplification [35] of mid-IR light in silicon waveguides up to 2400nm. However, applications operating deeper into the IR require precise knowledge of the nonlinear characteristics in this region. The third order nonlinearity in silicon has been reported for wavelengths up to 2350nm [36],[37]. In this chapter we provide measurements of nonlinear optical coefficients of silicon in this spectral range in which no experimental data previously existed. To fully verify feasibility of silicon as a mid-IR mixer we also investigate the strength of parasitic multi photon absorption.

The chapter initiates with a brief theoretical background on nonlinear absorption in dielectric media. Section 3.2 discusses experimental characterization methods of the nonlinear properties of silicon as a platform for parametric processes in the mid-infrared spectral region. The measurements of Kerr nonlinearity in silicon are

presented for the 2350nm to 2750nm wavelength range, where the three-photon absorption effect is present. We conclude the chapter with a comparison of Kerr interaction strength in the NIR spectral region to that above 2300nm.

3.1. Nonlinear Absorption

Silicon as an indirect band gap material, can absorb a photon and excite a carrier from a filled state in the conduction band to an unoccupied state in the same band, the effect referred to as the free carrier absorption (FCA). At NIR wavelengths, when the photon energy is higher than the half of the band-gap energy($E_{gi} / 2$), at low incident intensities silicon exhibits low propagation losses. However, at high intensities it begins to absorb light because of the two-photon absorption (TPA). In the TPA process two photons are absorbed to excite an electron from the valence band and into the conduction band. The TPA, in turn, creates a population of free carriers that can also absorb light through the FCA [38],[39]. Figure 3.1 illustrates a diagram of the FCA and TPA processes in an indirect band gap material.

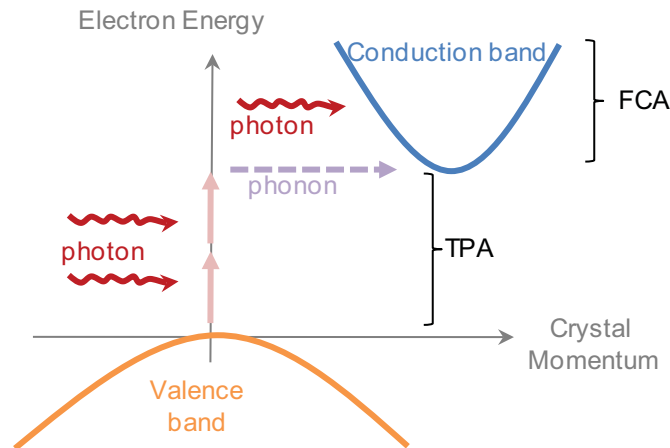


Figure 3. 1 Energy diagram of an indirect band gap material. For FCA the excited electron is in the conduction band. For TPA energy difference between the involved lower and upper states is equal to the sum of the energies of the two photons.

The inherent indirect electronic band structure of silicon causes, a low intrinsic recombination rate of free carriers – that of only 10^3 - 10^6 per second- compared with approximately 10^9 per second in direct-band structure semiconductors. Consequently, the free-carrier population can build up quickly at high light intensities, resulting in significant optical loss.

Mathematical description of the TPA can be understood by first considering the case of a linear medium where the intensity of the light after propagating over a distance z in the material is modeled as:

$$I(z) = I_0 e^{-\alpha z} \quad (3.1)$$

where I_0 is the incident intensity and α is the absorption coefficient.

When an optical material displays both the TPA characteristics, as well as linear absorption, the total absorption coefficient appearing in Eq. 3.1 should be replaced by:

$$\alpha = \alpha_0 + \beta_{TPA} I \quad (3.2)$$

here, β_{TPA} is the TPA coefficient. On the other hand, the TPA, in theory, corresponds to the imaginary part of the third order susceptibility ($\chi^{(3)}$) introduced in Chapter 2.

In the spectral region below 2254nm, the imaginary part of $\chi^{(3)}$ for silicon is significant since the photon energies are higher than the half of its bandgap. Due to the strong two photon absorption, free-carrier population quickly builds up, resulting in additional optical loss [39], [40]. In consequence, below the wavelength threshold of ~ 2254 nm, the three-photon absorption is present and can obscure the desired

nonlinear $\chi^{(3)}$ parametric process. On the other hand, this impairment becomes negligible for the incident light wavelengths above the TPA threshold wavelength,.

3.2. Silicon Nonlinearity Characterization in mid-IR

The viability of silicon as a parametric platform in the mid-IR can be quantified by a nonlinear response spectral mapping in the spectral region beyond 2350nm. Previously, it has been shown that the Kerr nonlinearity increases considerably over the spectral region from 1.2 to 1.9 μ m [37], it peaks near 1.9 μ m and decreases at longer wavelengths. The efficiency of parametric devices is limited by the intensity-dependent nonlinear losses. While, as mentioned in Section 3.1, two-photon absorption diminishes at wavelengths beyond 2254nm, another parasitic effect, three-photon absorption (3PA) [41], becomes significant. In the remainder of this chapter we report on the measurements of both nonlinear Kerr coefficient and three-photon absorption in 2384nm to 2745nm spectral range. This range was specifically selected as it corresponds to $E_{gi}/3 < \hbar\omega < E_{gi}/2$, where E_{gi} is the indirect bandgap energy, where TPA is not present but 3PA is significant.

3.2.1. Z-scan Measurement

To perform the Kerr coefficient (n_2) measurements in the presence of three-photon absorption coefficient (γ), we used a single beam z-scan technique [42]. This method was previously employed to obtain two-photon absorption coefficient, three-photon absorption coefficient (γ) and Kerr coefficient. The technique relies on intensity variations obtained by (longitudinally) scanning a material sample by a focused Gaussian beam. A simplified schematic of the z-scan technique operation is

illustrated in Figure 3.2. In the arrangement for Kerr coefficient measurement, a lens focuses a laser beam to a certain beam waist, after which the beam naturally defocuses.

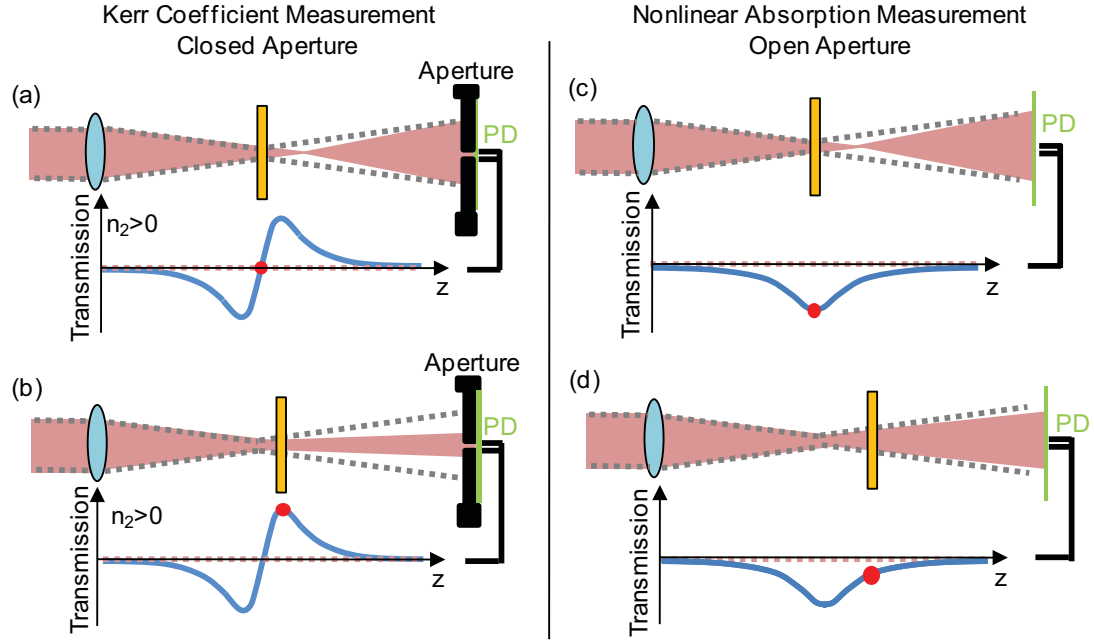


Figure 3. 2 Experimental setup used for z-scan measurements. Closed aperture measures Kerr nonlinearity and open aperture nonlinear absorption. The red dot specifies the location of sample with respect to focal point.

At a further distance, an aperture is placed in front of a detector ensuring that only the central region of the cone of light is incident on the detector. In this manner, the detector is made appropriately sensitive to any focusing or defocusing that a sample may induce. The sample is typically placed at the focus point of the lens, and then moved along the z axis. In case n_2 is positive, the laser beam incident on the nonlinear material, induces a refractive index variation within the material with a larger refractive index at the center of the beam than at its periphery [25]. Thus, the nonlinear material acts as if it were a positive lens, causing the beam to come to a focus within the material. In other words, the beam of light modifies its own

propagation (self-focusing) by means of nonlinear response of material medium. We employed the same technique for measurement of three-photon absorption and Kerr nonlinearity above 2300nm. Figure 3.3 shows a diagram of the z-scan experiment.

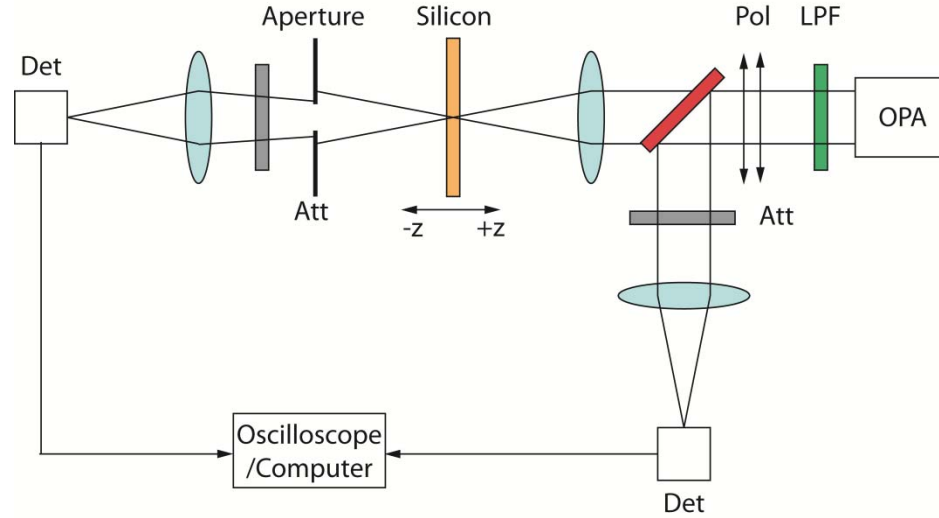


Figure 3. 3 Experimental setup used for z-scan measurements. OPA: optical parametric amplifier, LPF: long pass filter, Det: detector, Att: neutral density filter, Pol: crossed polarizers.

The experiments were conducted with an OPA (Spectra Physics-800CF) source tunable over $1100\text{nm} < \lambda < 2700\text{nm}$ spectral range. The OPA delivered 118fs (full width at half maximum -FWHM) having 1 kHz repetition rate. The light from the OPA was then filtered using a 2100nm long-pass filter to remove OPA idler centered at shorter wavelength. A pair of crossed polarizers were used to linearly polarize the light along the horizontal axis and to provide tunable attenuation of the pulsed power at the same time. The linearly polarized probe was then used to measure nonlinearity of a 460 μm thick intrinsic silicon polished on both surfaces to reduce scattering. The probe pulse was focused down at normal incidence onto the silicon wafer using a 10cm Calcium Fluoride (CaF_2) lens. The (111) silicon wafer was oriented such that the light was polarized along the [110] direction. Furthermore, the reference beam was

tapped from the source using a CaF_2 beam splitter in order to account for energy fluctuations in the incident pulse. The PbSe detectors (Thorlabs PDA20H) were used in both reference and signal arms. The transmitted light was then passed through silicon, filtered by an aperture and focused down onto the surface of the detector. The transmittance through the aperture was $S=0.2$. Three-photon characterization can be accomplished with an open aperture, while acquisition of the total third order nonlinearity effect requires closed aperture measurements. The output of the detector was observed on a real time oscilloscope and data was collected as the sample was scanned along the z -axis. The beam waist w_0 ranged $29\text{-}59\mu\text{m}$ for band of wavelengths, and was determined using a knife-edge measurement technique described in Appendix A. Fresnel reflection losses were incorporated in determining the peak intensity inside the sample.

3.2.2. Experimental Results

As mentioned in Section 3.2.1, an open aperture z -scan provides strict quantitative information on the three-photon absorption. To verify the measurements for the open-aperture case where only 3PA effect is present (for a pulse with intensity I), the attenuation was fitted to a numerical solution of [41],[43]

$$\frac{dI(z',r,t)}{dz'} = -\gamma[I(z',r,t)]^3, \quad (3.3)$$

where r and z' are beam radial and longitudinal coordinates within the sample and t is time. While the exact analytical solution describing close-aperture z -scan in presence of three photon absorption does not exist to date, an estimate of Kerr coefficient

contribution can still be approximated as the ratio of closed and open scans, from which the transmission is then given by

$$\frac{T_{close}(z)}{T_{open}(z)} = 1 - \frac{8\pi}{\lambda\sqrt{2}} \frac{z/z_0 (1-S)^{0.25} L_{eff} n_2 I_0}{(1+(z/z_0)^2)(9+(z/z_0)^2)} \quad (3.4).$$

In Eq. (3.4), z_0 is the confocal beam parameter, z is the longitudinal scan distance from the focal point of a Gaussian beam with peak intensity of I_0 inside the sample (taking into account Fresnel reflection), S is the aperture transmittance, and L_{eff} is the effective optical length; this experiment used $S=0.2$.

Figure 3.4 shows the z-scan transmission along with the numerical fit for three photon absorption and analytical solution fit for Kerr coefficient.

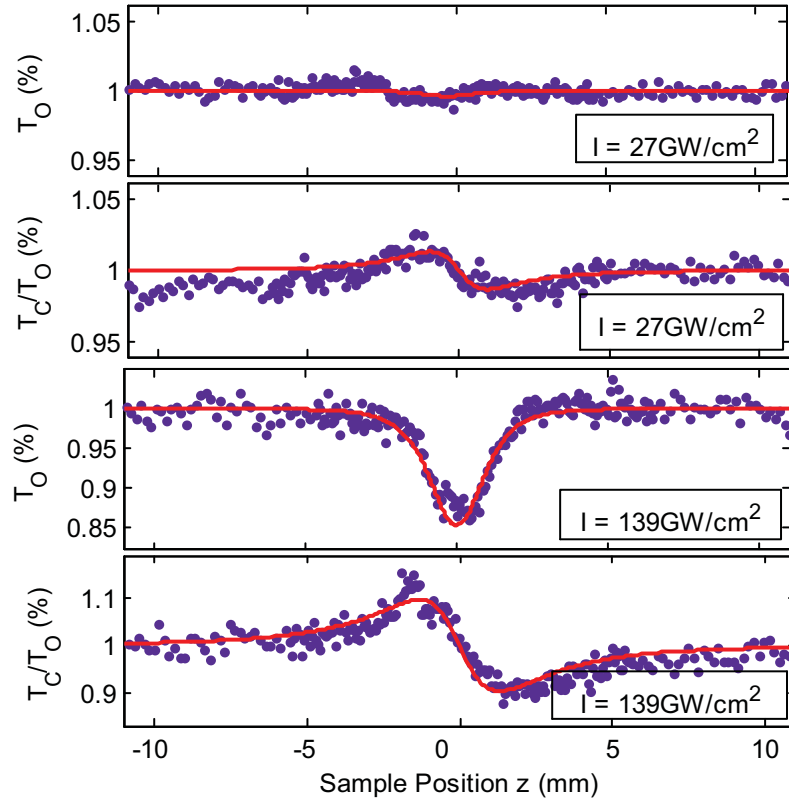


Figure 3. 4 Z-scan traces. Measurement data and calculated fit for 460 μm thick Si at 2598nm for peak intensities of 27GW/cm² and 139GW/cm².

Two different intensities of 27 and 139 GW/cm² were used in the experiment for light with wavelength of 2598nm. The afore-mentioned approximation gives a good agreement with data calculated using exact analytical solution in the presence of two-photon absorption. The noise was attributed to the energy fluctuation of the incident pulses and was measured to be 5%. To account for the effect of energy fluctuations, the transmitted signal was divided by the reference arm [42].

Figure 3.5 shows measured values of n_2 as a function of wavelength.

