Wavelength conversion in silicon using Raman induced four-wave mixing

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Conversion of digital- and analog-modulated optical signals from the 1550 nm band to the 1300 nm band is demonstrated in silicon waveguides. The conversion is based on parametric Stokes to anti-Stokes coupling using the Raman susceptibility of silicon. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1768310]

Silicon integrated optics has emerged as an attractive technology for realizing passive devices because of the efficient silicon-on-insulator (SOI) guiding structures and foundry compatible processing technology. However, silicon is generally perceived to be devoid of active optical properties that are needed to realize more sophisticated optical functions such as, amplification and wavelength conversion. We have recently reported the observation of stimulated Raman scattering (SRS)[1] and coherent anti-Stokes Raman scattering (CARS)[2,3] in silicon waveguides. In this letter, we demonstrate wavelength conversion of digital- and analog-modulated signals from 1542 to 1328 nm, using CARS. The conversion efficiency of this process was measured to be 1.37×10^{-5} and is limited by the phase mismatch between the optical waves. Quasi-phase matching can be achieved by engineering the rib waveguide structure to cancel out the contribution of material dispersion using waveguide dispersion and birefringence.

Silicon exhibits a gain coefficient for stimulated Raman scattering that is $\sim10^4$ times higher than in glass fibers.[4,5] This, along with a small mode area (due to high index contrast between silicon and SiO_2/air) offers the possibility to achieve amplification and wavelength conversion in chip-scale devices. In particular, parametric coupling via the Raman susceptibility, $\chi_R^{(3)}$ (which is $\sim$44 times larger than the third order nonresonant susceptibility, $\chi_{NR}^{(3)}$) offers a means to transfer information between the Stokes and anti-Stokes wavelength channels while preserving the phase of the signal. The conversion efficiency of this process is dependent upon (i) the intensity of the pump wave, (ii) the Raman susceptibility of silicon, and (iii) the phase difference between the three waves.

The detailed coupled mode analysis of this process has been reported in fibers[6] and has been analyzed in silicon waveguides.[3] The evolution of the anti-Stokes (aS) field in the presence of the pump (p) and the Stokes (S) fields, assuming no initial anti-Stokes signal, is given by:[2]

$$E_{aS}(z) = -ie^{i(\Delta k + RI_p)^{(z/2)}}\cdot[2R+ig_s(\Omega)]I_p\cdot\frac{\sinh Az}{2A}\cdot E_S(0), \tag{1}$$

where $\Delta k = 2k_p^{\mathrm{TE}} - k_S^{\mathrm{TM}} - k_{aS}^{\mathrm{TM}}$, is the phase mismatch between the three optical waves, with the polarizations as indicated, $\Omega = |\omega_{\mathrm{aS}} - \omega_{\mathrm{p}}| = |\omega_{\mathrm{p}} - \omega_{\mathrm{S}}| = 15.6$ THz is the Raman shift, I_p is the pump intensity, $R = 2\pi\chi_{\mathrm{NR}}^{(3)}\omega^2/c^2k$ $(=1.7\times10^{-9}$ cm/W) refers to the contribution of the electronic susceptibility, $g_s = -i4\pi\chi_R^{(3)}(\Omega_0)\omega^2/c^2k$ $(=3.7\times10^{-8}$ cm/W) refers to the Raman gain coefficient, $E_S(0)$ is the initial Stokes field launched into the waveguide and the coefficient A is defined as:

$$A = \sqrt{[2R+ig_s(\Omega)]I_p\cdot(\Delta k)/2-(\Delta k/2)^2}, \tag{2}$$

when $\Delta k \ll |4R + 2g_s(\Omega)|I_p = k_{th}$, the waves are close to phase matching. Here, parametric conversion process is efficient and dominates over stimulated amplification. The imaginary part of A results in a *sinc*^{2} dependence of power conversion efficiency on Δk as shown in Fig. 1. For silicon waveguides (5.4 μm^2 area) used in our experiments, 0.7 W of pump power requires $\Delta k_{\mathrm{th}} = 2.1$ cm^{-1} for efficient parametric interaction. We note that this model does not take into account the linear propagation loss and nonlinear absorption, both of which can lower the conversion efficiency.

The experimental setup shown in Fig. 2 consists of a cw pump at 1427.3 nm (TE), and an external cavity diode laser (ECDL) used as the Stokes source at 1542 nm (TM), which are coupled into the waveguide using a polarizing beam splitter (PBS). The ECDL is externally modulated and amplified using a high power EDFA before combining with the pump. The silicon-on-insulator (SOI) rib waveguides used are 1.8 cm long with a cross section area of 5.4 μm^2. At the output, a band-pass filter is used to extract the converted anti-Stokes signal at 1328.5 nm before photodetection and rf amplification by 40 dB. The total passive loss of the system is measured to be 20 dB, including 1.5 dB/cm for waveguide propagation.

