Quasi Phase Matching in SOI and SOS Based Parametric Wavelength Converters

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ABSTRACT

In this study, we demonstrate method for quasi phase matched silicon-on-sapphire waveguides suitable for MWIR wavelength conversion to achieve higher conversion efficiency than that can be achieved in uniform waveguide geometries. In particular we show that periodic change in waveguide width by 0.5μm and hence periodic change in waveguide dispersion can to reset phase accumulation and provide ever-increasing gain profile. With the fabrication flexibility of large cross-section of MWIR waveguides, the possibility of using quasi-phase-matching can provide >30dB conversion efficiency enhancement and increase the conversion bandwidth by 2 times. Such improvement may facilitate the fabrication of parametric oscillators that can improve the conversion efficiency by 50dB.

Keywords: Wavelength conversion, Waveguide, Quasi phase matching

1. INTRODUCTION

Mid wavelength infrared (MWIR) spectral range is the window for a wide variety of applications, including free space communication, thermal and biomedical imaging, optical sensing, chemical spectroscopy and military applications as missile guidance/countermeasures. While these applications are mostly achieved through free-space optics, their waveguided alternatives can be far more attractive. In telecommunication wavelength, silicon-on-insulator (SOI) waveguide is the most widely-used platform. However, this convenience can't be extended to MWIR wavelength due to high SiO_2 insulator losses [1]. Among all proposed solutions, silicon-on-sapphire (SOS) waveguide is a an attractive approach to circumvent this limitation, because sapphire substrate has a transparent window all the way up to 6um [2] Also, SOS wafers are commercially available and low loss SOS waveguide has been reported recently[3].

In particular, wavelength conversion based on SOS waveguide can deliver high efficiency signal processing at mid-IR wavelengths. Up to date wavelength conversion in silicon based planar waveguides has attracted many researchers to deliver chip scale solutions for applications pertinent to optical communication systems on both SOI and SOS platforms [4, 5]. In such kind of wavelength converters, the conversion bandwidth and conversion efficiencies are two most important figures of merits, which are mainly dominated by the phase-matching condition. Up to date, several techniques have been used to enhance these figures of merits [6, 7]. Up to date quasi-phase-matching technique has been widely-investigated in periodically poled $LiNbO_3$ waveguides or optical fibers [6-8]. However, quasi-phase-matching in pure silicon waveguides has not been investigated up to date. In this report, we demonstrate the design of quasi phase matched silicon-on-sapphire waveguides suitable for mid-IR applications through dispersion engineering to increase their efficiency. We show that alternating waveguide widths that can reset the phase mismatch in both SOI and SOS waveguides. In particular we show that periodic change in waveguide width by 0.5μm and hence periodic change in waveguide dispersion can to reset phase accumulation and provide ever-increasing gain profile. With the fabrication flexibility of large cross-section of MWIR waveguides, the possibility of using quasi-phase-matching can provide >30dB conversion efficiency enhancement and increase the conversion bandwidth by 2 times. Such improvement may facilitate the fabrication of parametric oscillators that can improve the conversion efficiency by 50dB.

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2. WAVEGUIDE DESIGN AND DISPERSION ENGINEERING

In order to design the quasi phase method system we should understand the dispersion characteristic on SOS waveguides. Here we use finite-element method (FEM) in COMSOL [9] to calculate the dispersion profile of proposed waveguides. It is well known that Silicon has a normal dispersion profile in MWIR, while Sapphire is an anomalous dispersion material at the same wavelength range. This implies that dispersion in SOS waveguides can be compensated between silicon and sapphire by controlling the cladding coupling. A flatter dispersion curve with zero dispersion wavelength (ZDWL) in MWIR is achievable and this can results in a very good condition for phase-matching in nonlinear processes, particularly four-wave-mixing (FWM) in this design. For instance, Figure 1 illustrates the dispersion curves for a 2.4μm×0.6μm channel waveguide and a 1.2μm×1.2μm rib waveguide. Both curves show ZDWLs in MWIR region and these ZDWLs are tunable over a wide wavelength range. By choosing the pump wavelength slightly above ZDWL, phase-matching in FWM are possible even when signal and idler wavelengths are widely spaced from pump wavelength. This phenomenon gives rise to a discrete band parametric nonlinear process [5]. Proper design of the waveguide geometries can be adapted for the optimum phase-matching condition for different signal and pump wavelengths combinations, which will result in an idler wavelength covering almost the entire mid-IR band. This provides adequate tunability over wavelength by geometry controlling. Mid wavelength infrared (MWIR) spectral range is the window for a wide variety of applications, including free space communication, thermal and biomedical imaging, optical sensing, chemical spectroscopy and military applications as missile guidance/countermeasures. While these applications are mostly achieved