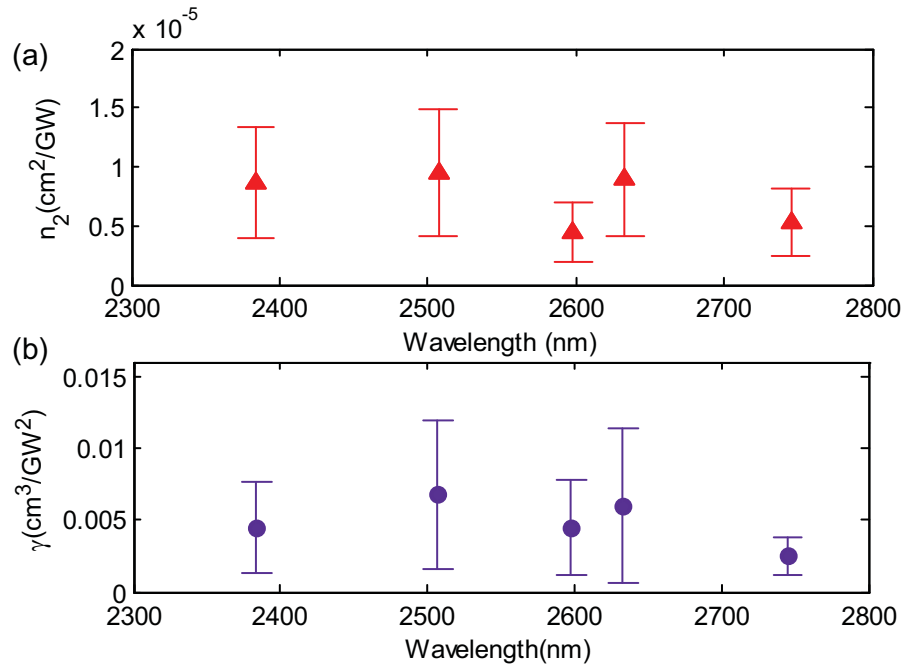


Figure 3. 5 Dependence on wavelength. Measured (a) n_2 (triangles) and (b) γ (circles) values for 460μm thick intrinsic silicon sample as a function of wavelength.

The experimental errors were dominated by the sources' peak intensity fluctuation, the variations in the beam shape induced by OPA tuning, the Gaussian beam profile assumption and the beam waist measurement error. The data fit indicated that Kerr nonlinearity remains at the same order of magnitude ($\sim 10^{-5}$ cm²/GW) as in previously reported 1.3 to 2.3 μm range [37],[36].

It is important to emphasize that the previously reported data show significant discrepancy in absolute values of n_2 , partly due to the different crystal orientation used in the experiments. However, we note that the results agree with respect to the order of magnitude. Furthermore, the Kerr nonlinearity dispersion shape is consistent across all of the published literature.

The Kerr nonlinearity measurement results were also validated by the theoretical prediction of Kerr nonlinearity from Kramers-Krönig transform of the two-photon absorption coefficients [44],[45], using the data from Bristow [36]. The spectral dispersion curve of the real susceptibility, corresponding to Kerr nonlinearity, can be related to the spectral response of the imaginary part of the susceptibility by the nonlinear Kramers-Kronig relation as

$$\chi_{eff}^{(3)} = \frac{4\varepsilon_0 c n^2}{3} n_2(\omega) = \frac{4\varepsilon_0 c^2 n^2}{3\pi} \int_0^\infty \frac{\beta_{TPA}(\omega, \omega')}{\omega'^2 - \omega^2} d\omega' \quad (3.5)$$

where ε_0 is the permittivity of free space and c speed of light (mathematical method explained in Appendix B).

The Kerr coefficient values obtained in our study are closer to the values reported by Lin [37] and follow the trend predicted by Kramers-Krönig transform. Additionally, the experimental value of $1.96 \cdot 10^{-5} \text{ cm}^2/\text{GW}$ reported for silicon at $10\mu\text{m}$ [46] confirms this trend and is similar to our measurements. Figure 3.5 illustrates the dispersion characteristic of 3PA data as well. The obtained γ values are approximately five times larger than the data reported by Pearl [41]. Finally, to verify that the observed n_2 value is consistent for different intensity levels, the measurements were repeated for several incident light powers. Figure 3.6 (a) plots the nonlinear coefficient

value obtained from the theoretical fits for the different peak intensities for 2598nm. Figure 3.6 (b) illustrates 3PA for the different peak intensities along with the theoretical fit.

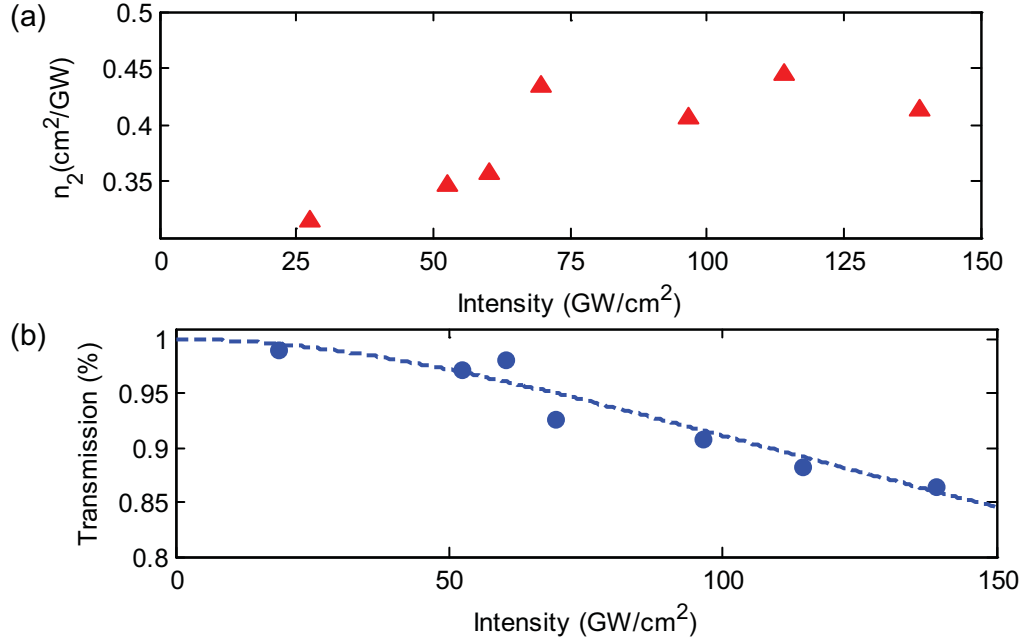


Figure 3. 6 Dependence on intensity. Values obtained from the fits to experimental data for (a) n_2 (triangles) and (b) 3PA (circles) as a function of peak intensity at 2598nm. Dashed line is theoretical fit based on 3PA.

As the input intensity gets higher, some features appear in the z-scan data; these signatures are attributed to free carriers that are generated by three-photon absorption and in turn induce refractive index change, or also due to fifth-order nonlinearity effects. However, it is expected that the effect of third-order nonlinearity is much stronger since fifth-order nonlinearity requires higher intensities.

To evaluate the performance of silicon as a parametric platform we define the nonlinear figure of merit (FOM) as $n_2/\lambda\beta_{TPA}$ [40] for TPA dominant region. For 3PA region, we define FOM as $n_2/\lambda\beta_{3PA}I$, where I is the intensity inside the nonlinear medium. For silicon waveguides that are of interest for mid-IR generation [41], this

intensity is typically less than $1\text{GW}/\text{cm}^2$. Figure 3.7 presents FOM plot using previously reported values in the region below $2.3\mu\text{m}$ and compares them with our obtained results.

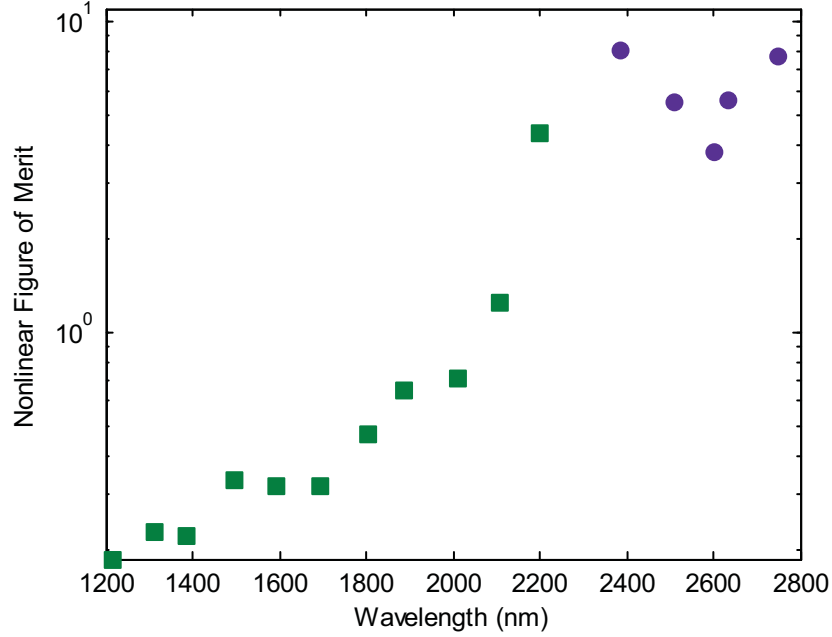


Figure 3. 7 Nonlinear figure of merit for region with TPA: squares (data from Ref. [37]) and 3PA: circles (measured data).

As expected, FOM is low in the near-infrared region but increases in the spectral region where the effects of TPA and 3PA diminish. We note that the minor drop in the figure of merit around $2.6\mu\text{m}$ coincides with the peak of 3PA. Even there FOM is larger than in 1550-nm band where it is dominated by TPA impairment.

3.3. Chapter Summary

This chapter exposed on rigorous measurements of the Kerr nonlinear coefficient in silicon by the z-scan technique in the spectral region beyond 2300nm where the three-photon absorption increases in strength. The measurement confirmed that the Kerr interaction strength is comparable to that in the near-infrared.

Furthermore, the measured dispersion trend for the Kerr coefficient is fully consistent with that obtained from the Kramers-Krönig relations using previously reported two-photon absorption coefficients. Additionally, the three-photon absorption was measured and its effect on nonlinear figure of merit in silicon appears not to be as restrictive as that of two-photon absorption. The results indicate that the strength of Kerr nonlinearity retains the same order of magnitude it has in near infrared region and leads to considerably higher FOM. The results identify silicon as a promising platform for parametric processes in mid-infrared spectral region.

Chapter 3, in part is a reprint of the material as it appears in Applied Physics Letters in the article authored by Faezeh Gholami, Sanja Zlatanovic, Aleksandar Simic, Lan Liu, David Borlaug, Nikola Alic, Maziar P. Nezhad, Yeshaiahu Fainman, and Stojan Radic, “Third-order nonlinearity in silicon beyond 2350 nm,” vol 99, issue. 08, pp. 1102 (2011). The dissertation author was one of the primary investigators and author/co-author of this article.

Chapter 4

Modulation-Capable Fiber SWIR Sources

The SWIR region has an important role in applications such as free-space communications, biological and chemical sensing, spectroscopy, as well as light detection and ranging (LIDAR) [1]. The sensitivity and efficiency of all these applications would greatly benefit from construction of a coherent SWIR source capable of encoding both amplitude and phase to an optical carrier. However, the conventional optical modulation components that are designed for NIR cannot operate in SWIR band for both practical and fundamental reasons. Distant-band translation can be employed as an approach for porting the mature modulation technologies pertinent to the telecommunication band to the infrared wavelength range in the electromagnetic spectrum [47],[48].

For distant-band wavelength conversions, an optimal translator possessing a net-positive optical gain, fast response, spectrally invariant nature, as well as being capable of preserving optical phase, amplitude, and/or quantum state can, in principle, be realized as a parametric mixer [49],[50]. As discussed in Chapter 2, among the materials that have been investigated as platforms for parametric conversion to distant bands[51],[52], silica HNLF has been both proposed and demonstrated [53], [17] as

one of the most important platforms that rigorously satisfies the conversion requirements by its inherent capability of mapping the entire signal state to a distant spectral range, particularly reinforced by the exceedingly low material loss.

This chapter reports the concept and experimental demonstration of modulation capable SWIR sources based on distant-band parametric translators. The first two sections of the chapter are dedicated to a discussion on major design challenges in constructing a fiber-based parametric distant band translator, focusing mainly on operation limitation due to fiber dispersion fluctuations and the stimulated Brillouin scattering. Section 4.3 describes the experimental demonstration and characterization of a 10Gb/s amplitude modulated SWIR transmitter. A demonstration of phase preserving 10Gb/s distant band translator is presented in Section 4.3, followed by concluding remarks in Section 4.5.

4.1. Fiber Dispersion Fluctuations

Although the nonlinear response is negligible in bulk silica material, its effect can be significantly enhanced in optical fibers. An optical fiber consists of a central glass core surrounded by a cladding layer, the refractive index of which is slightly lower than that of the core. Figure 4.1(a) shows a schematic illustration of the cross section and refractive index profile of a single mode step-index fiber. The enhancement of the nonlinear effects (and in particular the efficient mixing) is accomplished by the tight confinement of the optical power into a small core area and the long interaction length (i.e. hundreds of meters and even kilo-meters). In the specific case of the highly nonlinear fibers (Fig. 4.1(b)), a fiber is heavily doped in the core area, and a large refractive index difference between the core and the cladding is

achieved, resulting in even a smaller effective area and hence, enhanced nonlinearity coefficient according to Eq. 2.5.

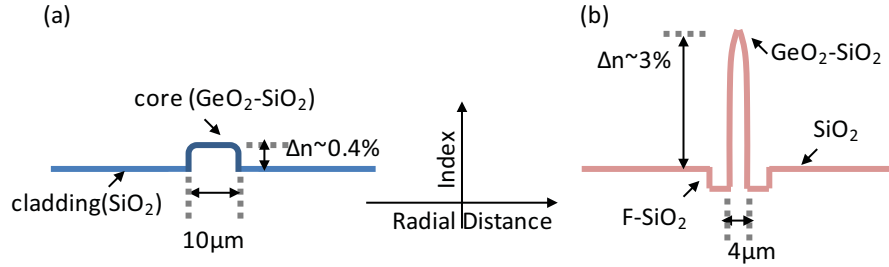


Figure 4. 1 Schematic refractive-index profile of a) single-mode fiber, b) highly nonlinear fiber.

Silica HNLF has been used as a platform for many applications, including optical amplifiers [54] and optical signal processing [55]. As discussed in Chapter 2, the phase-matching condition must be satisfied throughout the fiber length for an attainment of a highly efficient nonlinear interaction. Consequently, the chromatic dispersion, including higher orders, should be designed appropriately. Explicitly, the wavelength at which material dispersion and waveguide dispersion cancel one another, namely the zero dispersion wavelength (ZDW) should be precisely controlled in the longitudinal direction. However, in all commonly used fibers, the ZDW experiences significant fluctuations in the longitudinal direction due to the random variations in the core diameter which are a consequence of the manufacturing process. In particular, the core diameter variations seriously degrade the efficiency of the FWM-based parametric processes in highly nonlinear fibers due to the afore mentioned high index contrast [56],[57].

4.2. Stimulated Brillouin Scattering

Another significant obstacle to the development of fiber optical parametric amplifier and converter systems is the Stimulated Brillouin Scattering (SBS) [25]. This nonlinear optical phenomenon sets a hard limit to the maximum amount of optical power that can be coupled into a given fiber while maintaining a linear relationship with the output power. This limit comes as a result of a stimulated light scattering from induced alteration of acoustic properties of the medium. A schematic representation of the stimulated Brillouin scattering is illustrated in Figure 4.2.

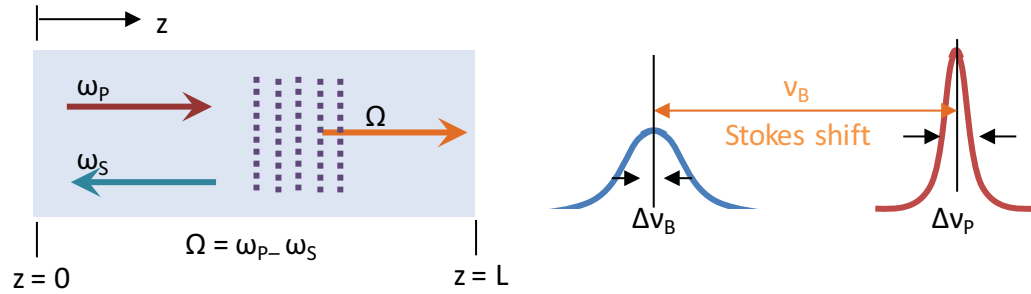


Figure 4. 2 Stimulated Brillouin scattering. The scattered light is shifted downward in frequency to the Stokes frequency. $\Delta\nu_B$ is Brillouin bandwidth and $\Delta\nu_p$ is the pump linewidth.

Brillouin scattering in fiber is a consequence of electro-striction by which a strong wave generates a small material density change in the material acting as a (moving) grating traveling at the speed of sound. In a single-mode fiber, photons will be scattered (backwards) from localized refractive index variations induced by sound or acoustic waves [58]. The grating strength is proportional to the power of the light wave and is inversely proportional to its coherence (i.e. laser linewidth), and for a high enough pump beam intensity. Ultimately, light from an intense forward-propagating signal (pump signal) can provide gain for a backward-propagating Stokes signal. The process is illustrated in Figure 4.2 depicting the inelastic scattering of the pump wave

down-shifted in frequency to the, so called, Stokes frequency $\omega_s = \omega_L - \Omega$, the stokes shift being equal to the Doppler shift of the moving grating. Above a certain incident light power, the SBS threshold, this generated back-ward reflected wave begins to increase in power exponentially and acts as to limit the power that can be coupled into a waveguide.