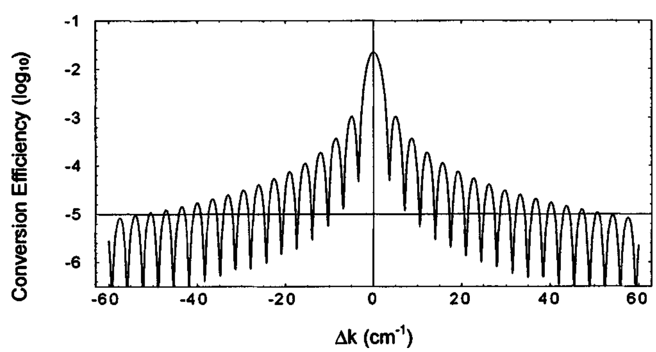

FIG. 1. Stokes to anti-Stokes conversion efficiency, calculated from Eq. (1), using an effective pump power of 0.7 W at the input facet of the waveguide. Measured conversion efficiency of $\sim10^{-5}$ is also shown in the plot.

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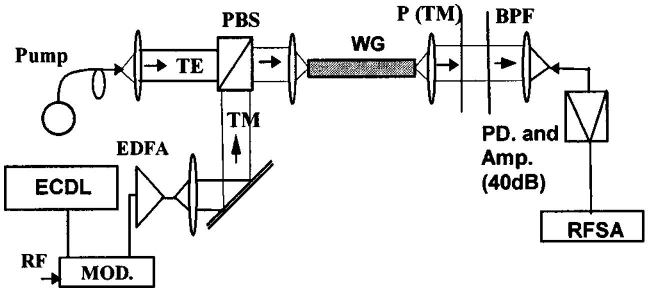

FIG. 2. Experimental setup for wavelength conversion, Pump: pump laser at 1427.3 nm, ECDL: external cavity diode laser at 1542 nm (Stokes), MOD.: modulator, PBS: polarization beam splitter, WG: waveguide, P(TM): polarizer to collect TM0 mode, BPF: band pass filter at 1328 nm (anti-Stokes), PD+Amp.: photodetector and amplifier, RFSA: rf spectrum analyzer, TE and TM refer to the modes which are coupled by the PBS.

Figure 3 shows the converted anti-Stokes signal spectrum measured with an optical spectrum analyzer (OSA). The total converted anti-Stokes power at the output facet of the waveguide was measured to be ~400 nW. The peak is blueshifted from the pump by 15.6 THz which is exactly the optical phonon frequency in silicon. The bandwidth of the wavelength conversion is ~210 GHz, determined by the finite pump linewidth. This can be increased by (i) broadening the pump linewidth, or (ii) using multiple pump wavelengths.

A single tone rf signal at 1.03 GHz with 12 dBm power was applied to the Stokes signal and the same modulation was detected at the anti-Stokes signal. The converted rf signal is shown in Fig. 4. The electrical signal-to-noise ratio (SNR) of the converted signal at 1.03 GHz modulation over a bandwidth of 100 Hz as a function of the input Stokes power is plotted in Fig. 5 (squares). The maximum SNR was measured to be 34 dBe.

Next, 1 Mbps PRBS (2^7-1) digital data were applied to the Stokes source. The eye diagram of the wavelength converted data is shown in Fig. 6. The maximum achievable bit rate and SNR of the converted signal are limited by the conversion efficiency.

It is determined that the noise level in the rf signal conversion experiments is dominated by the thermal noise of the optoelectronic front end. Figure 5 also shows the theoretical fit for the electrical SNR versus the input Stokes optical power (solid line). Excellent agreement between measured and calculated SNR is obtained using a conversion efficiency of 1.37×10^{-5} in the calculations. We note that comparable conversion efficiency was obtained from the slope of output anti-Stokes power versus input Stokes power plot.[2] From Fig. 1, this corresponds to phase mismatch of

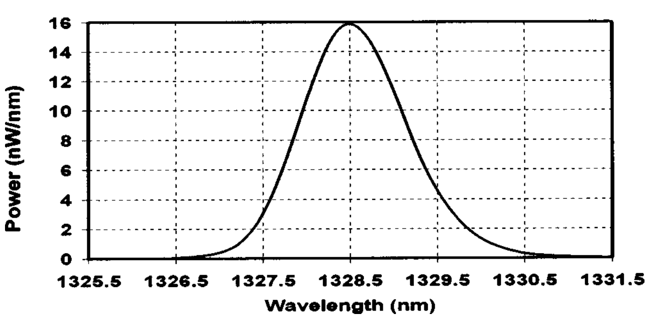

FIG. 3. Converted optical signal at 1328 nm as seen using an optical spectrum analyzer.

