Wavelength Conversion with Large Signal-Idler Separation using Discrete Four-Wave Mixing in a Silicon Nanowire

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Abstract: We have demonstrated wavelength conversion over 468 nm based on discrete bands phase matching in a silicon nanowire. CW light is converted from 1258 nm to 1726 nm with a CW pump at 1455 nm.

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1. Introduction

Wavelength conversion based on four wave mixing (FWM) in silicon waveguides has attracted considerable research interest due to the ultra-compactness, potential for integration with electronics, broad working bandwidth and high-speed operation of those waveguides [1-3]. In addition, the strong waveguide confinement facilitates dispersion engineering by nano-engineering the dimensions of the silicon waveguide. Broad band wavelength conversion using FWM relies on broad band phase matching, which requires careful control of the group-velocity dispersion (GVD), since in the undepleted-pump regime the bandwidth of the degenerate FWM is inversely proportional to the square root of the product of the interaction length and the GVD [4]. However, the GVD of the waveguide is very sensitive to the dimensions of the silicon waveguide, which leads to strict dimensional tolerances in the fabrication. Using higher-order waveguide dispersion to achieve phase matching in discrete bands can also enable wavelength conversion of signals with a large frequency separation. Recently, using a pulsed pump with a very high peak power, a mid-infrared optical signal was parametrically amplified and wavelength converted into the telecom L band [5].

In this paper, wavelength conversion across six telecommunication bands (O- E- S- C- L- and U- bands) from 1258 nm to 1726 nm is demonstrated using discrete FWM in a silicon waveguide with a continuous wave (CW) pump with a launched power of only 14.5 dBm.

2. Phase matching in discrete bands using higher order dispersion

In a FWM process, phase matching between the pump, signal and idler occurs at the pump frequency provided nonlinear phase mismatch due to Kerr nonlinearity can be ignored, which is the case at moderate pump power levels, and dispersion terms higher than β_3 can be neglected. Here and in the following β_i denotes the ith order derivative of the propagation constant β with respect to angular frequency. Depending on the value of β_2, this usually results in a continuous wavelength conversion bandwidth centered around the pump frequency. However, considering higher dispersion orders up to β_5 only are significant, the linear phase matching condition becomes

$$\Delta\beta = \frac{1}{12}\beta_4\Delta\omega^4 + \beta_2\Delta\omega^2 = 0 \tag{1}$$

where $\Delta\omega=\omega_s-\omega_p$ is the angular frequency separation between the signal and pump. If $\beta_2\beta_4<0$, phase matching also occurs for $\Delta\omega = \pm\sqrt{-12\beta_2/\beta_4}$, which gives rise to discrete wavelength conversion bands on top of the main (centre) conversion bandwidth.

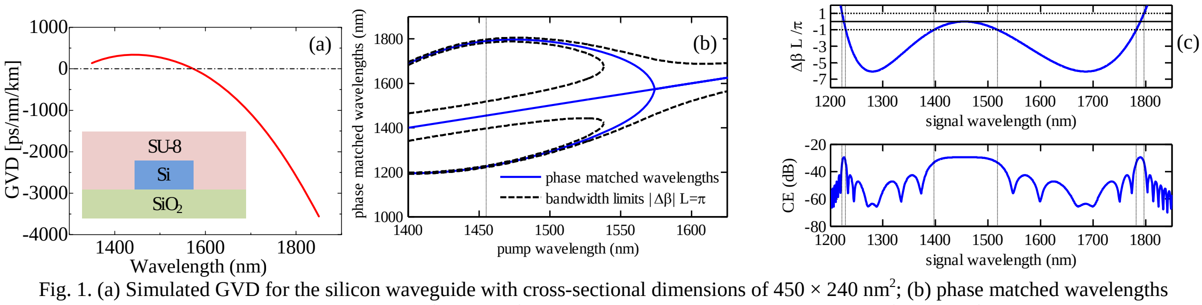

Fig. 1. (a) Simulated GVD for the silicon waveguide with cross-sectional dimensions of 450 × 240 nm^2; (b) phase matched wavelengths and corresponding conversion band limits as a function of pump wavelength; (c) phase mismatch as a function of signal wavelength and predicted conversion efficiency (CE) for a pump wavelength of 1455 nm.