As can be inferred, the presence of SBS severely limits the attainable parametric mixing efficiency and also causes detrimental effects on nonlinear generation [59]. Unfortunately, the SBS is strongly enhanced in HNLFs, therefore, development of techniques for SBS suppression is crucial for practical implementation of parametric devices. These techniques seek to increase the SBS threshold by manipulating either the Brillouin bandwidth (and thus the peak gain), or the incident laser linewidth in order to minimize the spectral overlap between the two, which in turn limits the gain experienced by the back reflected light. In the case of Brillouin bandwidth broadening some typical methods used to increase the SBS threshold include: introducing temperature gradients along the fiber, introducing longitudinal strains, and changing the dopant concentration in the fiber [60],[61],[62].

The active SBS suppression methods seek to instead broaden the linewidth of the incident light to reduce the amount of power experiencing gain in the generally narrow SBS bandwidth. Linewidth broadening can be achieved by either direct frequency modulation of the source or by phase modulation without introducing significant intensity modulation on the laser. In either case the laser is dithered in either phase or frequency. Typical waveforms used for dithering include sinusoids, combinations of multiple sinusoids, and pseudorandom bit sequences. Currently the

active methods of SBS suppression are more widely used due to the performance advantage, the lack of effects on the fiber dispersive properties, as well as ease of implementation. Both SBS suppression and fiber dispersion fluctuations control are addressed in the design of parametric systems presented in the rest of this chapter.

4.3. The Parametric SWIR Transmitter

Four wave mixing interaction between a CW pump wave and an arbitrary modulated seed signal can, in principle, fully translate the modulation from the signal wave to the idler wave. In this section we describe the translation of 10Gb/s non return-to-zero (NRZ) signal over 85THz from the O-band (1278nm) to the SWIR band (2 μ m). The SWIR transmitter was constructed using an HNLF-based parametric mixer and standard telecom band components, eliminating the need for specialized components such as SWIR high-rate optical modulators. The translator operates in the CW mode, whereas a major hurdle in this mode of operation is input power limitations due to SBS as described in Section 4.2. In the section that follows we first describe the SBS suppression technique employed in the translator design. The description is followed by experimental validation of FWM-based amplitude modulation distant band translation.

4.3.1. The SBS Suppression

In the case of distant-band wavelength conversion, the passive SBS suppression techniques are best avoided, since any dispersion alteration (e.g if the fiber is stretched) is detrimental to the dispersive properties in conventional HNLFs. However, among active SBS suppression methods, one candidate waveform used for

dithering the pump laser phase, is an RF noise source. The noise source covers an entire bandwidth of frequencies continuously [63]. The random nature of the noise source frequency components, amplitudes, and phases serves to efficiently spread the bandwidth of the carrier over a given bandwidth, with the stochastic nature of the modulation being responsible for decoherence of the Brillouin contributions. In this demonstration, the pump was spectrally broadened using a phase modulator (PM) driven by the RF noise source with 0.4GHz bandwidth to suppress stimulated Brillouin scattering in the HNLF, and then amplified using erbium-doped amplifiers (EDFAs). Carrier suppression was monitored on a high resolution SWIR optical spectrum analyzer (OSA). The carrier-suppressed phase-modulated spectrum of the pump is shown in Figure 4.3 which yields to an SBS threshold increase.

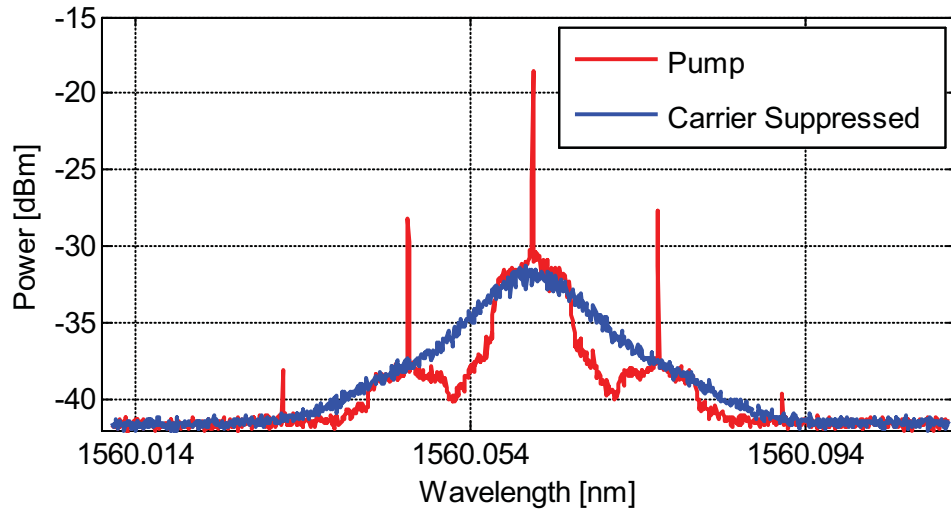


Figure 4. 3 Pump spectral broadening with an RF noise source for SBS Suppression. Spectrum of the pump phase modulated with a 1.5GHz noise source.

4.3.2. Experimental Setup

The experimental setup for the 10Gb/s modulated data streams' parametric conversion to $2\mu\text{m}$ in HNLF is shown in Figure 4.4. The signal seed, tunable between

1270-1360nm, was amplified using an O-band semiconductor optical amplifier (SOA). In addition, the SOA was placed immediately after the laser to preempt the SOA inherent relaxation oscillations. A polarization controller preceding the SOA ensured the proper input signal polarization. Subsequently, the seed was amplitude modulated (MZM) using 10Gb/s non-return-to-zero pseudo-random bit sequence (PRBS).

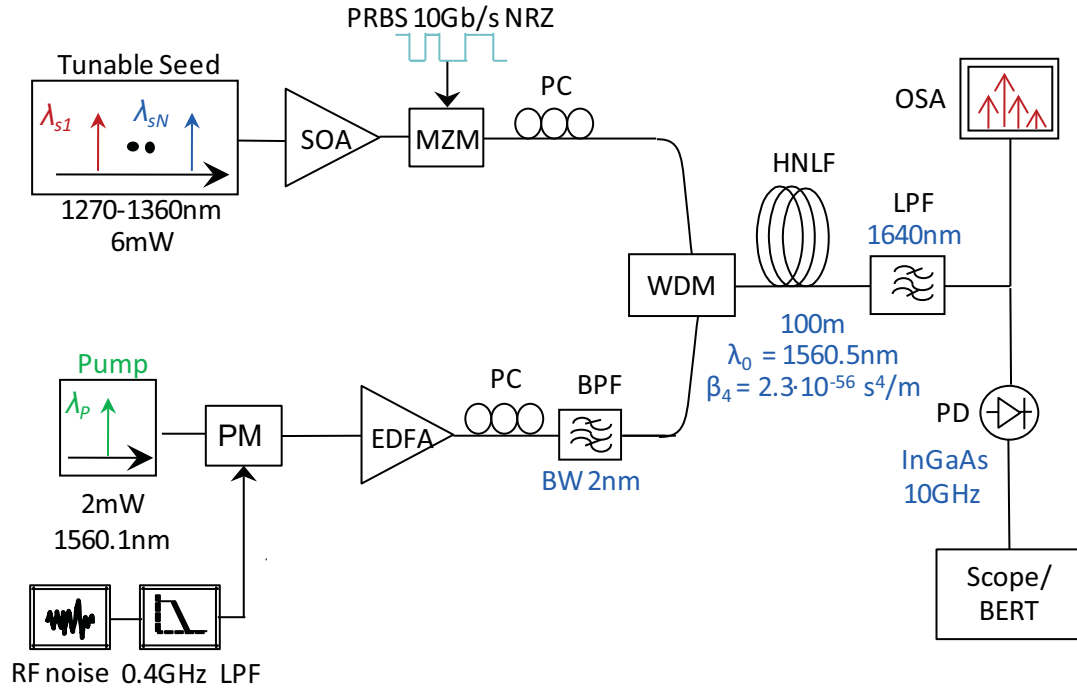


Figure 4. 4 Experimental setup. EDFA: erbium-doped fiber amplifier, SOA: semiconductor optical amplifier. MZM: mach-zehnder intensity modulator, WDM: Wavelength Division Multiplexer, PM: Phase modulator, PD: photodetector, ISO: isolator, HNLF: highly nonlinear fiber.

The continuous-wave (CW) pump was appropriately positioned at 1560.1nm close to the zero dispersion wavelength of the HNLF fiber. The excess amplified spontaneous emission after last stage EDFA was rejected using a tunable double-cavity band-pass filter with 2nm bandwidth. After filtering, the pump was combined with the signal using a wavelength-division multiplexer (WDM) and launched into ~100m of HNLF to generate an idler at ~2μm. The HNLF was characterized by a zero

dispersion wavelength of 1560.5nm, dispersion slope S of 0.026ps/(km nm²) and measured fourth-order dispersion coefficient β_4 of $2.3 \cdot 10^{-5} \text{ s}^4/\text{m}$. The pump power at the input to the HNLF was 2.5W, while the input signal power was 9.7dBm. After filtering out the seed and the pump using a long-pass filter (LPF) at 1640nm, the isolated 2.002 μm idler was directed to an OSA and a 10GHz InGaAs PIN-detector (PD) for its integrity analysis. The OSA was set to a resolution bandwidth of 0.2nm with a sensitivity of -70dBm. The signal from the PD was amplified using a limiting amplifier and the waveform was sampled using a digital oscilloscope and received by the analyzer section of the bit-error-ratio tester (BERT) for rigorous idler performance quantification.

4.3.3. Amplitude Modulated SWIR Source

The spectrum of the converted 2002nm idler is shown in Figures 4.5.

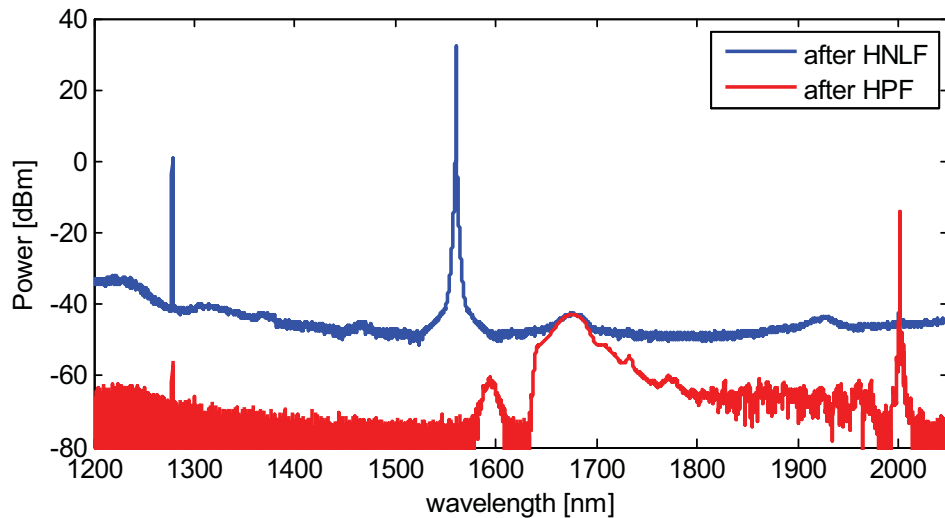


Figure 4. 5 Conversion spectrum after HNLF. Reflecting the response of 30dB of inline attenuator at high powers compared with spectrum after the LPF with pump and seed filtered out.

Due to the unavailability of proper filtering components in the $2\mu\text{m}$ region, standard telecom band long-pass filter was used to isolate the 2002nm idler in this experiment. The spectrum at the output of the HNLF before the LPF was obtained using a 30dB of inline attenuator and reflects its spectral response (Figure 4.6).

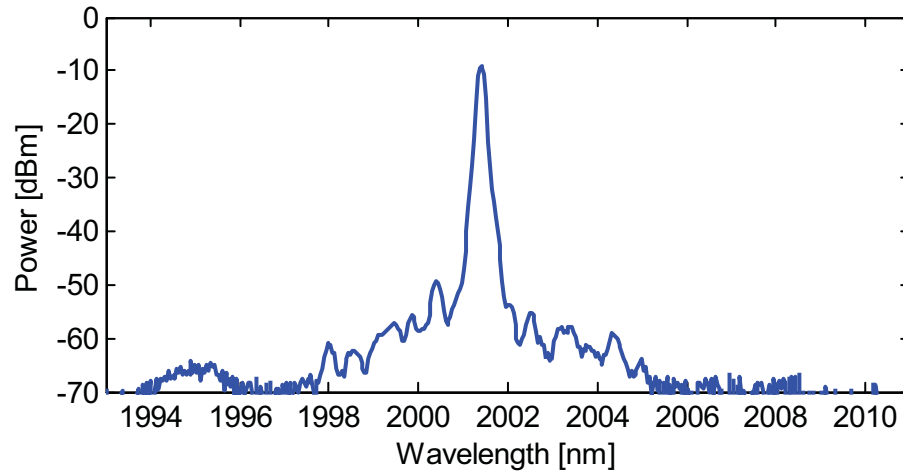


Figure 4. 6 Converted isolated idler at 2002nm.

The long-pass filter introduced a significant loss of 7dB at the idler wavelength. Consequently, actual generated idler power directly out of the HNLF was -0.5dBm (0.89mW) for the -7.5dBm power level measured after the LPF. The FWM conversion efficiency was, therefore, -10.2dB over the 700 nm range, with a noise floor around the $2\mu\text{m}$ -idler 40dB lower than the peak idler power. The transmitter performance was further hampered by the LPF transfer characteristic which passed a significant amount of the wide band ASE noise around the pump (with a total power of $\sim -18\text{dBm}$) originating from the Raman gain in this spectral region, that was unimpededly present at the detector, thus significantly deteriorating the performance. A $2^{31}-1$ long PRBS pattern was used to capture the transmitter performance (i.e. the

eye diagrams) and to measure the bit-error-ratio (BER). Both responses at 1278nm seed and 2.002 μ m idler were measured using the same 10GHz detector.

Two modulation speeds, 2.5Gb/s and 10Gb/s were used in the experiments. The eye diagrams for 2.5Gb/s modulation are shown in Figure 4.7(a). Figures 4.7 (b) shows eye diagrams for 10Gb/s modulation. The slow rise and fall time were typical for the 10GHz band-limited detector.

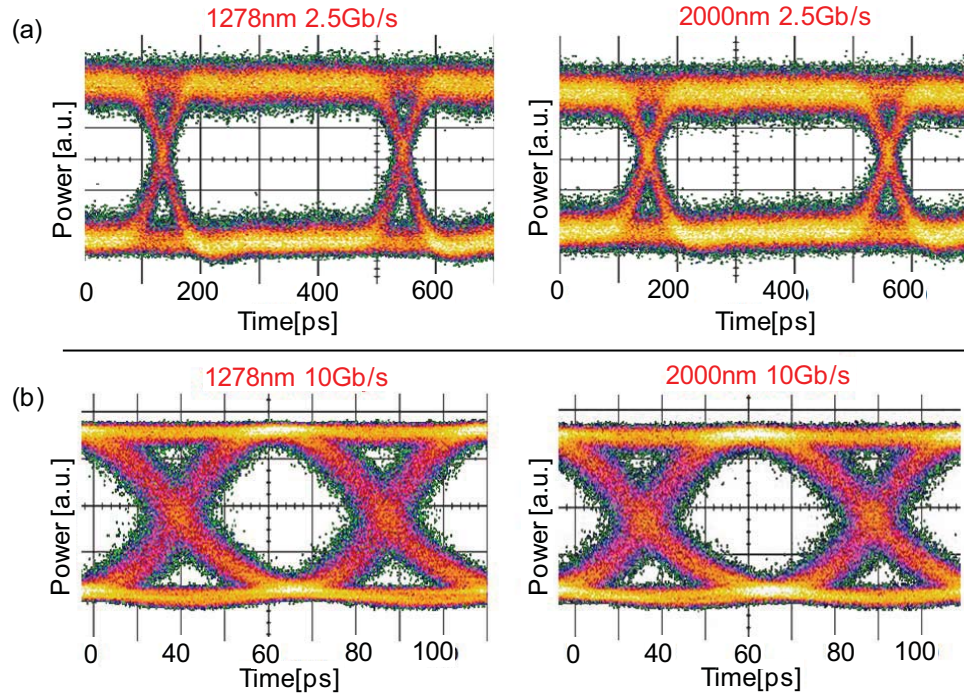
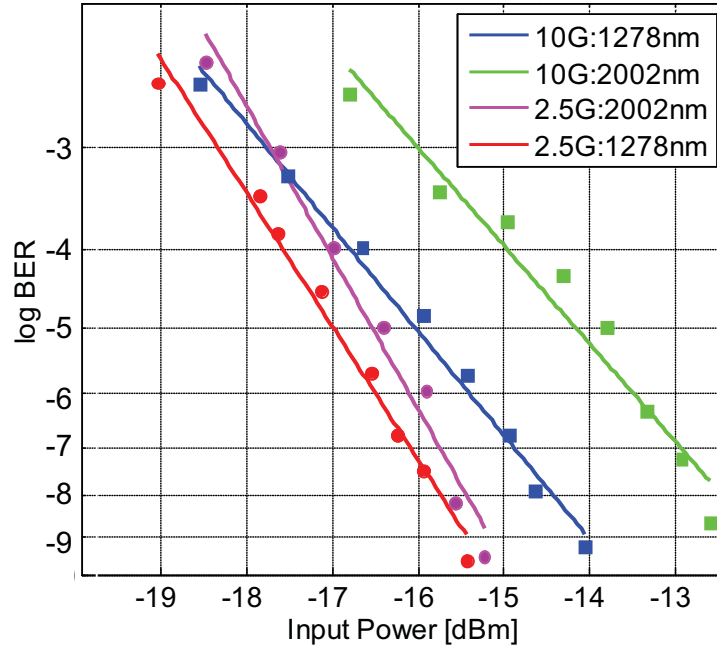


Figure 4. 7 Eye diagrams. a) 2.5Gbps signal b) 10Gb/s signal.

