

First Demonstration of Quasi-Phase-Matched Four-Wave-Mixing in Silicon Waveguides

Jeffrey B. Driscoll^{1,2}, Noam Ophir², Richard. R. Grote^{1,2}, Jerry I. Dadap^{1,2}, Nicolae C. Panoiu³,
Keren Bergman², and Richard M. Osgood, Jr.^{1,2}

¹: Microelectronics Sciences Laboratories, Columbia University, New York, NY 10027, USA

²: Department of Electrical Engineering, Columbia University, 500 W. 120th Street, New York, NY 10027, USA

³: Department of Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, UK
jbd2112@columbia.edu

Abstract: We demonstrate quasi-phase-matched four-wave-mixing in silicon nanowires with sinusoidally modulated width. We observe ~11 dB conversion efficiency enhancement for targeted wavelengths >100 nm away from the edge of the 3-dB conversion bandwidth.

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1. Introduction

Four-wave-mixing (FWM) in silicon (Si) nanowire waveguides (SiNWGs), utilizing the strong, ultra-fast nonlinearity inherent to Si, serves as a promising approach to ameliorating the electrical bottleneck in modern networks by performing important data-processing operations, such as wavelength conversion (WC), in the optical domain. FWM has also been suggested as an enabling technology for mid-IR processes, including optical parametric amplifiers [1], and WC [2]. However, these applications frequently require efficient conversion over large spectral spans. The most common approach to facilitating broadband FWM is dispersion engineering *via* SiNWG geometry [3], however this places high demands on precise nanofabrication to create devices exhibiting low dispersion for predetermined wavelengths.

Here we experimentally demonstrate, for the first time to our knowledge, quasi-phase-matched (QPM) FWM in SiNWGs. QPM serves as an effective, alternative technique for extending the spectral reach of FWM, and our approach is based on SiNWG width-modulation (*w*-modulation). We demonstrate > 11 dB conversion efficiency (CE) enhancement for an idler wave generated from a signal wave > 100 nm beyond the edge of the standard 3-dB conversion BW, with an overall CE of ~ -37 dB. This enables efficient WC to be realized over >250 nm, using a dispersive SiNWG.

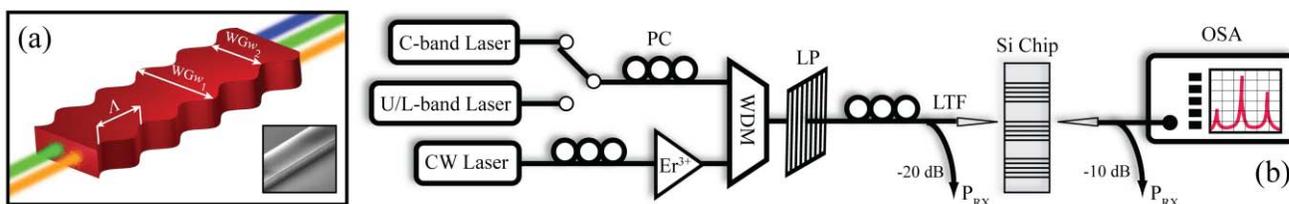


Fig. 1. (a) Schematic depicting the efficient generation of an idler wave in a *w*-modulated SiNWG from an input pump and signal wave. Inset: SEM of a typical fabricated SiNWG. (b) FWM experimental set-up: PC = polarization controller, WDM = wavelength division multiplexor, LP = linear polarizer, LTF = lensed tapered fiber, P_{RX} = power meter, OSA = optical spectrum analyzer.

2. Principle of Operation

FWM is a parametric $\chi^{(3)}$ (Kerr) process whereby photons are annihilated and created in accordance with conservation of energy and momentum [1-7]. For a given set of frequencies which satisfy conservation of energy, there will be a phase mismatch, $\Delta\beta$, in the presence of dispersion. However, it has been shown that $\Delta\beta$ can be compensated *via* QPM by using a grating, with periodicity $\Lambda = 2\pi m / \Delta\beta$ for integer m [4-7]. We form a grating *via* sinusoidal *w*-modulation, expressed as $w(z) = \Delta w \sin(2\pi z / \Lambda) + w_{DC}$, where $\Delta w = (w_1 - w_2) / 2$, $w_{DC} = (w_1 + w_2) / 2$, and $w_{1,2}$ are the max and min w , as illustrated in Fig. 1(a). To reduce backscattering, one uses a shallow grating, *i.e.*, $\Delta w \ll w_{DC}$. *w*-modulation has the effect of modulating γ and n_{eff} (and implicitly, β), which are responsible for the nonlinear and linear phase shifts, respectively. These terms affect the overall phase-shift experienced by co-propagating waves, and QPM allows the relative phase mismatch between the waves to be periodically reduced, enhancing the overall CE for a specific set of wavelengths. As an example, for a 250 nm × 600 nm ($h \times w$) SiNWG clad with SiO₂, $\Delta\beta$ for pump, signal, and idler wavelengths ($\lambda_{p,s,i}$) of 1543 nm, 1687 nm, and 1421 nm, respectively, can be compensated by a $\Lambda = 1$ mm grating.

3. Experiments and Results

We demonstrate QPM FWM by fabricating two devices. The first is a *w*-modulated 5-mm-long SiNWG with $\Delta w = 30$ nm, $w_{DC} = 600$ nm, $h = 250$ nm, and $\Lambda = 1$ mm, and the second a straight 5-mm-long 250 nm × 600 nm SiNWG for comparison.