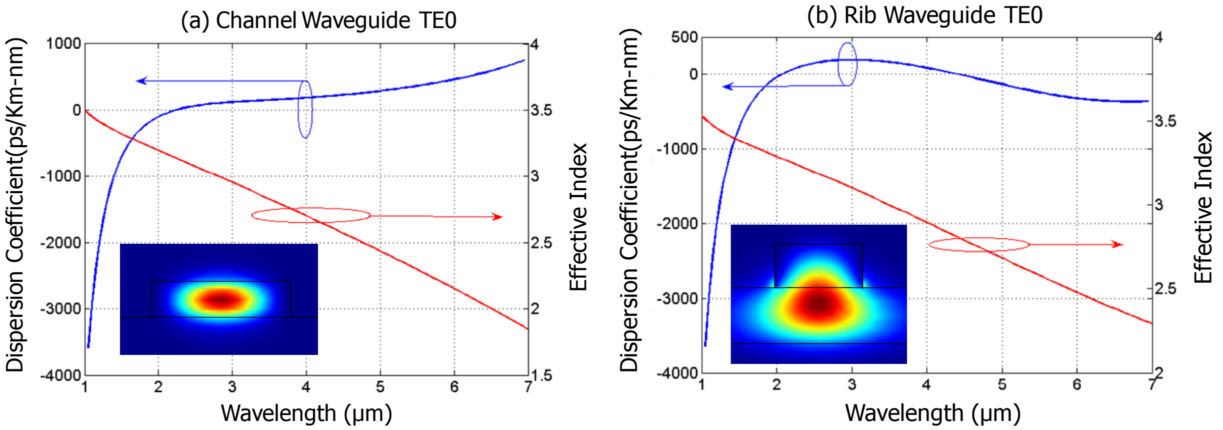


Figure 1. Dispersion curve versus wavelength (red: effective index, blue: dispersion coefficient) for (a) Channel waveguide and (b) Rib waveguide.

3. WAVELENGTH CONVERSION

With strong pumping power, the FWM process is capable of converting signal from one wavelength to another [11]. The process is characterized by numerically solving the nonlinear Schrödinger Equation [10]. However, the conventional Schrödinger Equation is no longer valid for accurate assessment due to the fact that pump, signal and idler wavelengths are not closely spaced and the assumption of identical wavelength and uniform overlap integral is not true anymore. In other words, the effective areas accounting for overlap integrals between different wavelengths are different. A modified form of Schrödinger Equation as in Eq.(1) is adopted throughout the analysis to take the mismatch in overlap integral into account.

$$\frac{dA_p}{dz} = -\frac{\alpha_p}{2}A_p + \frac{j2\pi n_2}{\lambda_p}[\frac{|A_p|^2}{A_{eff}^{pp}} + \frac{2|A_s|^2}{A_{eff}^{sp}} + \frac{2|A_c|^2}{A_{eff}^{cp}}]A_p + \frac{j2\pi n_2}{\lambda_p A_{eff}^{fwm}}A_p^* A_s A_c e^{j\Delta kz}$$

$$\frac{dA_s}{dz} = -\frac{\alpha_s}{2}A_s + \frac{j2\pi n_2}{\lambda_s}[\frac{|A_s|^2}{A_{eff}^{ss}} + \frac{2|A_p|^2}{A_{eff}^{ps}} + \frac{2|A_c|^2}{A_{eff}^{cs}}]A_s + 2\frac{j2\pi n_2}{\lambda_s A_{eff}^{fwm}}A_p A_p A_c^* e^{-j\Delta kz}$$

$$\frac{dA_c}{dz} = -\frac{\alpha_c}{2}A_c + \frac{j2\pi n_2}{\lambda_c}[\frac{|A_c|^2}{A_{eff}^{cc}} + \frac{2|A_p|^2}{A_{eff}^{pc}} + \frac{2|A_s|^2}{A_{eff}^{sc}}]A_c + 2\frac{j2\pi n_2}{\lambda_c A_{eff}^{fwm}}A_p A_p A_s^* e^{-j\Delta kz} \qquad (1)$$