The BER curves (Figure 4.8) show error-free performance at 2002nm with penalty of 0.25dB compared with back-to-back signal at 1278nm. The penalty is partially imposed by inefficient rejection of the spectral noise beyond the 1640nm due to non-standard components that were used to filter out the converted signal at 2002nm (Figure 4.5).



(AQN) generation. Indeed, the AQN depletes the pump and contributes to the signal and idler phase noise [64]. As a matter of fact, the latter limitation can be overcome by taking advantage of a narrow-band parametric mixer relying on negative fourth-order dispersion which eliminates the generation of a wide-band AQN.

As discussed in Section 4.2, an additional important impediment that needs to be taken into account in wide-band parametric converters is that of the dispersion fluctuations of the mixing medium. We mentioned that in practice, the phase-matching in a conventional HNLFs is extremely sensitive to dispersive fluctuations caused by transversal geometry fluctuations resulting in the fiber drawing process [65] [66]. Recently, a new class of highly nonlinear fibers possessing dispersive characteristics invariant to these transverse geometry fluctuations has been introduced [67],[68] by our group. The new fiber design is based on an index profile that reduces dispersion shifts as the transverse geometry of the fiber is varied, allowing for a precise and maintained control over the phase matching condition along the entire length of the waveguide. In particular, the fiber is specifically tailored for parametric generation phase-matched by negative fourth-order dispersion (β_4). More importantly for practical considerations, the new waveguide design fully maintains the dispersive properties even under longitudinal strain, thus allowing for stimulated Brillouin scattering suppression [69] (by fiber straining) without affecting the phase-matching properties, making the novel fiber design a perfect phase-matching retaining translator with an increased Brillouin threshold [68].

In this section, we first discuss the benefits and challenges of operating in a narrow-band phase-matched region for phase-preserving wavelength conversion.

Section 4.4.1 describes the advantage of operation in a narrow-band phase matched regime over wide-band schemes. In Section 4.4.2 we investigate the effect of random dispersion fluctuations on conversion efficiency of the mixer as well as the tolerance to dispersion fluctuations within a narrow bandwidth. Finally, in Section 4.3.3, we demonstrate that the combination of characteristics of the new dispersion fiber enables a pristine conversion of phase-coded optical signal to a spectrally distant (SWIR) band, with an error-free performance by employing an optical parametric translator operating in the pulsed regime.

4.4.1. Narrow-band Parametric Translation

The recently developed capability to accurately tailor the dispersion of silica-based HNLFF allows for precise control of the dispersion coefficients [31],[32]. In the most commonly used parametric translators such as the demonstration in Section 4.3, for which a broadband gain is sought, the optimal phase matching is achieved by choosing the fiber with a positive β_4 and situating the pump frequency at the anomalous dispersion region resulting in operation negative β_2 dispersion regime. As presented in Chapter 2, the simultaneous occurrence of a positive β_4 and negative β_2 provides spectrally flat, vanishingly small phase mismatch over a wide spectral band. As an illustration, we show the theoretical conversion efficiency spectra for operation in this phase matching regime in Fig. 4.9.

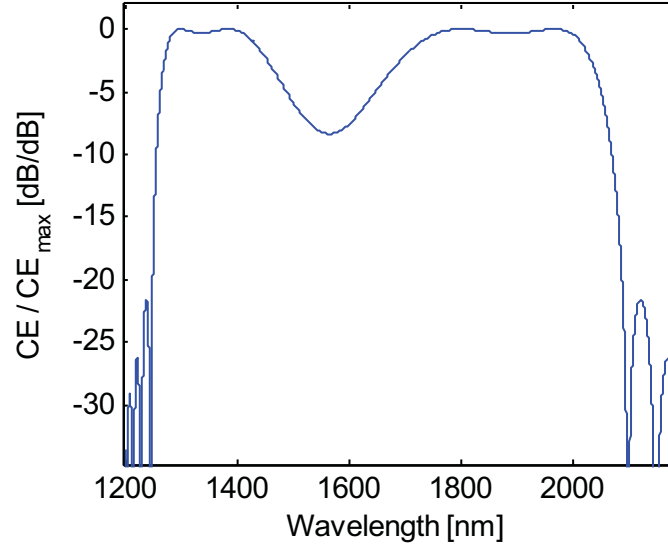


Figure 4. 9 Theoretical conversion efficiency (CE). Spectra for wide band parametric converter.

The HNLF used for this simulation was characterized by a low positive $\beta_4=4.2 \cdot 10^{-7} \text{ s}^4/\text{km}$. In this wide-band phase matching mode, a broad out-of-(pump)-band AQN is generated which is present at the detector and significantly deteriorates the performance of the translator [48].

As discussed in Chapter 2, an alternative approach consists of adopting a negative β_4 fiber and a pump frequency at the normal dispersion region (resulting in positive β_2) which leads to a pair of narrow spectral bands formed at spectrally distant frequencies. Figure 4.10 shows an example of the theoretical conversion efficiency spectra obtained for a fiber designed for operation in the negative β_4 phase matching mode. The fiber used for this simulation is a recently designed highly nonlinear fiber [15] which was employed later in this work for distant-band phase-preserving translation. The fiber (at 1550 nm) was characterized by a nonlinear coefficient of $5.2 \text{ W}^{-1}\text{km}^{-1}$, a propagation loss of 0.4 dB/km , a zero-dispersion wavelength of 1593 nm , and a dispersion slope of $0.067 \text{ ps/nm}^2/\text{km}$. [70].

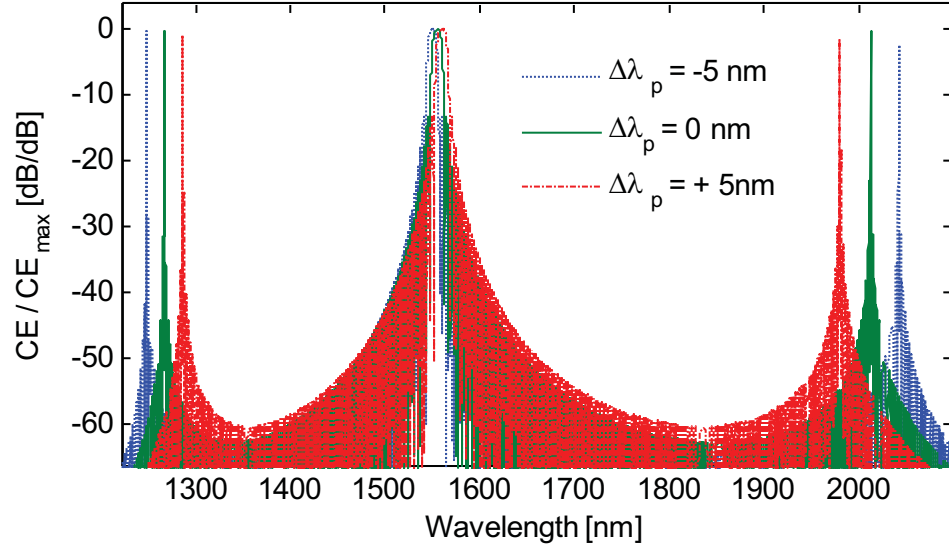


Figure 4. 10 Theoretical conversion efficiency (CE). Narrow-band parametric converter ($\lambda_p=1556.5\text{nm}$ and $\Delta\lambda_p$ is the shift from this wavelength).

Figure 4.10 clearly shows a potentially wide tuning and far reaching range of the process: The calculation implies that tuning the pump wavelength by 60nm results in phase-matched doublets at 1200 and 2100 nm. It is important to emphasize that this operational mode for a fiber-optical parametric converter allows access to distant bands devoid of generating excessive AQN, inherent to wide-band parametric wavelength translators [48]. Moreover, in the case of a wide-band translation (i.e. wide-band phase matching), the AQN depletes the pump, thus imposing a higher pump power requirement for an equally efficient conversion. In practice, the latter condition, unfortunately, limits the generated idler power since the pump power must be kept well below the Brillouin threshold, lest significant degradations of the translated signal integrity materialize. Additionally, in the case of phase modulated signals, the AQN noise contributes to the phase noise transferred to the signal and

idler waves during the distributed interaction in a HNLF [64], and should, thus, be kept at a minimum level.

4.4.2. Effects of Dispersion Fluctuations

In spite of the translator performance improvement by operating in the negative- β_4 phase matched regime, a typical HNLF which is designed based on the conventional single-core design strategy, is highly sensitive to dispersion fluctuations due to the transversal geometry fluctuations along the fiber [71],[72]. In the analysis which follows in this section, we investigate the translator performance degradation due to dispersion fluctuations along the fiber and we demonstrate that by employing the recently designed multi-layered waveguide design [67], which allows for high dispersion stability, specific mixer performance limitations can be significantly suppressed.

In Section 4.1 it was pointed out that the high modal confinement of a conventional HNLF induces a high sensitivity of its dispersive properties to the ever present microscopic random fluctuations of the core geometry created in the drawing process. These intrinsic core fluctuations cause considerable dispersion variation [32]. Ultimately, these dispersion fluctuations not only affect the conversion efficiency of the translator, but also lead to undesirable high dispersion accumulation within the narrow band phase-matched window. In this section we discuss two important system degradations. We describe the impact of random dispersion fluctuations on translator conversion efficiency and phase-preservation.

To incorporate the random dispersion variations into the evolution of the interacting waves along the fiber, a random perturbation to the mean second-order dispersion is introduced as follows [73]:

$$\delta\beta_2(z) = \delta\beta_2(z - \delta z) \exp(-\delta z / L_c) + p\sqrt{1 - \exp(-2\delta z / L_c)} \quad (4.1)$$

In Eq. (4.1) L_c corresponds to the correlation length of the random fluctuation, where the perturbation is represented by p ; a random process with ensemble-wise Gaussian statistics of $N(0, \sigma_b)$, i.e. zero-mean Gaussian random variable with standard deviation of σ_b , and an auto-correlation $\sigma_b^2 \exp(-\Delta z / L_c)$. When Eq. (4.1) is incorporated into the well-known coupled-mode equations for degenerated (single-pump) parametric interaction, the resulting stochastic model describes the effect of dispersion fluctuations on conversion efficiency. Figure 4.11 shows simulation results of the impact of random dispersion fluctuation on the conversion efficiency of a narrow-band fiber converter. In particular, the result in Fig. 4.11 shows an ensemble average of the CE of five hundred realizations in a waveguide whose dispersion was a Gaussian random variable, with a correlation length set to 1m, and a pump peak power of 4W.

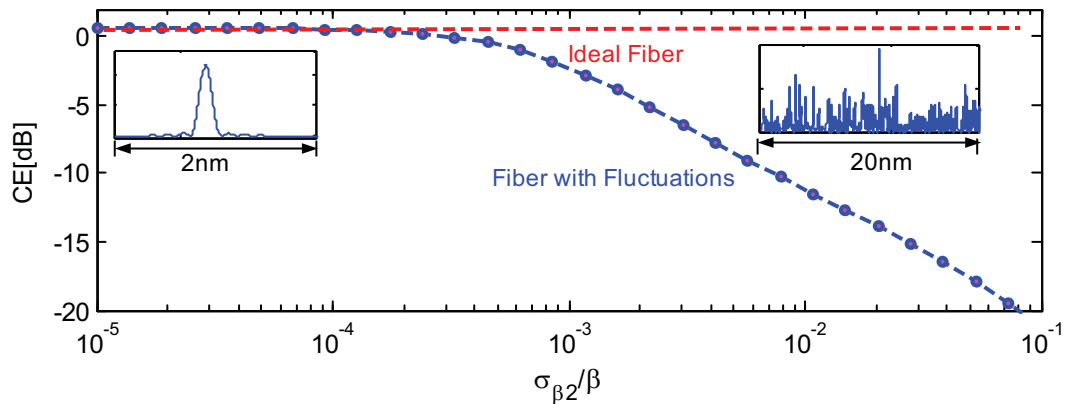


Figure 4. 11 Theoretically calculated average conversion efficiencies as a function of random dispersion fluctuations. Red dotted line denotes the conversion efficiency for an ideal fiber in the absence of dispersion fluctuations.

Figure 4.11 clearly shows a significant effect of dispersion perturbation on the attainable CE in non-ideal fibers. While the conversion window is confined to a single peak in ideal case, the presence of substantial dispersion fluctuations splits the conversion window into fine structures, as shown in the inset of Fig. 4.11. The spread of conversion window in the dispersion-fluctuations-impaired mixer results in efficiency reduction. The observed trend clearly emphasizes the benefit of the newly designed fiber exhibiting more than one order of magnitude lower dispersion fluctuations along its length compared to conventional HNLFs. Moreover, the result illustrated in Fig. 4.11 can be used to demonstrate the advantage of the new fiber when tension-based Brillouin suppression technique [74] is employed in a parametric mixer. While both conventional HNLFs and new fiber [67] can be stretched to suppress SBS, large dispersion variation in conventional HNLFs due to the applied stress will indeed prohibit parametric mixing across the spectral span demonstrated in this work. To illustrate the challenge in synthesizing Brillouin-suppressed parametric mixer with conventional HNLF, it should be noted that the dispersion of a conventional HNLF will vary by at least 0.1 ps/nm/km if the same stress profile used in this work is applied [75]. Using the analysis presented in Fig. 4.11, the introduced dispersion variation will imply a 20-dB penalty from the ideal conversion efficiency, even before the intrinsic dispersion fluctuations are taken into account. In sharp contrast, the exceptional resistance to dispersion change demonstrated by the new HNLF avoids the efficiency penalty associated with stretching for suppressing the SBS [68], thereby allowing phase-preserving conversion in this demonstration by alleviating the needs for pump phase dithering.

In addition to the effect on the conversion efficiency degradation, dispersion fluctuations lead to another impairment in the case of a phase preserving translator which arises from dispersion accumulation along the fiber. In the analysis which follows we investigate this important system degradation.

The constricted bandwidth provided by narrow-band phase-matched translators leads to rapid phase variations over the conversion spectral window, as a consequence of causality conservation described by Kramers-Kronig relations [76],[77]. In fact, the narrow-band nature of the conversion process may lead to highly dispersive characteristics, particularly in the presence of dispersion fluctuations where the conversion windows split into fine structures. To understand the severity of dispersion accumulation in the conversion process, the additional dispersion within the translation bandwidth was studied using the stochastic model introduced in by Equation 4.1. The dispersion introduced by the conversion process D is determined from the following relationship by considering the phase rotation β of the optical field relative to the phase at the conversion peak with wavelength λ :

$$D = -\frac{2\pi c}{\lambda^2} \frac{d^2 \beta}{d\omega^2} \quad (4.2)$$

Figure 4.12 shows the effect of dispersion fluctuations on the accumulated dispersion, obtained by the described approach. The result in Fig. 4.12 was obtained as an average of 500 realizations of a Gaussian-perturbed stochastic parametric converter. The result shown in Fig. 4.12 clearly demonstrates the manner in which dispersion fluctuations can significantly increase the amount of accumulated dispersion of a narrow-band parametric converter within the phase-matched window.

The trend can be attributed to rapid phase rotation within the converted signal bandwidth in the presence of dispersion fluctuations, thereby adding significant dispersion.

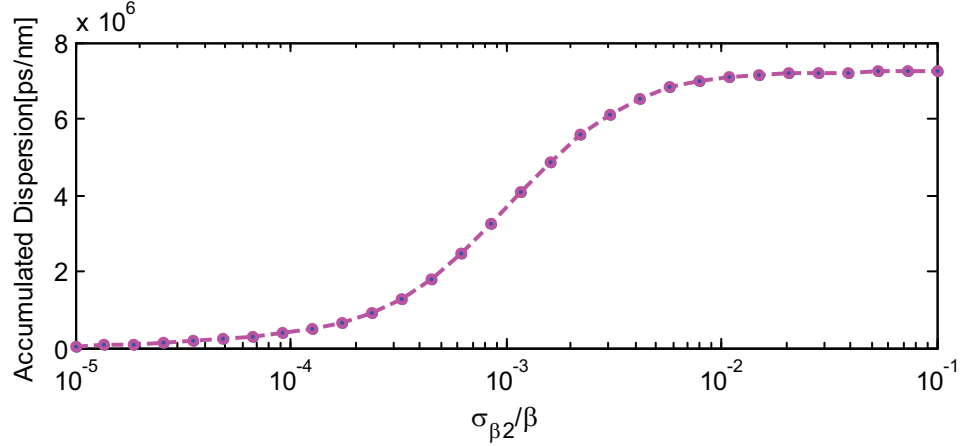


Figure 4. 12 Accumulated dispersion within the narrow phase-matching window in the presence of fiber dispersion fluctuation. Calculated for a fiber length of 45m and a fluctuation correlation length of 1m.