Both devices exhibit inverse-tapers at each facet for efficient coupling, and were fabricated on an SOI substrate with a 3 μm buried-oxide-layer at the Center for Functional Nanomaterials at Brookhaven National Laboratories. The patterns were defined using e-beam lithography and reactive-ion-etching using HBr/Cl chemistry, passivated with 3 μm of PECVD oxide, and cleaved. Fiber-to-fiber insertion loss was measured to be 10.1 dB for the quasi-transverse-electric (QTE) mode at $\lambda = 1550$ nm, with an estimated 3 dB/facet and 8 dB/cm optical losses attributed to coupling and propagation loss, respectively.

The experimental setup is shown in Fig. 1(b). A continuous-wave (CW) pump is generated by amplifying the output of a laser tuned to 1543 nm using an erbium-doped fiber-amplifier. The CW probe is generated by either a laser tunable within the C-band, or within the U/L-bands. Both the pump and probe are combined in a wavelength-division-multiplexer after passing through polarization controllers (PCs). The waves are then sent through a polarizer, and subsequently launched on-chip using a lensed tapered fiber (LTF). An additional PC is employed to selectively excite the QTE mode. The power of the pump and probe before launch was measured to be 22.4 dBm and 5.0 dBm, respectively. Another LTF is used to collect the output light, which is sent to an optical-spectrum-analyzer (OSA) for analysis.

The experimental results are shown in Fig. 2. First, the straight SiNWG is characterized. A peak CE (defined as the ratio of output idler power to output signal power) of -25.5 dB is observed, with a 3-dB CE BW of ~ 70 nm. The CE decrease as the probe is detuned, and for $\lambda_s = 1676$ nm, is measured to be ~ -48 dB. However for the w -modulated device, a CE of ~ -37 dB is observed for $\lambda_s = 1676$ nm, resulting in a ~ 11 dB CE enhancement in comparison to the straight SiNWG, as shown in Fig. 2(b). The enhancement region exhibits a 3-dB BW of ~ 15 nm and centered ~ 100 nm beyond the edge of the 3-dB CE BW. Figure 2(a) shows the output spectrum as the λ_s is detuned from λ_p . As λ_s approaches 1680 nm, the power of the generated idler near 1430 nm experiences a considerable enhancement as a result of QPM, and efficient WC over > 250 nm can be achieved despite the relatively high dispersion ($D_\lambda \sim 500$ ps nm $^{-1}$ km $^{-1}$) of the SiNWG under test.

We model this QPM FWM process using a previously reported approach [7], using the experimental parameters. We find reasonable agreement between experiment and theory [Fig. 2(c)] when the sidewall angle after Si etching is taken into account, confirming that the observed CE enhancement is a result of QPM. Our modeling has also revealed that the overall CE in the enhanced region scales with the peak CE, indicating that QPM should enable the direct detection of converted data signals at wavelengths well outside the standard conversion BW for low-loss devices.

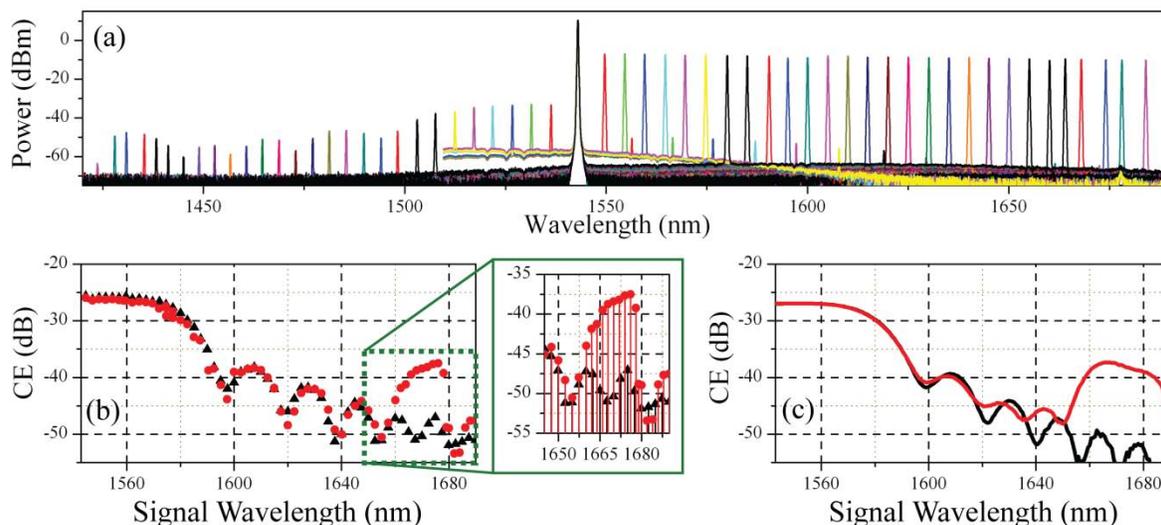


Fig. 2. (a) Measured output spectrum for the w -modulated SiNWG, for varying λ_s . OSA RB = 0.5 \AA . (b) Experimental results demonstrating a ~ 11 dB CE enhancement near $\lambda = 1.68$ μm for the w -modulated device (\bullet) compared to the straight device (\blacktriangle). (c) Modeling results, using the same parameters as in the experiment. The black curve (---) represent the straight SiNWG, and the red curve (---) represents the w -modulated SiNWG. Modeling results match well with the experimentally obtained data.

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