Discrete Parametric Band Conversion in silicon for mid-infrared Applications

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Abstract:

Mid-infrared has great potential for silicon photonics. Engineering the dispersion by IR compatible cladding materials and waveguide dimensions enable broadband discrete wavelength conversion. We show that >1.2μm discrete wide-band conversion is achievable at 4μm pumping.

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OCIS codes: (230.7370) Waveguides; (190.4410) Nonlinear optics, parametric processes.

1. Introduction

Mid wave infrared (MWIR), defined as the wavelength range from 2μm to 6μm, has potential for silicon photonics because 1) crystal silicon has good transparent windows for energy below band gap for 1.2μm all the way to 6.6μm). Recently, two photon absorption has been shown to be negligible in the MWIR range [1] and Raman effect is strong enough to generate 12dB of Raman amplification at 3.4μm in bulk silicon with 2.9 μm pump wavelength [2]. Recent progress in silicon photonics for MWIR wavelength applications mostly focuses on fabrication and waveguide design to satisfy single mode operation. Although silicon is transparent in MWIR, the cladding and substrate material is also critical for high efficiency operations. In particular, silicon dioxide, the most widely used cladding and substrate material, has large absorption at the MWIR region, (10dB/cm above 4 μm) [3]. A solution has been proposed by Soref [4] suggests the use of silicon on different substrates, such as silicon nitride or Sapphire, that is transparent in MWIR [4]. Sapphire (Al_2O_3) is <80% transparent from visible up to 5.5μm [3] and SOS wafer is widely available from commercial suppliers. The material of cladding on the waveguide is also critical for low loss operation. Sapphire deposition and nitrite deposition on silicon have been investigated for various applications and adaptable to silicon photonics applications for cladding layer [5].

Here we focus on potential applications of SOS waveguides with different cladding layers. We show that engineering the dispersion by IR compatible cladding materials and waveguide dimensions enables broadband discrete wavelength conversion between near-IR and MWIR. In a particular study we estimate that >3μm discrete wide-band conversion is achievable at 4μm pumping with -12dB conversion efficiency in a 1cm long waveguide. We also show that engineering the dispersion allows broadband continuous wavelength conversion over 1.1μm by using mid-IR pumping at 4.3um.

2. Theoretical Background

Kerr effect is a third order nonlinear effect which induce intensity dependent refractive index change. This index change can contribute to nonlinear effects, such as self phase modulation, cross phase modulation and four wave mixing. It is well known that n_2 will scale with 1/λ. The nonlinear index change n_2 can be calculated from two photon absorption coefficient using Kramer-Kronig relation. Theoretical models have been proposed so far describes the dispersion of third order nonlinearity include TPA and Kerr nonlinearity in silicon [6-8] at wavelengths <2μm. In order to analyze the parametric process in silicon we estimate the nonlinear property of silicon for longer wavelengths by using two photon absorption coefficient based Kramer-Kronig relation[6]. Also, nonlinear index Measurements performed at 1550nm (n_2 = 4.5e-14) used as fitting parameter and to estimate n_2 at

978-1-55752-884-1/10/$26.00 ©2010 IEEE

MWIR wavelengths.

In addition to nonlinearity calculation, the waveguide dispersion is estimated in silicon rib channel waveguides by using full wave simulations. Here we use waveguides with cross sectional area from 1µm^2 to 9µm^2 to find the effective index and effective area of the waveguide for wavelength range from 2µm to 6µm. The dispersion D and β_2 can be obtained from the estimated index profile. With similar waveguide geometry, waveguide dispersion can drastically change the total dispersion of the silicon waveguide and provide a means to control the zero-dispersion-wavelength. For instance, Figure 1(b) illustrates the dispersion of rib/ridge waveguide with air and sapphire cladding. The dispersion of the waveguide is estimated to be D<*200ps/km nm* for wavelengths range from 2µm to 4µm in a 1µm by 1µm waveguide with both air and sapphire cladding, fig. 1 (b)(c). These low dispersion values are suitable for broadband continuous wavelength conversion. Also, the estimated nonlinear dispersion profile can facilitate discrete band conversion by using pump lasers away from the zero dispersion wavelength.

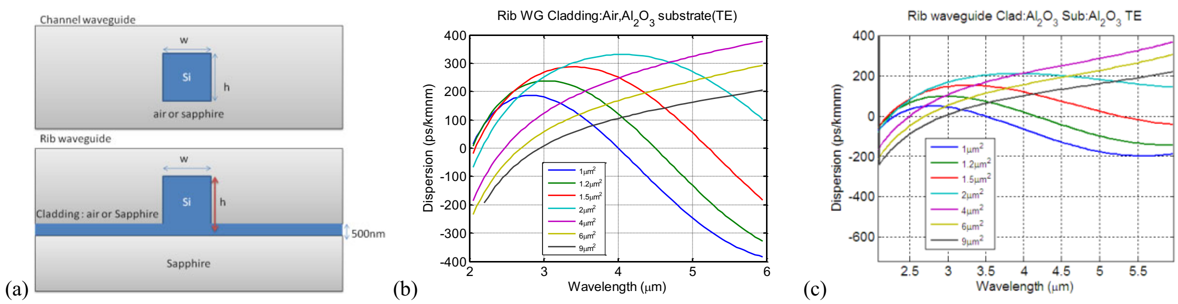

Fig. 1 (a) Two simulated waveguide structures. The calculated dispersion of rib waveguide with (b) air and (c) sapphire cladding.