In consequence, this result implies that the fluctuation-resilient characteristics of the newly developed HNLF, with more than an order of magnitude lower dispersion fluctuation compared to conventional HNLF, also lead to a low chromatic dispersion accumulation along the translator, thus identified the novel fiber design as a highly suitable platform for a phase-preserving conversion.

4.4.3. DPSK SWIR Parametric Frequency Translator

The excellent dispersion stability in the stretched new HNLF was employed to construct a differential phase-shift keying (DPSK) SWIR parametric frequency converter. A varying tension profile [78] was applied to the fiber to increase the Brillouin scattering threshold. During the spooling process the fiber was strained to the

profile shown Fig. 4.13(a). With such stress profile the parametric interaction would experience sudden change in phase mismatch in consecutive sections.

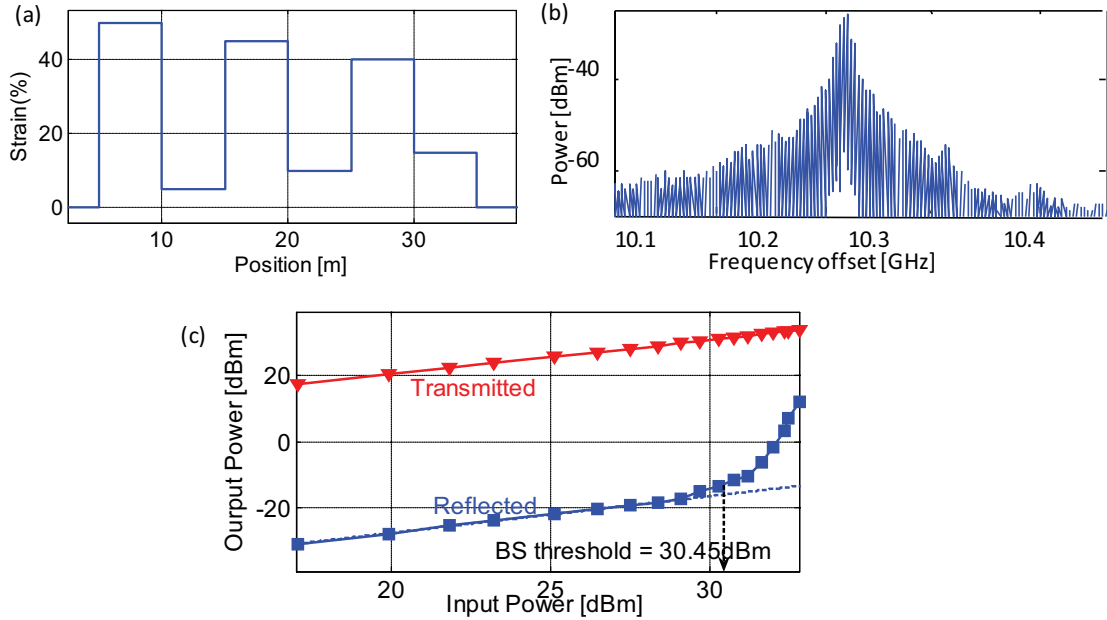


Figure 4. 13 Employed fiber stretching SBS suppression technique. (a) strain profile applied to the 45-m fiber, (b) SBS spectra of the stretched fiber, (c) power transfer characteristics of stretched fibers, showing the shifted Brillouin scattering threshold.

As shown in Fig. 4.13(b), the narrow linewidth Brillouin gain spectrum spread over 200MHz due to the induced strain. The Brillouin scattering threshold which is defined by the input power level adequate to produce a 3-dB deviation in back-reflection power from the Rayleigh scattering contribution was measured to be shifted to 30.45dBm (Fig. 4.13(c)). Although the applied stress raised the SBS threshold of the new fiber by a considerable margin (7 dB demonstrated in Ref. [68]), the resultant conversion efficiency remained inadequate to overcome the excessive loss in the telecom-band passive devices along the mixer output path (1.5 dB) as well as the loss in the DPSK demodulator (6 dB). Consequently, this demonstration was performed with pulsed pump to further enhance the conversion efficiency. Figure 4.14 shows a

demonstration experiment of the DPSK SWIR translator constructed with a 45-m section of the new fiber.

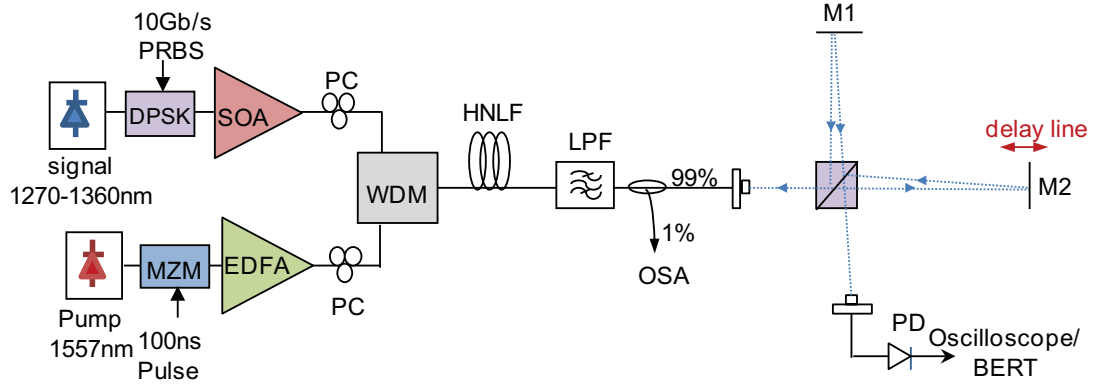


Figure 4. 14 Experimental setup schematic of the parametric SWIR converter. Acronyms: MZM: mach–zehnder modulator; SOA— semiconductor optical amplifier; EDFA—erbium-doped fiber amplifier; PC—polarization controller; WDM—wavelength multiplexer.

The pump source was a fixed distributed feedback (DFB) laser, which was amplitude modulated for Brillouin suppression, resulting in quasi-CW 102.4-ns long pulses with a 1/16 duty cycle that was subsequently amplified to 4W. An external-cavity laser (ECL), tunable from 1260 to 1360 nm, was chosen as the signal source. A MZM driven at twice its V_π characteristic was employed to imprint a differentially-encoded DPSK 10 Gb/s PRBS onto the signal carrier. The signal seed was subsequently amplified to 50mW using an O-band SOA. The amplified 1550 nm pump pulse was coupled with the 10 Gb/s DPSK signal into a 45 m-long segment of longitudinally tensioned HNLF with a nonlinear coefficient of $5.2 \text{ W}^{-1}\text{km}^{-1}$, characterized by a ZDW at 1593 nm, a slope of $0.067 \text{ ps/nm}^2\text{-km}$, and a negative fourth-order dispersion coefficient measured at $-5 \times 10^{-4} \text{ ps}^4/\text{km}$. After filtering out the seed and the pump using a long-pass filter at 1640 nm, a 99/1 tap was used, which enabled an unimpeded monitoring of the SWIR idler ($2.002 \text{ }\mu\text{m}$) on an OSA. The idler

was then directed to a free-space (one-bit) delay Michelson interferometer (shown in Figure 4.14) that was used to decode and successfully receive the differentially encoded phase modulated information stream. The mirror M1 was placed on a controlled motorized stage to enable flexible adjustment of the optical path mismatch between the two arms of the interferometer. The decoded (and phase to intensity converted by the interferometer) wave was received by a single 10 GHz InGaAs PIN-detector and sampled using a digital oscilloscope and/or received by the analyzer section of the BERT to rigorously evaluate the transmitter performance. The O-band receiver simply circumvented the parametric stage.

The wavelength conversion characteristics of the system were captured after the HNLF (before filtering the pump and seed), which is illustrated in Fig. 4.15. All spectra were measured using an OSA operating in a continuous 1.2-2.4 μm range. Figure 4.15 clearly demonstrates the benefit of adopting the negative- β_4 phase-matching scheme due to the absence of parametric fluorescence noise.

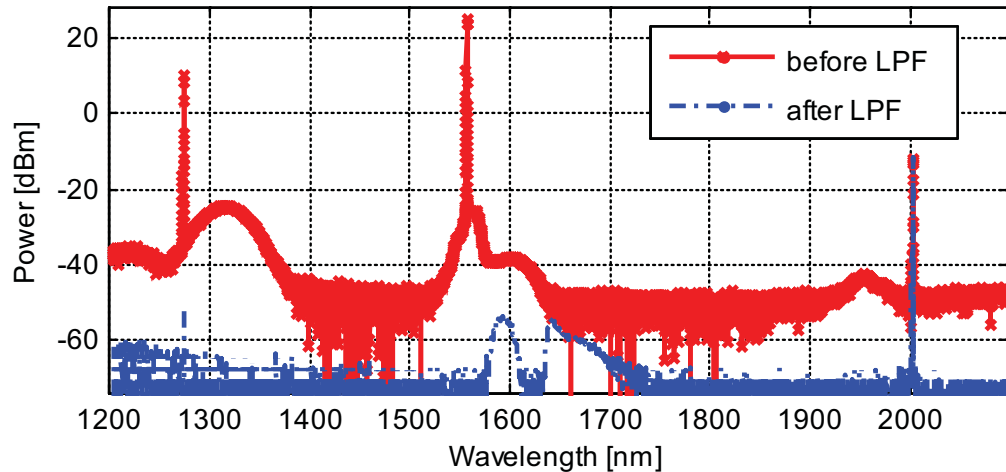


Figure 4. 15 Spectral response. Spectra was measured at the output of the HNLF reflecting the response of 20dB attenuator compared with spectrum after the LPF with pump and seed filtered out. The extent of the measurement is limited by the OSA operation range.

A 1550-nm band 99/1 coupler was used to capture the spectrum at high power. The coupler induced a uniform 20 dB attenuation from 1400 nm to 1700 nm, but, as strictly determined in a separate characterization, departed from a uniform attenuation characteristic outside of its specified operation band. Hence, the diminished power reading around the seed wavelength in Fig. 4.15. In addition, the idler after the telecom-band long pass filter experienced an additional 1.5 dB loss at 2002 nm. The best conversion efficiency was obtained by positioning the pump at 1556.5 nm and the signal at 1273 nm. The attained conversion efficiency of -15 dB, taking into account the excess loss of the coupler, was almost in accordance with the theoretical projection (13-dB below the ideal conversion efficiency (CE) at 0.6 dB) in Fig. 4.11, when the intrinsic dispersion fluctuations (0.016 ps/nm/km) were taken into account.

The performance of the DPSK translation was measured for a 10 Gbps signal beam phase modulated with a 2^{14} long NRZ PRBS (the order of which was dictated by the quasi-CW pump condition). The DPSK data cast on the signal wave were translated to the SWIR idler and the performance of the DPSK translation was then strictly quantified. Note that the single-port-based DPSK receiver introduced an excess 3 dB power loss, clearly implying a higher achievable sensitivity by a balanced detector. Consequently, the total forward loss in the system was characterized at 6 dB. A performance contour plot stringently characterizing the performance margin of the system is shown in Fig. 4.16. and Figure 4.17(a) and 4.17(b) show the typical eye diagram in the O- and SWIR bands. The slow rise and fall times are typical for the 10 GHz band-limited detector.

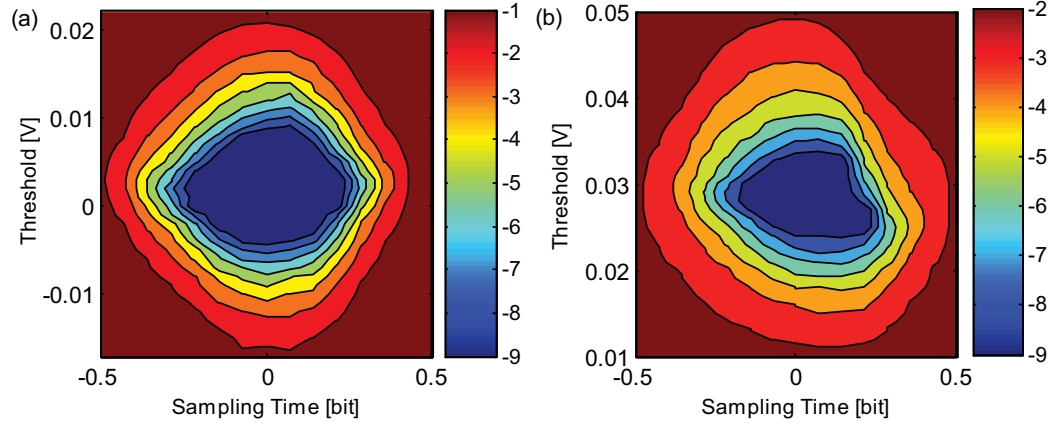


Figure 4. 16 Signal integrity (BER). Contours plot for (a) the O-band signal and (b) the SWIR idler.

To quantify the sensitivity and demonstrate the robustness of the transmitter, a BER measurement was performed on the received signal. Due to the 100ns duration of the pulsed envelope of the idler data sequence, the first and the last two bits within the pump-defined envelope were ignored, in order to allow for proper synchronization of the BERT. The idler power incident onto the receiver was varied by tuning the signal power. Figure 4.17 (c) shows the plots of BER as a function of the received signal power for both O- and SWIR-bands.

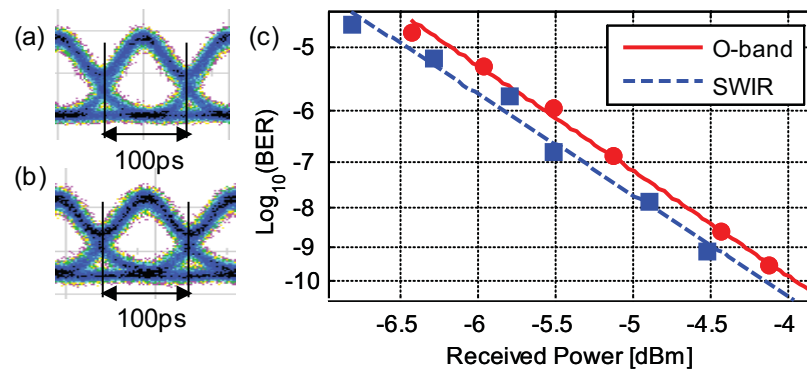


Figure 4. 17 Data stream waveform and eye diagrams of the 10Gbps DPSK signal. (a) signal in the O-band and (b) idler in SWIR region., c) BER plots of the 10Gb/s O-band signal (red circles) and SWIR idler (blue squares).

As demonstrated by the measurement, the BER curves exhibit an error-free performance at 2002 nm. The observed negative penalty (for the converted SWIR signal) is due to a lower detector responsivity at 1273 nm, as compared to that at 2002 nm. The total SWIR power penalty compared to signal at 1273 nm, taking into account the detector sensitivity, amounts to 1.8 dB.

4.5. Chapter Summary

This chapter examined the operation of a parametric 10Gbps SWIR transmitter. The SWIR channel generation was accomplished by a translation of 2.5Gb/s and 10Gb/s NRZ modulated signals over 85THz from the fiber-optic communication window (O-band) to the SWIR (2 μ m) band. The first OC-192 SWIR channel was characterized by an error-free performance. At 2002nm, -0.5dBm (0.890mW) of optical power was generated by means of a parametric conversion in a highly non-linear fiber. Measured penalties at 10Gb/s and 2.5Gb/s data streams, for the SWIR transmitter were to 1.9dB and 0.25dB , respectively, as compared to the back-to-back signal at 1278nm. The experimental demonstration validates the parametric SWIR transmitter concept for free-space communications, sensing and LIDAR applications, and is compatible with cm-scale footprint inherent to HNLF micro-coils.

In addition, an error-free translation of the 10 Gb/s phase-modulated signal from the O- to SWIR (2 μ m)-band was also demonstrated. The critical element in the experiment was the newly developed dispersion fluctuation resilient HNLF with a negative β_4 , that served as a vehicle for a narrow-band distant parametric conversion. The impact of dispersion fluctuations on narrow band phase preserving parametric

translators based on four-wave mixing was also investigated. The results further reinforce the benefit of adopting a newly designed highly nonlinear fiber with low dispersion fluctuations, observed in the experiments.

Chapter 4, in part is a reprint of the material as it appears in *Optics Express* in the article authored by Faezeh Gholami, Bill P.-P. Kuo, Sanja Zlatanovic, Nikola Alic, and Stojan Radic, "Phase-preserving parametric wavelength conversion to SWIR band in highly nonlinear dispersion stabilized fiber," vol. 21, issue 9, pp. 11415-11424 (2013). Chapter 4, also contains in part material presented at the Optical Fiber Communication Conference in the article contributed by Faezeh Gholami, Sanja Zlatanovic, Evgeny Myslivets, Slaven Moro, Bill P.-P. Kuo, Camille-Sophie Brès, Andreas O. J. Wiberg, Nikola Alic, and Stojan Radic, "10Gbps Parametric Short-Wave Infrared Transmitter," OThC6, Los Angeles, 2011. The dissertation author was the primary investigator and author/co-author of the journal paper and was the presenter of the conference presentation.