Fig. 1a shows the GVD simulated using a custom-made finite-difference mode solver for the transverse-electric (TE) mode of a silicon waveguide with cross-sectional dimensions of 450 × 240 nm^2. For this waveguide, the condition $\beta_2\beta_4<0$ for which discrete band phase matching occurs is satisfied for pump wavelengths up to 1574 nm. In practice, however, even dispersion orders higher than β_4 need to be considered for ultra-wideband processes and equation (1) needs to be modified accordingly. The phase matching diagram (Fig. 1b) represents the values of the phase matched wavelengths as a function of pump wavelength, assuming no nonlinear phase mismatch contribution and dispersion orders up to β_{14}. The diagram also shows the wavelengths for which $|\Delta\beta{\cdot}L|=\pi$, which are a good approximation of the limits of the wavelength conversion bands. On top of a continuous conversion band around the pump wavelength, two discrete conversion bands appear up to a pump wavelength of about 1535 nm, over which they merge with the centre continuous conversion band. It should be pointed out that the exact values of the phase matched wavelengths represented in Fig. 1b depend on the accuracy of numerical prediction of the dispersion profile, which is itself strongly dependent on the exact dimensions of the waveguide. Fig. 1c also shows the phase mismatch factor and the numerically predicted conversion bands when the waveguide is pumped at 1455 nm.

3. Experiment and results

The silicon nanowire used in the experiment is a dispersion engineered straight 3.6-mm long silicon waveguide, which includes tapering sections for low-loss interfacing with optical fiber. The main waveguide section is ~3 mm long and has a cross section of 450 × 240 nm^2 while the tapering sections are ~0.3 mm long each and their width is inversely tapered from 450 nm to 20 nm [6]. This tapering enables efficient coupling between the silicon waveguide and the larger polymer waveguide (SU8-2005) into which the whole silicon structure is embedded. The device has a silicon-on-insulator (SOI) structure, with the silicon waveguide placed on a SiO_2/Si substrate. At 1550 nm, the measured propagation loss is 4.3 dB/cm and the fiber coupling loss is 1.5 dB per facet while at 1250 nm those values are 3 dB/cm and 4.3 dB per facet, respectively.

The CW light at 1455 nm is generated by a Raman laser source, acting as the pump of the FWM process. Three tunable CW lasers spanning the O- E- S- and C-bands (1250 nm – 1565 nm) are used as the signal source. The pump and signal are coupled together using a 3-dB coupler and then launched into the silicon nanowire. Both the pump and signal are aligned to the TE polarization. The launched pump power is 14.5 dBm. The conversion efficiency is measured as a function of the signal wavelength, as shown in Fig. 2a. We can see the main conversion bandwidth of 100 nm around the pump wavelength and the discrete conversion bandwidth of 10 nm around 1258 nm. Fig. 2b and 2c show the input and output spectra with the CW pump at 1455 nm and the CW signal at 1258 nm, respectively. A conversion efficiency of -36 dB is obtained for the wavelength conversion from 1258 nm to 1726 nm. In addition, a peak from the Raman Stokes-shifted pump is observed at 1575 nm.

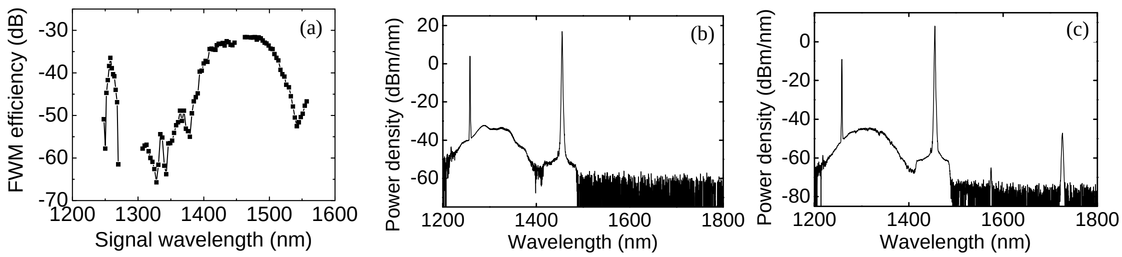

Fig. 2. (a) Measured FWM efficiency as a function of signal wavelength for the pump at 1455 nm; (b) and (c) spectra at the input and output of the silicon nanowire with the CW pump at 1455 nm and the CW signal at 1258 nm.

4. Conclusions

We have demonstrated 468-nm wavelength conversion based on phase matching in discrete bands using higher order dispersion in a silicon nanowire. CW light at 1258 nm is converted to 1726 nm using FWM between discrete bands with a CW pump at 1455 nm. These results show the feasibility of inter-band wavelength conversion between different telecommunication bands.

5. References

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