Figure 2(a) shows a typical wavelength conversion gain spectrum in SOS waveguide. Besides the conventional conversion band around the pumping wavelength, strong conversion also occurs in the sideband as a discrete conversion band [5]. This type of conversion is extremely useful to achieve wide-range wavelength conversion spanning from near-IR to mid-IR. Figure 2(b) shows that signal at 1.55um can be converted to a wide range of different mid-IR wavelengths using SOS waveguides with different geometries. This corresponds to almost the whole mid-IR spectra and suits to a wide range of applications. For example, signal at telecommunication window can be imaged to the 3.8um atmospheric window for free space optical communication purpose. In free space communication, optical signals are transmitted through atmosphere and the transmission is wavelength dependent. Therefore, the choice of carrier wavelength is very important for high-quality long-distance communication. Although high-performance transceivers are more available in telecommunication window, atmospheric absorption, scattering and turbulence are less severe in MWIR near the 3.8μm atmospheric window [11]. Figure 3(a) shows peak conversion efficiencies over 0dB near the 3.8um channel and tunability can again be offered by varying the geometry. Figure 3(b) shows a typical OOK input and output sequence with a 10GHz repetition rate. The pulse broadening is caused by dispersion and walk-off between signal and idler. This shows the converter's capability of serving as adapter between the two optical communication systems.

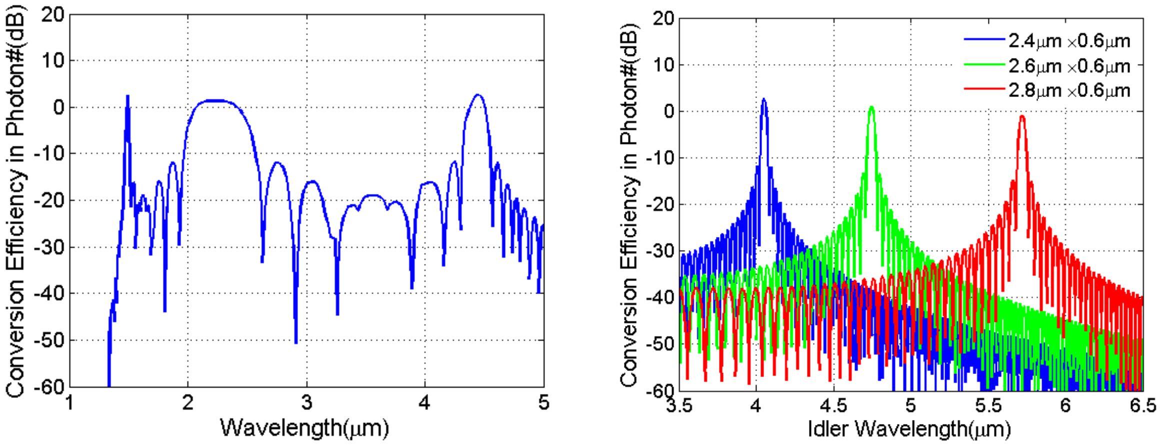


Figure 2. (a) Wavelength conversion over the entire band and strong conversion present both around the pump wavelength and in the sidebands. (b) Capability of achieving wavelength conversion from 1.55um to the entire mid-IR band by tuning the waveguide geometries.

Meanwhile, proper tailoring of the waveguide geometries may also produce ultra wide conversion band around the pumping wavelength. As we can observe from Fig.1(b), the slope at the second ZDWL can be very slow in rib waveguide due to higher degree-of-freedom on geometry and compensating condition. If we choose the pump wavelength near this ZDWL, phase-matching condition is promising to be met over a wide range of wavelength and a broadband wavelength converter can be expected. As shown in Fig.4, a flat profile is displayed on a bandwidth of more than 1um. -10dB conversion efficiency can be expected in a 1cm waveguide with a pump intensity of 5W/μm^2. Optimal pump wavelength varies for different geometries and the ultra broadband converter is tunable with geometrical parameters, which makes it highly adaptable for different applications.