Chapter 5

Bi-directional Fiber Spectral Translation

Spectral translation is a practical path to sensing and detection in SWIR and mid-IR spectral bands [1],[79]. Yet, the present translators are inadequate for supporting advanced applications inherent to their lack of modulation-capable sources on the transmit side [80],[81] and/or advanced-sensitive detectors at the receiver end [82],[83]. Among the various techniques for generating and detecting light in SWIR spectral band [1], spectral band translation by FWM is of particular interest because of its inherent capability of preserving the optical phase, amplitude, and/or the quantum state [84]. Moreover, it provides a contiguous wide mode-hop-free tuning range owing to its cavity-less nature [16]. Previously, a number of FWM configurations for frequency conversion between the near-infrared and SWIR frequency bands has been reported in which the newly generated frequencies were used as a light source, or for indirect sensing [30], [82]. Table 5.1 summarizes the reported FWM based translator demonstrations between mid-IR and NIR along with the corresponding optical source and detector employed in the experiments.

Table 5. 1 Sources and detector used for demonstrations of wide-band spectral trasnalation.

Device/ Material	Device/ Material	Pump Source	Modulation Capable	Optical Detector
Wadsworth et. al.[85]	photonic crystal fiber	Nd:YAG laser	x	photodiode
Liu et. al. [82]	silicon nanowires	Cr ²⁺ :ZnSe/S lasers	x	telecom detector
Kuo et. al. [68]	silica HNLF	telecom source	√	2μm InGaAs photodiode
Lau et al. [86]	silicon nanowires	thulium fiber laser	x	--
Zlatanovic et. al.[30]	silicon nanowires	telecom derived source	√	2μm InGaAs photodiode

Most previous demonstrations ([85], [86],[82]) have relied either on optical parametric oscillator-based pumping or optical parametric amplifiers which is not consistent with advanced sensing and free-space communication application primarily requiring narrow linewidth sources amenable to a high integrity phase and amplitude modulation. More importantly, in the case of down-conversion from NIR to mid-IR , all demonstrations to-date [87],[35] have been restricted to using mid-IR photo-detectors, inherently severely limited in terms of operation condition, noise performance and speed, compared to their NIR counterparts [88].

To this aim, in Section 5.1 we address the above hindrances by realizing a versatile bi-directional frequency translator capable of a high integrity signal conversion from the telecom- to the SWIR-band followed by an up-conversion back to the telecom-band, done upon propagating through the target medium, in which sensing is performed. In Section 5.2 we report the first 90 THz-wide (i.e. from 1,263 nm to 1,987 nm) two-way spectral translation, in a single fiber device. In Section 5.3 we demonstrate the practical importance of the bi-directional translator which by means of a 40-dB signal-to-noise-ratio improvement has enabled an indirect detection of

weak signals in the vicinity of the 1,960 nm wavelength that is not achievable by direct means.

5.1. Principle of Operation

The bi-directional translation is performed in a time-gated manner enabling both down- and up- conversions to be realized in a single highly nonlinear fiber (see Figure 5.1).

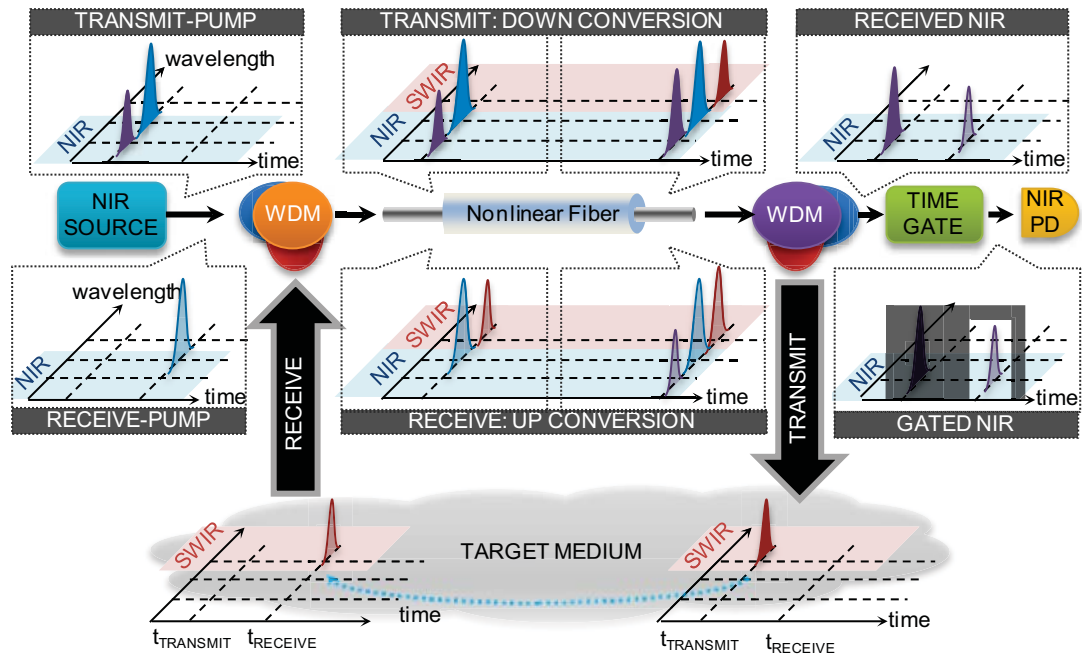


Figure 5. 1 Bi-directional translator operation principle. A NIR source generates two pump pulses around 1.5 μm . The first for down-conversion from NIR to SWIR (transmit-pump), and the second for up-conversion from SWIR back to NIR (receive-pump). The delay between these two pulses is determined by the propagation time in the target medium.

A source constructed only from telecom components produces two appropriately time-delayed 5-ns pulses at 1.55 μm with a 0.61MHz repetition rate. The delay between these two pulses is determined by the propagation time in the target medium. One of the two pulses serves as the pump for down-conversion, in effect generating a 1.9- μm transmitter, whereas the other one acts as a pump for up-

conversion back to 1.3- μm , thus availing information detection with telecom-band receivers. A NIR source generates a quasi-continuous-wave amplified seed signal in the 1.3 μm range. An optical WDM directs the amplified pump pulses into the HNLF together with the seed signal near 1.3 μm . Wavelength division multiplexers are used at both ends for a proper (i.e. SWIR, or NIR) band selection. The SWIR idler is generated by a degenerate parametric FWM process between the leading pulse and the NIR seed signal. Mixing is accomplished in a 100 m-long segment of dispersion stabilized HNLF [68]. Subsequently, the generated SWIR tone is directed to the target sensing material. Following the latter, the SWIR-band-residing probe, is coupled back to the HNLF through the input WDM and is combined with the secondary pump pulse facilitating up-conversion back to the NIR region. The received 1.3 μm tone is time-gated and spectrally isolated before detection by a telecom band receiver.

A detailed description of the experimental setup used for demonstration of the two-way spectral translation is shown in Figure 5.2. The pump source was an external cavity laser tunable in C-band, which was amplitude modulated to produce two quasi-continuous-wave 5-ns long pulses with a 50/16384 duty cycle that were subsequently amplified to 40W. An ECL, tunable from 1260 to 1360 nm, selected as the seed source, was also modulated with a MZM to generate 5-ns pulses. The seed signal was then amplified using an O-band SOA. The amplified ~ 1550 nm pump pulses and the seed pulse were combined using a WDM with cut-off wavelength at 1,375nm. Subsequently, the pump and the seed were coupled into a 100-m-long segment of HNLF using a telecom compatible LPF with cut-off at 1,640 nm. The HNLF was characterized by a nonlinear coefficient of $8.8 \text{ W}^{-1}\text{km}^{-1}$, a zero dispersion wavelength

at 1,567.3 nm, a slope of 0.082 ps/nm²-km, and a negative fourth-order dispersion coefficient measured at -6.8×10^{-4} ps⁴/km.

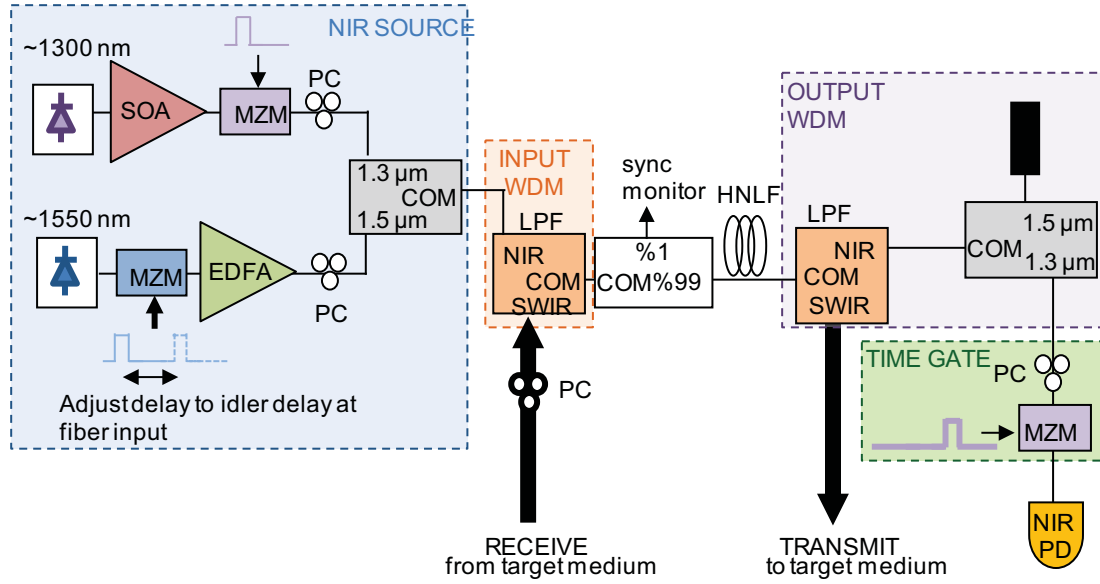


Figure 5. 2 Bi-directional translator experimental setup MZM, mach–zehnder modulator; SOA, semiconductor optical amplifier; EDFA, erbium-doped fiber amplifier; PC, polarization controller; WDM, wavelength division multiplexer; HNLF, highly nonlinear fiber; LPF; long pass filter ; NIR; near-infrared; SWIR, short-wave infrared; PD, photo detector.

At the output of the fiber, after filtering out the seed and the pump using a LPF similar to the input WDM, the SWIR idler was isolated and directed to the target medium. After propagation through the medium the SWIR idler was directed to the input LPF. A 99/1 tap was used to monitor and synchronize the SWIR tone with the second pump pulse. The received SWIR signal was combined with the second pump pulse to generate a near-infrared tone at around 1,300nm. At the output of the fiber after the LPF, the pump was filtered out and blocked and an MZM was used to select the up-converted telecom signal in time, which was then received by a telecom photo-detector and sampled using a digital oscilloscope.

5.2. Parametric Conversion Characterization

Efficient FWM was achieved by a proper nonlinear waveguide design ensuring an optimal phase-matching condition among the pump, signal, and the idler waves. A silica-based highly nonlinear fiber was used as the mixing platform precisely due to its inherent properties combining a relatively high effective nonlinearity with a remarkably low loss resulting in an efficient parametric mixing. Moreover, as discussed in previous chapters recent developments in silica-based HNLF fabrication process offer precise dispersion engineering of the fiber [32]. Choosing a negative fourth order dispersion term (β_4) [16] fiber and situating the pump frequency at the normal dispersion region (operation in positive second order dispersion term β_2 dispersion regime) results in a pair of gain windows formed at spectrally distantly separated frequencies [89]. Although the optimal dispersion profile matching such parametric mixing response can be easily synthesized in a conventional HNLF with a single-layer core, the local dispersive characteristics of such a commonly used mixing medium are overly sensitive to radial geometry variation in effect significantly reducing the conversion efficiency over wide spectral ranges. As has been described in Chapter 4, a multi-layer core structure can be used effectively reducing the influence of the fiber geometry fluctuations on the waveguide dispersion, thereby improving dispersion stability (and therefore the conversion efficiency). In our experimental setup, the normal dispersive characteristics of the fiber in the C-band combined with the negative fourth-order dispersion term allow parametric mixing in the SWIR band using NIR pump and seed laser sources, as shown by the phase-matching contour in Fig. 5.3.

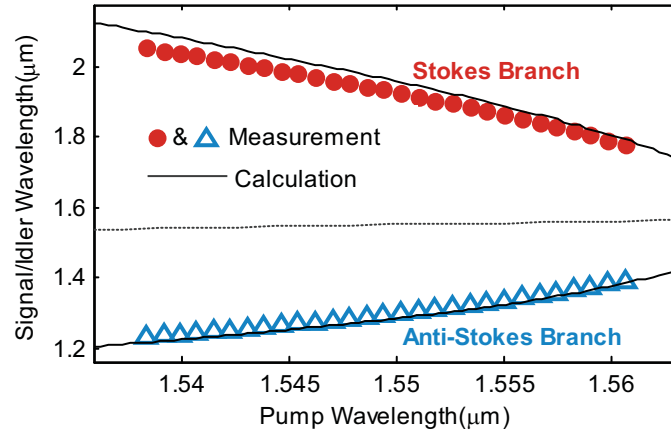


Figure 5. 3 Phase-matching contours for the HNLF parametric translator. Phase-matched signal and idler wavelengths for the FWM spectral translation process in HNLF. The translation bands were tuned by changing the pump wavelength and could be separated experimentally as far as 820nm. Symbols mark the experimentally measured spectral locations of the gain window as a function of pump wavelength. Solid line shows the expected theoretical contour based on fiber specifications. The dashed line marks the pump wavelength.

The efficiently phase matched bands for translation can be tuned by changing the pump wavelength and can be separated by as much as 820nm. A further optimization of the fiber dispersion properties in terms of the positioning of the zero-dispersion wavelength as well as a lower fourth order dispersion coefficient avail translation to even longer wavelengths.

The translation spectra of the HNLF are shown in Fig. 5.4. Figure 5.4(a) shows the output spectra for down conversion with the pump centered at 1,557 nm while the seed signal is tuned into resonance with the peak of the gain spectral window, at 1,349 nm. When the pump is injected into the fiber, the seed signal experiences strong parametric amplification, and is also down converted to a SWIR-band idler at 1,839 nm. The pump peak power at the fiber input was 40W, and the input signal power was kept at 15mW. Owing to the pulsed nature of the pump, the generated idler and amplified signals assume a quasi-constant wave characteristic.

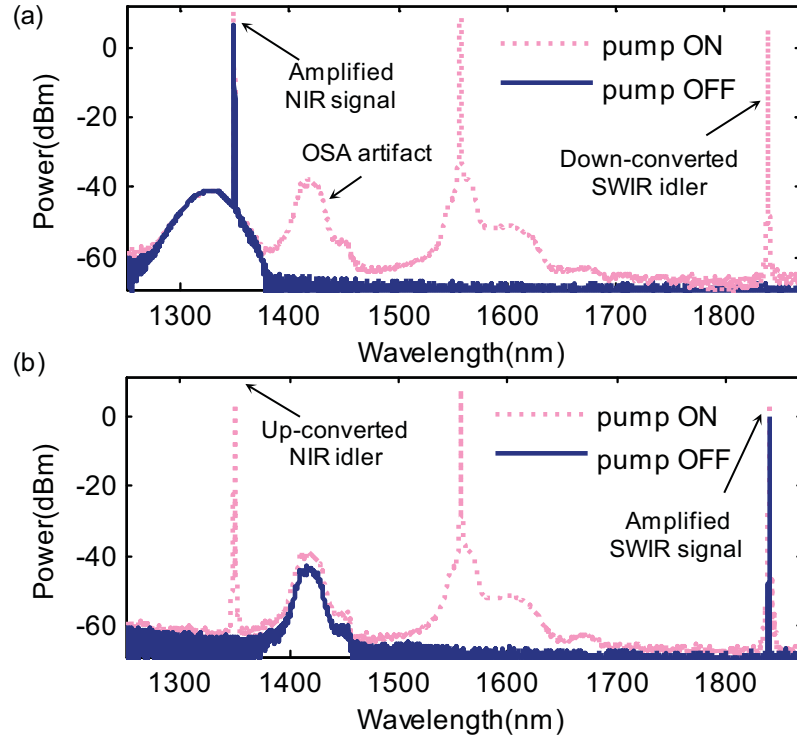


Figure 5. 4 Nonlinear translation characteristics. a) Up conversion spectra. A seed signal in the NIR is injected into the fiber and when the pump is present the telecom-band signal is amplified and an idler in the SWIR band is generated. b) Down conversion spectra. A SWIR signal enters the fiber and when the pump wave is present, the SWIR signal is amplified and an idler in the telecom band.