3. Phase matching and dispersion engineering in MWIR region

Parametric wavelength conversion and amplification is a nonlinear process that requires phase matching of the pump, signal and idler wave that is given by $\Delta k = \Delta k_{linear} - \Delta k_{nonlinear}$. Here $\Delta k_{nonlinear} = 2\gamma P_{pump}$ is the nonlinear phase mismatch and $\Delta k_{linear} = k_{signal} + \Delta k_{idler} - \Delta k_{pump}$ is the linear phase mismatch. The final parametric gain can then be written as [9]

$$G = 1 + \left[\frac{\gamma P_{pump}}{g} \sinh(gL) \right]^2 \quad (1)$$

Where $g = [(\gamma\ P_{pump})^2 - (\Delta k_{linear}/2]^2\ ]^{0.5}$ is the parametric gain parameter, and L is the interaction length.

Figure 2 illustrates the result of discrete and continuous wavelength conversion in dispersion optimized silicon waveguides. The waveguides we use are silicon waveguides built on SOS waver and has air cladding. Here we estimate the dispersion profile of TE and TM polarizations separately as illustrated in Figure 2 (a) (b). Figure 2(c) shows the conversion efficiency of a discrete wavelength conversion by using a 10W pump wavelength at 4.3 µm for TE mode. Unlike conventional wavelength conversion, here the nonlinear dispersion profile is being utilized by using a pump laser 350 nm away from the zero dispersion wavelength. Under discrete wavelength conversion the silicon operates in parametric regime at the vicinity of the pump laser and achieves the modulational instability at a discrete wavelength band 1.5µm. We show that under this configuration wavelength conversion of 6.2um to 3um is possible with 3dB conversion band of 15 nm. We also show that using different waveguide geometries provide wavelength conversion between bands from 2um to 6um and opens a possibility that long range wavelength conversion that convert MWIR to communication wavelength.

Figure 2(d) illustrate the conventional continuous band wavelength conversion that is estimated in 1.18µm by 1.18µm silicon rib waveguide. The simulation results show that -13 dB conversion efficiency can be achieved within 1.1 µm continuous bandwidth in a 1.183µm by 1.183µm waveguide. Furthermore, the dispersion has positive at 2-4 µm and negative everywhere else. The phase matching condition can be satisfied by setting the pump wavelength around 4 µm where a separate island wavelength conversion can be achieved for the same waveguide. The result shows that the wavelength at 6.3 µm can be converting to 3µm.

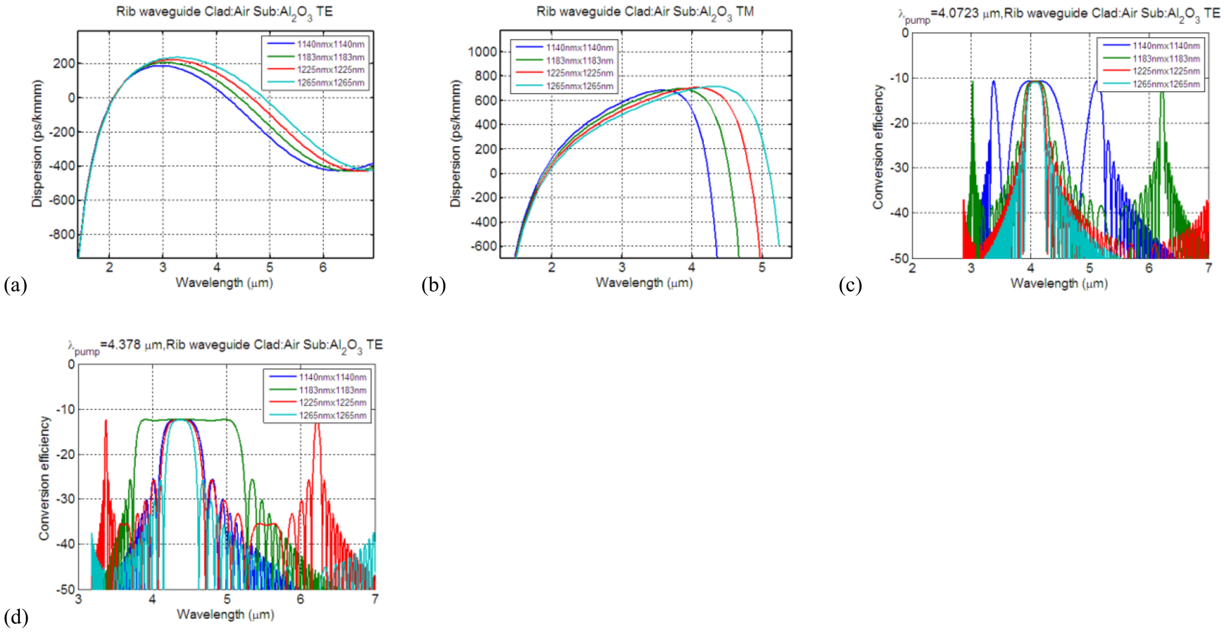

Fig. 3 Dispersions of the SOS rib waveguide with air cladding for (a)TE and (b)TM mode. (c) Parametric conversion for pump wavelength at 4.07 µm. (d) Parametric conversion for pump wavelength at 4.38 µm.

4. Conclusion

MWIR in silicon has great potential for next generation optical communication applications. We show that by manipulating the waveguide dimensions, the zero dispersion wavelength can be tuned from 3.5 µm to 4.8 µm. Also, 1.2 µm wide broadband wavelength conversion is achievable in the 1.18µm x1.18µm waveguide with pump wavelength at 4.38 µm. We estimate that >3µm discrete wide-band conversion is achievable at 4µm pumping with -12dB conversion efficiency in a 1cm long waveguide. In addition, these results can be extended to waveguides with silicon nitride, which has low loss transmission loss from 0.2µm to 6.6µm. However, the lack of refractive index measurements in MWIR region impedes the modeling of silicon waveguides with silicon nitrate cladding.

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