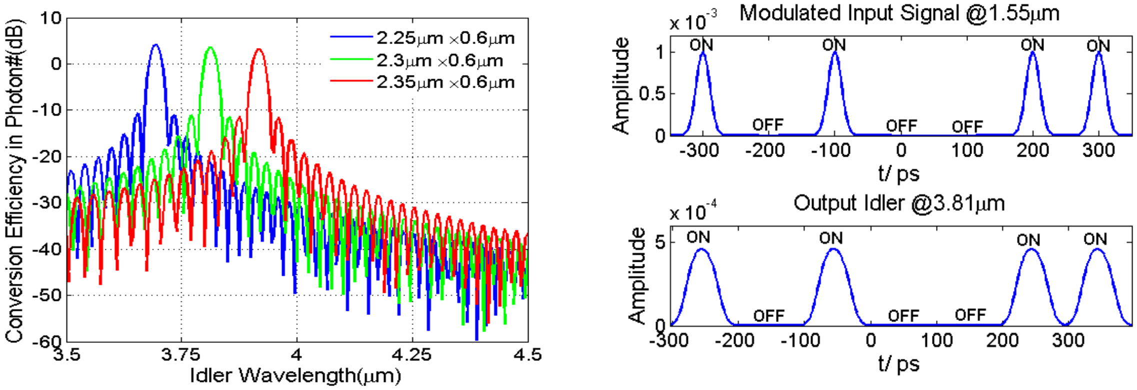


Figure 3. (a) Conversion Efficiency to 3.8 free-space communication window, (b) Conversion of Modulated OOK signal

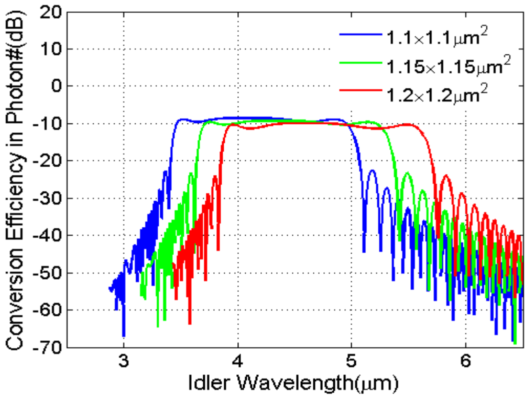


Fig.4 Ultra broadband wavelength conversion.

4. PERFORMANCE IMPROVEMENT USING QUASI PHASE MATCHING

With low phase-mismatch, energy is transferred from pump to signal and idler. However, when phase-mismatch is larger than π, the energy will be transferred back to pump in an opposite way. If we cascade sections with opposite dispersion coefficient at specific wavelength, phase-mismatch will be compensated and the energy will be constantly transferred to idler, which can enhance the conversion efficiency. Figure 5 illustrates the concept of quasi-phase-matching in silicon waveguides and the alternating sections are channel waveguides with different widths but the same height. Since the dimensions of the proposed waveguides are large the fabrication of alternating sections with large geometries is feasible for fabrication by using standard photolithographic techniques. Figure 6(a) shows that the idler power increases continuously along the SOI waveguide if we repeatedly compensate the phase to preserve a positive phase-mismatch for FWM. Figure 6(b) is the corresponding conversion efficiency spectrum. Here two alternating sections with 2.4μm×0.6μm and 2.8μm×0.6μm, respectively, are cascaded. The conversion efficiencies without quasi-phase-matching with the same total waveguide length for the two straight waveguides are -17.0dB and -23.8dB, which means that the conversion efficiency is enhanced by more than 30dB with quasi phase matching. Figure 6(c) and (d) are similar results in SOS waveguides as (a) and (b). The two alternating sections are 2.3μm×0.6μm and 2.8μm×0.6μm. With 3cm uniform waveguides of 2.3μm ×0.6μm and 2.8μm×0.6μm given conversion efficiency of -4.0dB and -22.3dB respectively in SOS waveguide, >30dB enhancement is also achievable.