For the purpose of up conversion characterization, for the same pump position, a SWIR signal at 1,839 nm was fed simultaneously with the pump into the HNLF. As shown in Fig. 5.4(b), similarly to the down conversion translation case, the SWIR tone is significantly amplified and concurrently up-converted to the telecom band (Fig. 5.4(b)). The figure clearly demonstrates that the parametric fluorescence noise inherent to wide-band parametric translators is no longer present when the negative- β_4 phase-matching scheme is adopted [48].

To characterize the fiber as a FWM-based frequency translation platform, both up-conversion and down-conversion performance were considered. To down convert from NIR to SWIR an external cavity laser (EMCORE TTX1994) tunable in C-band

was used as pump source. The pump laser was amplitude modulated, resulting in quasi-c.w. 5-ns long pulses with a duty cycle of $d = 5ns \times 0.61MHz$ that was then amplified with an EDFA to 40W peak power. An external-cavity laser (Santec TSL-210), tunable from 1260 to 1360 nm, was chosen as the signal source. The seed signal was subsequently amplified using an SOA. The amplified C-band pump pulse was coupled with the signal into the fiber under test (FUT) to generate an idler at the SWIR band. By tuning the pump and seed, the SWIR idler could be tuned from 1,840 to 1,990 nm. For the reversed scenario, characterizing up-conversion from SWIR to NIR, a parametric source identical to that described above was employed. A LPF at 1640 nm was used to filter out the seed and the pump. The isolated SWIR tone was injected into the FUT simultaneously with a pump in C-band which resulted in generation of NIR idler tunable from 1,263 to 1,350 nm. The spectra were captured at the output of the fiber using an optical spectrum analyzer (OSA, Yokogawa AQ6375) operating in a continuous 1.2-2.4 μm range. The spectral data were processed to obtain the signal, pump and idler wavelength and powers and consequently, to characterize the spectral translation efficiency. Signal parametric gain was defined as the ratio of peak power of signal at the output of the fiber when the pump signal was present (pump on) to the peak power of signal in absence of pump (pump off), $G = P_{signal\ pump\ ON} / P_{signal\ pump\ OFF}$. Accordingly, the parametric conversion efficiency was calculated from $\eta = P_{idler\ pump\ ON} / P_{signal\ pump\ OFF}$. The peak powers were calculated from the measured time-averaged powers captured by the OSA. To convert the OSA reading to peak power the pulsed nature of the signals (duty cycle) was taken into account. The wavelength dependence of the parametric gain for signal and idler conversion

efficiencies were rigorously characterized from the recorded translation spectra for a range of pump wavelength positions, with the input signal tuned to the gain peak, with results shown in Fig. 5.5.

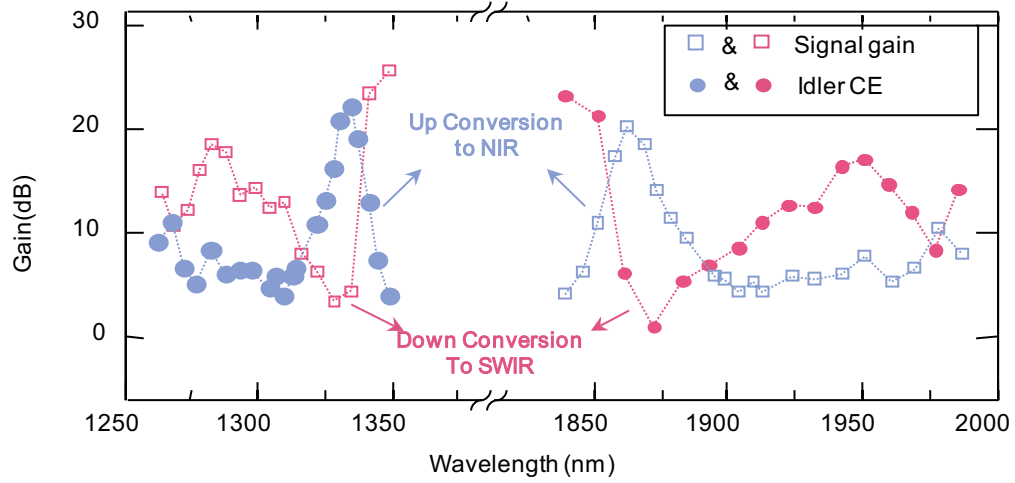


Figure 5. 5 Signal gain and idler conversion efficiency for both down- and up-conversion. A transparency window of 85 nm in the telecom band and 147 nm in the SWIR was attained. Maximum up-conversion conversion gain was 23 dB and for the down-conversion 22 dB.

Figure 5.5 demonstrates that, for both the down- and up-conversion, the HNLF mixer obtained optical transparency across 85 nm in telecom band from 1,263 to 1,349 nm and a transparency window of 147 nm in the SWIR band from 1,839 to 1,987 nm. A peak conversion gain of 23 dB was attained at 1839 nm in up conversion and in the reverse scenario, for down conversion, the maximum conversion gain was 22 dB at 1335nm. Therefore, the measurements indicate that the fiber device produces parametric gain large enough for practical applications in sensing and communication.

5.3. Applications in Sensing and Communication

With a particular aim of demonstrating the practical importance of the bi-directional translator, two rigorous demonstrator experiments were performed: first, the parametric translator was used for detection of carbon dioxide, whereas a separate

experiment explored the feasibility of a SWIR transceiver. In this section we describe both demonstrations in detail.

The ability to detect carbon dioxide is of critical importance for a wide range of applications [90],[91]. In our experiment, the transmitted SWIR pulse generated in the down-conversion process was sent through a 225-mm long CO₂ cell at a pressure of 600 Torr. The SWIR idler was precisely tuned (by adjusting the pump wavelength) to three different positions, out of which two coincided with CO₂ absorption lines, whereas the third position was intentionally chosen outside of the target absorption spectrum. After propagating through the cell, the SWIR signal was, as explained in the previous section, up-converted to the 1.3 μ m telecom band. The received pulses in the NIR region, corresponding to the three different SWIR wavelength positions, were displayed on an electrical equivalent-time oscilloscope (Fig. 5.6).

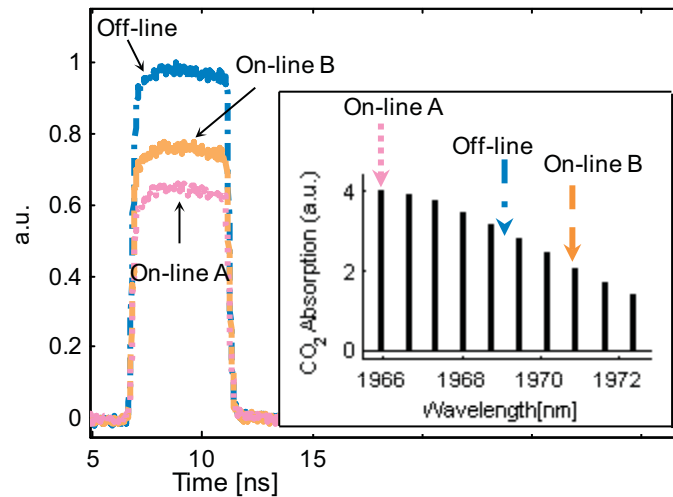


Figure 5. 6 Sensing applications for the bi-directional spectral translator. Detection of the trace levels of carbon dioxide by a telecom photo-detector. Inset shows the CO₂ absorption data obtained from HITRAN2008 database. Measured up-converted pulses corresponding to three different wavelengths of 1,966nm (On-line A), 1,969nm (Off-line), and 1,970nm (On-line B).

The relative strengths of the different absorption peaks were obtained from the absorption spectrum of the CO₂ from the HITRAN2008 database [92] (Fig. 5.5 inset). In full accordance with the data from HITRAN2008 database, the on-line tones with shorter wavelengths were attenuated more strongly by the CO₂ cell. Furthermore, the relative attenuation of the pulses in the NIR uniformly equalled that in the SWIR region, fully validating the translator operation (Figure 5.7).

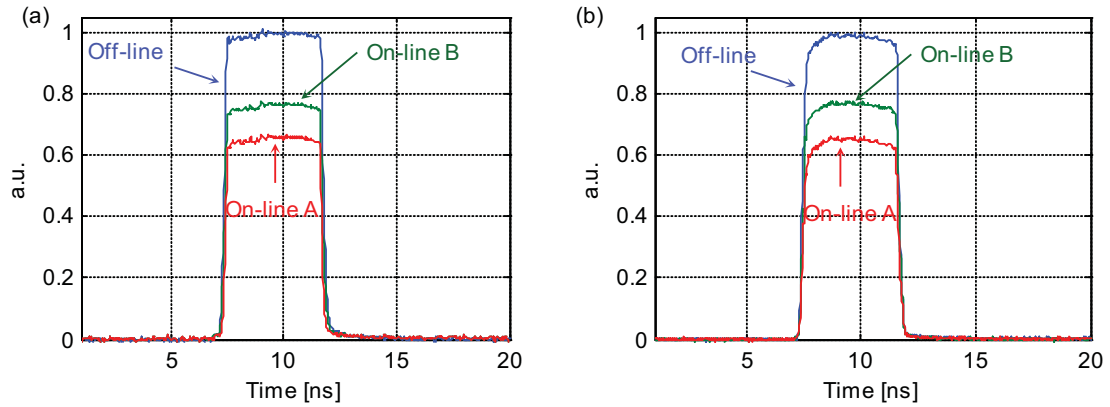


Figure 5. 7 Detection of trace level of CO₂. The relative attenuation of pulses detected with a (a) 2- μ m InGaAs detector compared to (b) indirect detection with an NIR detector after up-conversion from SWIR to NIR. The inset illustrates CO₂ absorption data obtained from HITRAN2008 database.

Figure 5.7 demonstrates that the relative attenuation of pulses detected with a 2- μ m InGaAs detector is the same as that for indirect detection with an NIR detector after up-conversion from SWIR to NIR. This validates the proper operation of the bi-directional translator for such applications. The inset illustrates CO₂ absorption data obtained from HITRAN2008 database.

In addition to the above, both forward and backward translation of a 10 Gb/s amplitude modulated signal from NIR to SWIR were also demonstrated. The significance of the demonstrations is that it fully attests to the applicability of the

adopted scheme to generation, processing, and detection of high speed, arbitrary complex modulated SWIR signals.

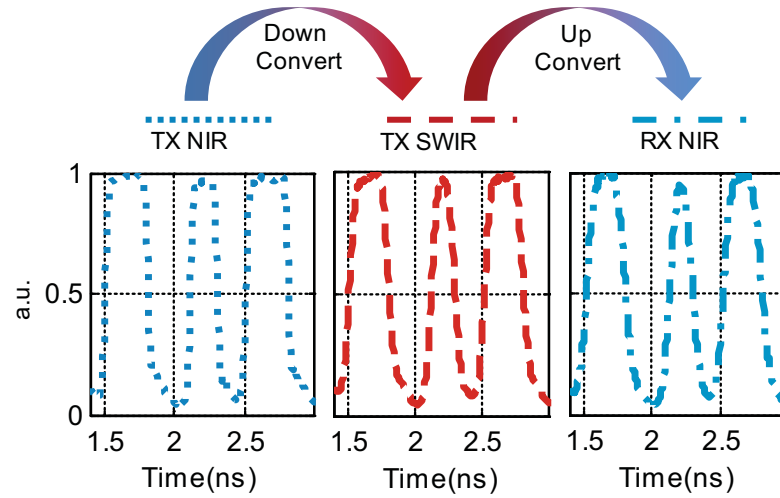


Figure 5. 8 Bi-directional translator application in communication. Generation and indirect NIR detection of amplitude modulated SWIR signal. TX, transmitted; RX, received.

As a final important example, the bi-directional translator was utilized to address the limitation of detecting weak signals in SWIR. Indeed, a direct detection of a weak 100- μ W SWIR tone, output from the cell in the CO₂ sensing experiment, is not possible with a commercially available 2- μ m detector due to its inherent low responsivity. In sharp contrast, as demonstrated in Figure 5.9, by up-converting the SWIR tone to the NIR region, the signal can be detected by a commercial NIR photo-detector.

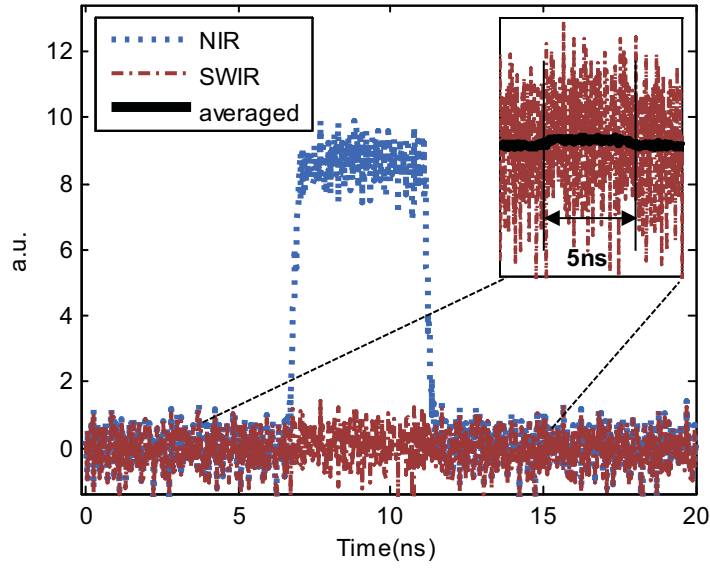


Figure 5. 9 Bi-directional translator applications in communication. Generation and indirect NIR detection of amplitude modulated SWIR signal. TX, transmitted; RX, received.

The SNR enhancement due to indirect detection was evaluated by comparing the results of direct and indirect detection of a weak SWIR signal. For direct detection a commercially available 7-GHz, 2- μm , extended-band InGaAs p-i-n photodetector (EOT Inc.) was used, while the indirect detection was achieved by wavelength conversion to NIR and subsequently, detection with a telecom photodetector (Agilent 83440C). To derive the SNR in each case, N points were taken from the pulsed signal data captured by the oscilloscope in time domain ($X_i, i = 1..N$), where the SNR was defined as the ratio of the mean ($\mu = 1/N \cdot \sum_{i=1}^N X_i$) to the standard deviation ($\sigma = \sqrt{1/N \cdot \sum_{i=1}^N (X_i - \bar{X})^2}$) of the measurement, $SNR = \mu^2 / \sigma^2$. Furthermore, the SNR improvements was calculated as, the ratio of the SNRs for the telecom detector to that of the 2- μm detector, $SNR_{near-IR} / SNR_{shortwave-IR}$. Results show that the indirect

detection following the wavelength conversion can improve the SNR by as much as 40 dB with respect to direct detection in the SWIR band.

5.4. Chapter Summary

In summary, we introduced and demonstrated a bi-directional translation scheme between NIR and SWIR bands. The scheme eliminates the necessity for reliance on SWIR receivers with limited capabilities and, at the same time, allows for arbitrary phase and amplitude modulation of the SWIR signals, presently unachievable by direct means. The exceptional performance of the proposed concept was more than validated in the presented experimental implementations of high practical interest, particularly exemplified in the demonstrated higher than 40dB SNR improvement in detection of weak signals in the SWIR band.

Chapter 5, in part is a reprint of the material as it appears in an article prepared for submission to the Nature Photonics contributed by Faezeh Gholami, Nikola Alic, and Stojan Radic, “Eliminating the quest for shortwave-Infrared processing by bi-directional spectral translation to telecom-band.” The dissertation author was the primary investigator and author/co-author of this article.

Chapter 6

Conclusion

6.1. Dissertation Summary

A demand for light sources, detectors and nonlinear optical devices operating in the SWIR and mid-IR wavelength regions has experienced a tremendous increase in recent years. Indeed, these unconventional spectral bands are of interest for a broad range of applications, from biological and chemical sensing to free-space communication and LIDAR. On the other hand, the drive for mid-IR research also arises from the desire to develop silicon-based photonic integrated circuits (PICs) for telecommunications. However, in telecommunication band, the silicon platform efficiency falls significantly short of the required properties due to the nonlinear absorption, making it necessary to consider alternative approaches. The primary objective of this dissertation was aimed at introducing novel alternative concepts for efficient light generation and detection in the SWIR band. Additionally, properties of silicon as a nonlinear platform for optical processing in the mid-IR was also investigated .

Silicon platform excels from mature and cost-efficient fabrication technology and the high volume production, making it highly desirable for the optical

telecommunication industry. However, performance of silicon nonlinear devices such as converters and amplifier is hampered by an inherent high nonlinear loss in the telecom band. On the other hand, this loss theoretically vanishes at longer wavelengths. In consequence, the Chapter 3 of this dissertation was focused on strict characterization of nonlinearity and nonlinear absorption of silicon in the spectral region above the TPA absorption. The first measurements of its kind revealed that the nonlinearity FOM in mid-IR is at least an order of magnitude higher than that in the NIR, fully supporting the claim of silicon being a promising platform for nonlinear optical processing in the mid-IR.