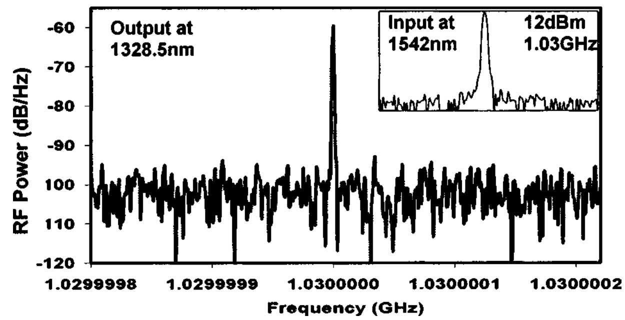

FIG. 4. Converted 1.03 GHz modulation obtained using a rf spectrum analyzer (RFSA). A 40 dB rf preamplifier was used prior to the RFSA. The input rf signal at the Stokes wavelength is also shown in the inset.

$|\Delta k|>10$ cm^{-1}. Previous results[2] on this waveguide indicate a value of $|\Delta k|\sim30$ cm^{-1}. Further increase in conversion efficiency requires narrower range of Δk and a reduced lower bound. Thus it is imperative that the phase mismatch is close to zero to maximize the conversion efficiency.

In our experiments, the phase mismatch between the optical waves depends on the material, waveguide dispersion, and birefringence due to different polarizations of the pump and the Stokes signal. By proper rib structure design, the effect of material dispersion can be compensated by waveguide dispersion and birefringence.[3] Under the phase matched condition, the conversion efficiency is calculated to be 2% at 0.7 W of pump power into a waveguide with 5.4 μm^2 cross sectional area. Waveguides with smaller cross section (~1 μm^2) can increase the efficiency to 65% for comparable pump powers. However, this has to be balanced against the potential reduction in fiber-to-waveguide coupling efficiency.

Under the current scattering configuration, based on the Raman selection rules, the Pump and Stokes signals have to be cross polarized for parametric Raman coupling.[7] The cross-polarized waves experience negligible coupling, hence it is possible to double the throughput using polarization multiplexing, although phase matching conditions for both polarizations requires careful design considerations.

In conclusion, we have demonstrated coarse wavelength conversion in silicon waveguides based on parametric Stokes to anti-Stokes coupling using the Raman susceptibility. Conversion efficiency of 1.37×10^{-5} has been achieved and conversion of analog- and digital-modulated data from a 1500 band to 1300 nm band has been experimentally demon-

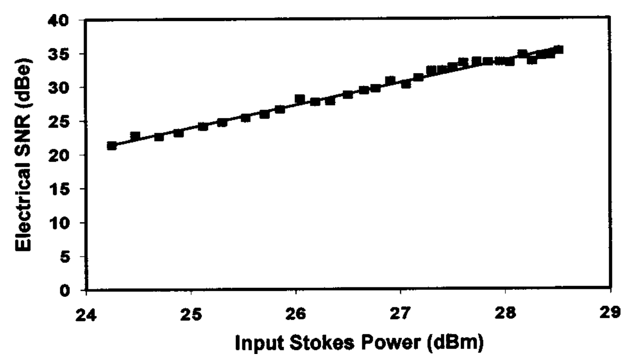

FIG. 5. Electrical SNR (in dBe) as a function of input Stokes optical power (in dBm). Square marks show the experimental data with maximum SNR of 34 dBe measured. Theoretical fit to this plot as shown by the solid line gives a conversion efficiency of 1.37×10^{-5}.

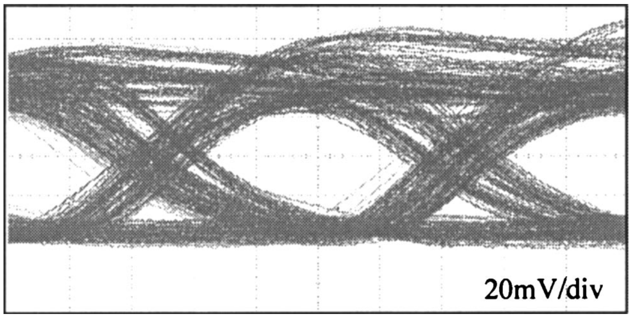

FIG. 6. Eye diagram of the wavelength converted PRBS data at 1 Mbps.

strated. The conversion efficiency and hence the SNR and bit rate supported by the conversion process are limited by the phase difference between the optical waves and the magnitude of the Raman nonlinearity. Quasi phase matching can be achieved by proper rib-waveguide design to cancel out material dispersion using the birefringence in the waveguides and hence result in high conversion efficiencies. The Raman nonlinearity can be increased by using waveguides with smaller cross-section area.

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