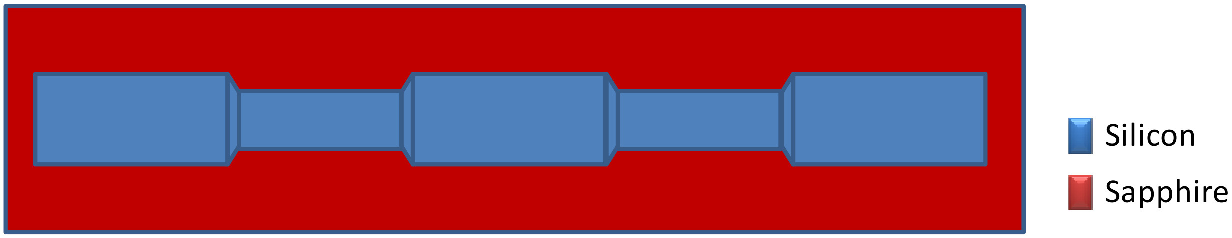
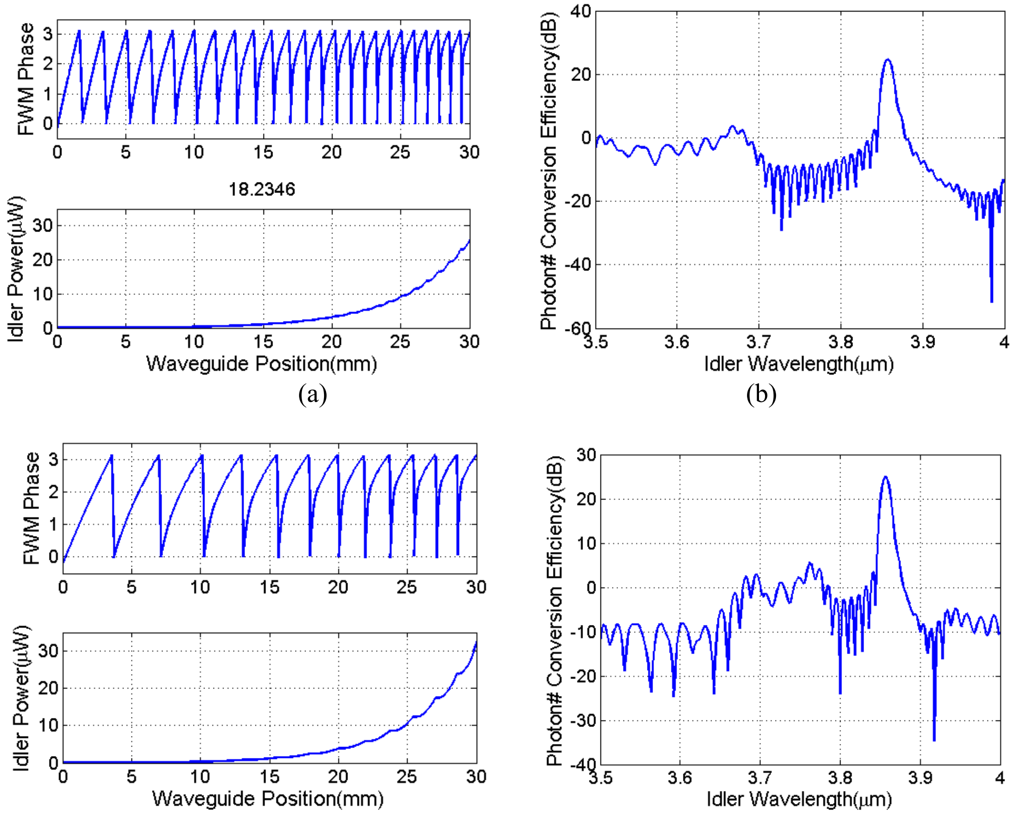


Figure 5. A conceptual illustration of quasi phase matching in SOS waveguide, waveguides are channel waveguide with identical height.



(a) (b)

(c) (d)

Figure 6. Conversion Efficiency enhancement by QFM.