Recognizing the need for modulation-capable sources in SWIR for advanced applications in sensing and communication, in Chapter 4 we presented schemes for construction of stable coherent SWIR sources amenable to arbitrary amplitude and phase modulation. In particular, the SWIR source operation relied on spectral translation from NIR to SWIR based on four-wave mixing. Such spectral translation ports the advanced modulation and detection technology available in the NIR to the SWIR spectral band. In these demonstrations, silica HNLF was employed as the mixer platform, fully validating the superior nonlinear performance of this platform in both NIR and SWIR spectral ranges. Furthermore, it was demonstrated that the waveguide design with substantially improved dispersion stability in high-confinement fibers, can significantly improve the performance of wide-band translators in the narrow-band phase-matching regime.

Although wide-band spectral translation of modulated signals introduces new potentials for the SWIR light generation, this band still suffers from a lack of

advanced-sensitive detectors. With respect to the latter obstacle, Chapter 5 disclosed a novel concept for transceiver design in the SWIR region. The introduced approach, eliminates the necessity for SWIR specific devices by a two-way spectral translation. The predicted benefits of the scheme were fully verified by the performed experimental demonstration of forward and backward translation of a 10 Gb/s amplitude modulated signal, detection of carbon dioxide, and indirect detection of weak SWIR signals. The proposed transceiver design, constructed only from telecom components, opens the possibility for generation, processing, and detection of high speed, arbitrary complex modulated SWIR signals. Perhaps the most impressive result related to the last experiment and this whole dissertation concerns the demonstration of as much as 40 dB of signal to noise improvement of the signal when, upon translation, detected in the NIR region with a superior quality detector (rather than the one currently available in the SWIR band), in a way, most prominently emphasizing the concepts developed in this dissertation.

6.2. Future Directions

The introduced bi-directional parametric translation scheme in Chapter 5 of this dissertation, along with validation of modulation capability of the FWM-based SWIR sources in Chapter 4, represents a significant enabler for a wide range of applications in the SWIR region. Specifically, applications requiring high power operation with low noise would greatly benefit from the presented scheme. One of the many potential applications to exploit in the future utilizing the demonstrated SWIR transceiver would be light detection and ranging remote sensing technique which demands high-power, high-frequency-fidelity, tunable laser sources in conjunction

with low-noise photodetectors. Although, the presented work in this dissertation tremendously facilitates applications in the SWIR region, many problems remain unanswered and require further investigations. The presented concept can, in principle, be extended to high speed applications as well. However, in the presented work, the translator was limited to the 10GBps speed, dictated by the operation under the narrow band phase-matched scheme. On the other hand, technological advancements in fiber design and fabrication can further the fiber mixer efficiency over wider bandwidths, thus removing the present operating speed limit.

Extension of the concept of the bi-directional translator to other spectral bands such as Visible, Ultra-Violet (UV) and mid-IR represents an additional high potential direction of the work presented. Light wave in the visible band, in particular the blue-green region, has been a continuous research interest because of the atmospheric transparency window, in addition to being a low-loss transport window in the ocean water [93]. More importantly, visible and UV generation is of high practical interest in spectroscopic applications. Current methods for generating tunable visible and UV light are very limited. Applications in these bands could greatly benefit from a transceiver with capabilities similar to the scheme presented in this work for SWIR. The employment of the transceiver concept in other bands requires investigation of new mixer platforms suitable for operation in those bands. In that respect, utilization of the silicon as the mixing platform is of particular interest for reaching the mid-IR band. As mentioned in Chapter 3, nonlinear loss is much less significant in silicon in the wavelength region above $2.2\mu\text{m}$ compared to silica glass fiber which exhibits high material loss at wavelengths above $2.1\mu\text{m}$. However, it ought to be stressed that

efficient silicon FWM mixers manufacturing remains a challenge due to the coupling and linear propagation losses associated with this platform. Such approaches do not fit the current infrastructure of silicon fabrication, but nevertheless present an interesting alternative. The research direction presented in this dissertation offers a possibility for scientific exploration of alternative mixer platforms beyond the limits imposed by the existing technology.

Appendix A

Gaussian Beam Waist Measurement

The z-scan technique employed for Kerr nonlinearity and nonlinear absorption measurement in Chapter 3 requires precise knowledge of the incident laser beam waist size. This appendix describes the knife edge measurement technique used for specifying the spot size of the incident laser beam.

An optical beam is considered a Gaussian beam if the intensity distribution in any transverse plane is a circularly symmetric Gaussian function centered about the beam axis [93]. A Gaussian beam propagating in the z-direction in theory can be defined as

$$U = U_0 e^{i(kz - \omega t)} \frac{e^{ikr^2/2q}}{q}, \quad r^2 = x^2 + y^2 \quad (\text{A.1})$$

here due to paraxial approximation, x and y , the coordinates on the plane vertical to the beam axis, are much smaller than z , U is the optical wave electric field amplitude and k is the propagation constant. q is known as the complex radius and can be represented as

$$q = z - z_{\text{waist}} - iz_R \quad (\text{A.2})$$

The Gaussian beam is narrowest at $z = 0$ (or $z = z_{waist}$), indicating the position of the beam waist) and z_R is the Rayleigh range which relates to the distance over which a Gaussian beam can be collimated before it spreads significantly due to diffraction, or equivalently, the distance which the beam area doubles in size. A diagram indicating the parameters of a Gaussian beam is illustrated in Figure A.1.

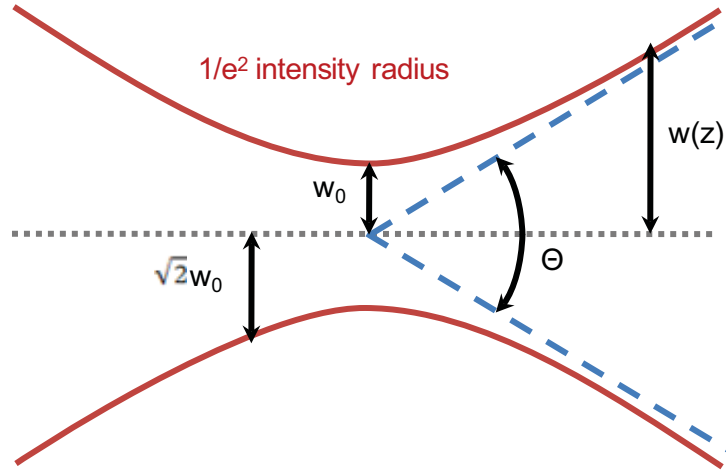


Figure A. 1 Gaussian beam parameter notations.

Here, the $1/e^2$ radius in the intensity distribution or the 'spot size', $w(z)$, is indicated from

$$w(z) = w_0 \sqrt{1 + \frac{z^2}{z_R^2}} \quad \text{with} \quad z_R = \frac{\pi w_0^2}{\lambda} \quad (\text{A.3})$$

In practice measurement of micron sized radius of Gaussian laser beam is possible with a scanning knife-edge technique through recording the total power in the beam as a knife edge placed on a calibrated translation stage is translated through the beam [94]. Figure A.2 illustrates schematics of the measurement technique.

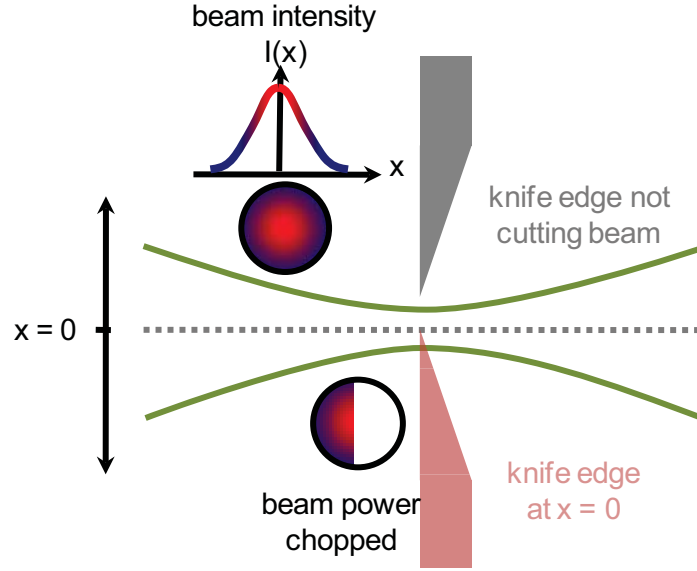


Figure A. 2 Knife edge beam waist measurement schematic. When the laser beam is vertically chopped by the knife edge, the total power incident on the detector decreases.

The intensity distribution of a Gaussian beam $I(x, y)$ is given by

$$I(x, y) = I_0 \exp\left(-\frac{2x^2}{w_x^2} - \frac{2y^2}{w_y^2}\right) \quad (\text{A.4})$$

where I_0 is the peak intensity, and x , y the coordinates on the plane vertical to the beam axis. w_x , w_y are the $1/e^2$ radii of the beam in the x and y directions, respectively [95]. When the laser beam is vertically chopped in x -direction by the knife-edge, the transmitted laser power, after simple mathematical derivations, can be described using the standard definition of the Error Function as

$$P(x) = \frac{P_{TOT}}{2} \left[1 - \operatorname{erf} \frac{\sqrt{2}x}{w_x} \right] \quad \text{with} \quad P_{TOT} = \frac{\pi}{2} I_0 w_x w_y \quad (\text{A.5})$$

where P_{TOT} is the total power at the beam waist.

We used Eq. A.5 to fit the knife edge measurement data in order to find the beam width, w_x . Figure A.3 shows a sample set of data points.

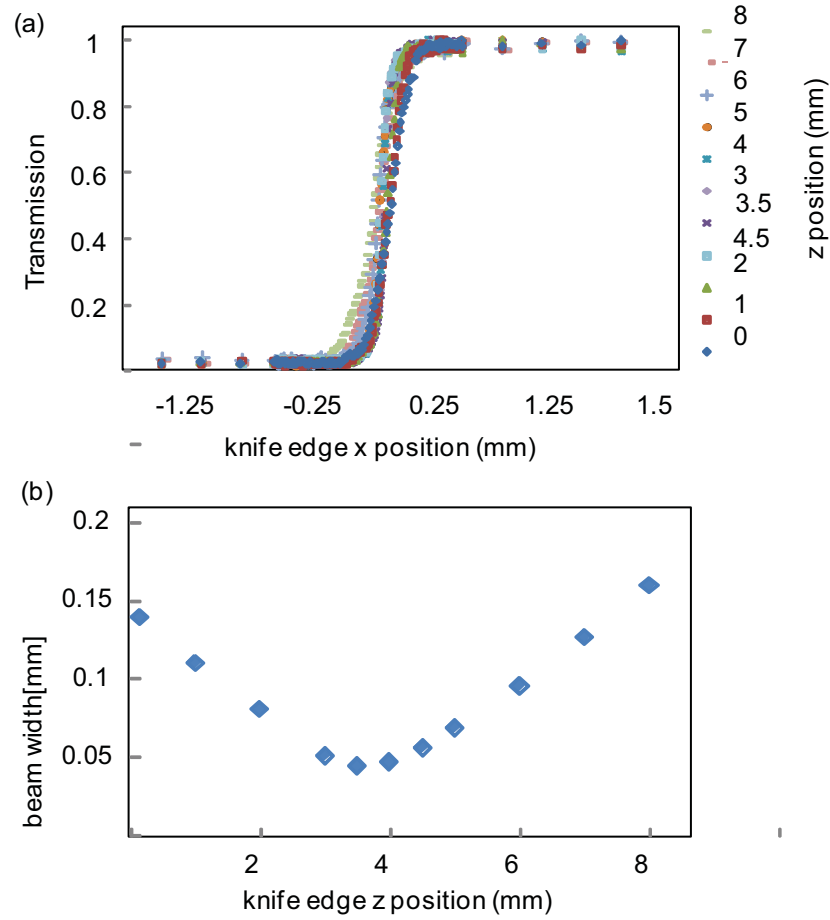


Figure A. 3 Knife edge beam width measurement results. (a) raw data points for total power incident on power meter depending on knife edge position on x axis. Measurements were repeated for various z positions along the beam axis. (b) beam width calculated from error-function fit to data.

The results presented in Figure A.3 correspond to measurements of beam width for OPA output laser at 2700nm. The beam waist was measured to be 44 μ m. For each knife edge position along the beam axis in z-direction, the data illustrated in Figure A.3 (a) was fit to the error-function given in Eq. A.5. The measurements were

repeated at different points along the beam axis to ensure exact beam waist calculation. Fig. A.3 (b) shows the $1/e^2$ intensity radii of the laser.

Appendix B

Kramers-Kronig Relations

The Kramers–Kronig (KK) relations are relations between the real and imaginary parts of the dielectric function [96]. The Kramers–Kronig relations can be derived by considering an integral of the form:

$$I = P \int_{-\infty}^{+\infty} \frac{f(x)}{x-a} \left[\lim_{\delta \rightarrow 0} \int_{-\infty}^{a-\delta} \frac{f(x)}{x-a} dx + \int_{a+\delta}^{+\infty} \frac{f(x)}{x-a} dx \right] \quad (\text{B.1})$$

P in Eq.B.1 shows the principal value of the integral. To obtain the Kramers-Kronig relations, we change the parameters in Eq.B.1 by $x \rightarrow \omega'$, and $f(x) \rightarrow \chi(\omega')$.

Here ω' represents the complex angular frequency $\omega' = \omega'_1 + i\omega'_2$, and $\chi(\omega')$

shows the dielectric susceptibility expressed by $\varepsilon = 1 + \chi$. We also replace a in Eq.

B.1 with a constant $\omega(\omega > 0)$. By using these replacements, Eq.B.1 simplifies to

$$I = P \int_{-\infty}^{+\infty} \frac{\chi(\omega')}{\omega' - \omega} d\omega' \quad (\text{B.2})$$

An alternative, yet equivalent form of the KK relation was introduced by Sheik-Bahae *et al.* [97] to compute the nonlinear refractive index $\sim \text{Re } \chi^{(3)}$ from the two photon absorption coefficient for wide-band-gap semiconductors. The formula by

Sheik-Bahae *et al.* resembles that of the linear optical KK relations and relates refractive index changes $\Delta n(\omega; \xi)$ induced by some perturbation to the corresponding change of absorption $\Delta \alpha(\omega; \xi)$ in the following way:

$$\Delta n(\omega; \xi) = \frac{c}{\pi} P \int_0^{+\infty} \frac{\Delta \alpha(\omega'; \xi)}{\omega'^2 - \omega^2} d\omega' \quad (\text{B.5})$$

Consequently, since Kerr coefficient and TPA coefficient can be linked by using Kramers–Kronig transformation, values of the Kerr coefficient can be estimated for longer wavelengths from the measurements of TPA coefficient. The functional form of Kerr coefficient calculated by using data for TPA from Bristow et al. [36] and fit based on the above calculations is plotted in Fig. B.1.

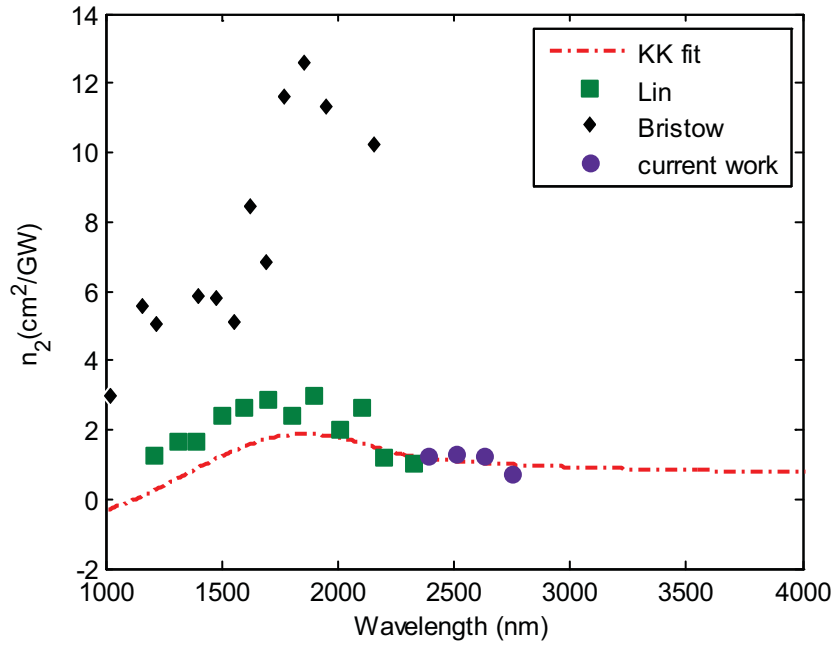


Figure B. 1 Prediction of Kerr coefficient from two-photon absorption coefficient based on Kramers-Kronig transformation.

The calculations underestimate the value of the Kerr coefficient compared to measured values by Bristow et. al. since they neglect Raman and quadratic Stark

contributions but is closer to data obtained by Lin et al. In spite of this discrepancy in absolute values, the Kramers–Kronig relations should accurately predict the functional form for the Kerr nonlinearity. The calculations based on KK relations accurately predict an experimentally obtained peak wavelength position for n_2 that was found to be around 1800 nm. They also predict that n_2 decreases slowly for wavelengths beyond 1800 nm, but keeps the value on the same order of magnitude as in the NIR band all the way up to 6 μm .

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