In a similar fashion, if we cascade sections with opposite dispersion slope yet the same overlapped ZDWL, phase-mismatch can be compensated both below and above ZDWL. Efficient conversion is possible over a broader bandwidth. Conversion bandwidth can be enhanced by this quasi-phase-matching (QFM) mechanism. Figure 6 shows the effects of QFM on bandwidth enhancement. Blue and green curve are spectrum for uniform waveguide structures and the red curve is the conversion efficiency spectrum when the two sections are periodically cascaded. Bandwidth is broadened by about a factor of 2.

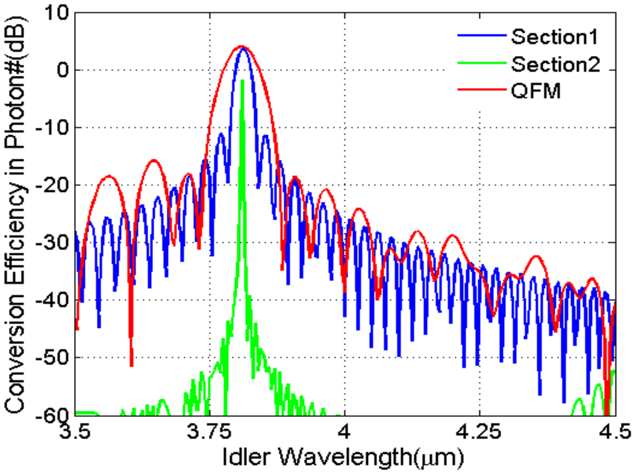


Figure 7. Conversion bandwidth enhancement by QFM.

5. OPO DESIGN

In order for more practical conversion and lasing, an optical cavity is formed to support optical parametric oscillation[12] . Here we designed a linear cavity for demonstrating purpose. Because the spacing between signal, pump and idler are large, it is easy to design cavity mirrors selectively reflect the idler wavelength. This makes a cavity for idler only and makes it easier to manipulate pulse operation. The cavity is 7.25mm long and this reduces the walk-off between pump and signal and hence alleviates the idler pulse spreading. Figure 8 shows the wavelength conversion efficiency in the designed OPO. A conversion efficiency of >40dB is achieved with a pumping intensity of 5W/μm2, which is 20dB more than that in a 30mm long single-pass waveguide. Also due to the oscillating effect, the bandwidth is reduced.

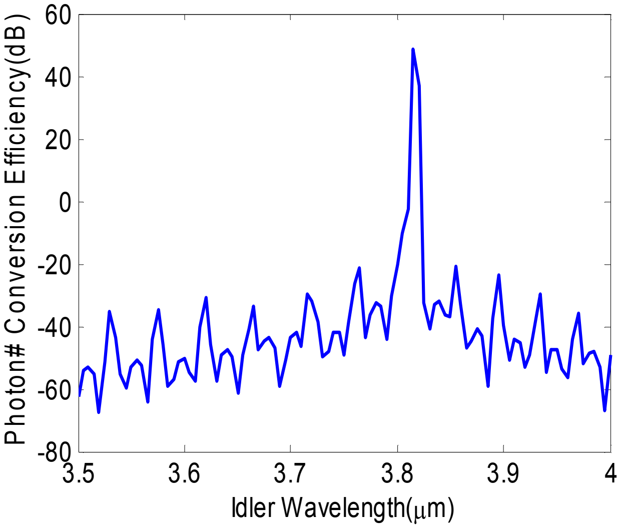


Figure 8. Conversion efficiency in optical cavity.

6. SUMMARY

A guided wave mid wavelength infrared (MWIR) platform is advantageous over its free-space counterpart to facilitate a wide variety of applications. Conventional SOI platforms cannot deliver a solution due to substrate loss and planar devices on silicon-on-sapphire (SOS) platform are considered as prospective replacement for MWIR applications. Here we investigate SOS based planar waveguide converters to facilitate use of near-IR sources and detectors at telecommunication wavelengths for mid-IR applications. In particular we show that quasi phase matched SOS waveguides can provide over 30dB higher conversion efficiency and 2× more bandwidth than that can be achieved in uniform waveguide geometries. Finally by forming a cavity for the idler, the efficiency is further improved by 20dB to > 40dB.

7. ACKNOWLEDGEMENT

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