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Experimental Demonstration of Phase Sensitive Parametric Processes in a Nano-Engineered Silicon Waveguide

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Abstract: We demonstrate experimentally phase-sensitive processes in nano-engineered silicon waveguides for the first time. Furthermore, we highlight paths towards the optimization of the phase-sensitive extinction ratio under the impact of two-photon and free-carrier absorption.

OCIS codes: (190.4410) Nonlinear optics, parametric processes; (190.4390) Integrated optics.

1. Introduction

Silicon-on-insulator (SOI) waveguides have been successfully employed to demonstrate a wide range of optical processing functionalities exploiting parametric processes, including amplification and wavelength conversion [1], regeneration [2], as well as Tbit/s signal processing [3]. Phase-sensitive parametric processes have recently been the object of a renewed interest, resulting in the demonstration of novel signal processing applications such as phase regeneration [4]. Phase-sensitive signal processing functionalities have also been demonstrated in semiconductor optical amplifiers [5] and in periodically-poled lithium-niobate waveguides [6]. Being able to realize phase-sensitive processing in SOI waveguides would allow a wealth of new applications on this versatile platform. However, apart from a recent numerical study [7], this option has, to the best of our knowledge, not been explored so far. In this paper, we demonstrate experimentally phase-sensitive parametric processes in a nano-engineered silicon waveguide for the first time. Numerical optimization of the process towards higher peak gain and larger extinction ratio is also reported. Paths towards enhanced phase-sensitive extinction ratio under the presence of both two-photon absorption and the induced free carrier absorption are highlighted.

2. Experimental setup

The experimental setup is shown in Fig. 1. Phase coherent waves are generated from a frequency comb obtained by phase modulation of a continuous wave (CW) external cavity laser with a 40 GHz radio frequency signal. A wavelength selective switch (WSS) is then used to select the two pumps and the signal from the frequency comb and to adjust the pump-to-signal power ratio as well as to vary the signal phase. The interacting waves are in the dual-pump degenerate-idler configuration. The dual-pumps and phase-shifted signal are then amplified by an erbium-doped fiber amplifier (EDFA). A polarization beam splitter (PBS) is used in combination with polarization controllers (PCs) to align the waves to either the TE or TM mode of the waveguide. The resulting phase-sensitive gain and extinction ratio of the signal and higher-order idlers (at λ_{i1} and λ_{i2}, as defined in Fig. 1) are then measured by an optical spectrum analyzer (OSA). The nano-engineered silicon waveguide under test has a height of 300 nm, width of 650 nm and is 16.3 mm long. The waveguide is designed to have embedded taper structures on its two output ends (length 300 μm) to minimize coupling loss to tapered fibers to less than 2 dB per facet. The propagation loss of the waveguide is 5.1 dB/cm. The dispersion of the waveguide is engineered to be close to zero at 1560 nm for both the TE and TM modes. The signal wave is tuned to this wavelength with the dual pump symmetrically surrounding it. The pump-to-signal power ratio at the waveguide input was set to 10 dB with a total input power of 15 dBm injected. A distinctive phase-sensitive power curve can be clearly seen for both signal and idlers in Fig. 2. However, the signal extinction ratio is limited to about half a dB. In contrast, the extinction ratios of the higher-order idlers reach up to 9 dB. In what follows, the magnitude of this phase sensitivity will be analyzed theoretically and paths to enhance the gain and extinction ratio will be defined.

3. Simulation optimization

The phase sensitive gain and extinction ratio for such a waveguide are further estimated. An extended simulation is carried out using the experimental waveguide parameters. Wave propagation in the silicon waveguide is simulated by numerically solving the nonlinear Schrödinger equation using the split-step Fourier method. The numerical model includes terms for both two-photon absorption (TPA) and free-carrier absorption (FCA) [8].

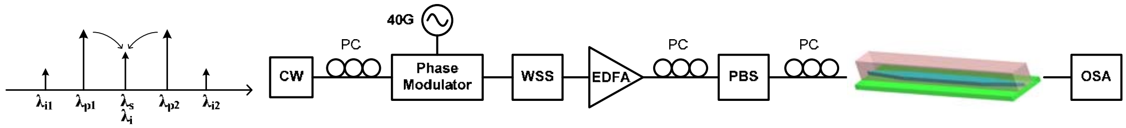

Figure 1 – Experimental setup for measuring the phase sensitive processes in a nano-engineered silicon waveguide.

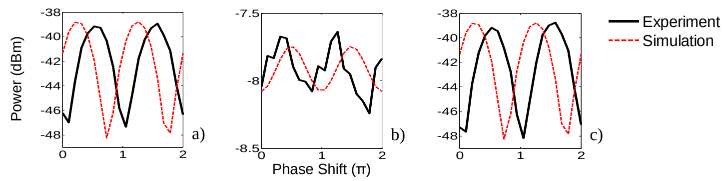

Figure 2 – Experimentally measured phase sensitive curves of a) idler at the shorter wavelength λ_{i1}, b) signal, and c) idler at the longer wavelength λ_{i2}, matched to numerical simulation, with agreement in peak gain level and extinction ratio.

The effective area is 0.16 μm^2 and the nonlinear parameter γ is estimated to be 152 $W^{-1}\cdot m^{-1}$. The phase sensitive extinction of the idlers is calculated to approximately 9.5 dB, and the signal extinction ratio is found around 0.5 dB, in good agreement with the experiment, as shown in Fig. 2. The signal extinction ratio needs to be further enhanced to make it possible to utilize such Si-based phase sensitive processes for desired applications such as amplitude and phase regeneration. Simulation optimization results in three cases are shown in Fig. 3: 1) with the numerical model including both two-photon and free-carrier absorption, modeled using two different carrier lifetimes; 2) with the two-photon absorption effect only, without free-carrier absorption term; and 3) an ideal case without either types of nonlinear absorption. Fig. 3 shows that, when the carriers generated by TPA have a long lifetime (10 ns), the signal extinction ratio saturates at high pump power levels. Due to free-carrier absorption, the signal gain drops drastically with increasing pump power. Using a reduced carrier lifetime equal to 1 ns, the saturation in signal extinction ratio and the drop in gain are relaxed. In this case, a 5 dB higher extinction can be achieved by using 33 dBm total pump power. Another 3 dB improvement in signal extinction ratio can be obtained by reducing the waveguide propagation loss down to a realistic state-of-the-art value of 1 dB/cm from the current 5.1 dB/cm. Considering the case with TPA and without FCA, the signal extinction for this specific waveguide is predicted to be up to 30 dB at 33 dBm total pump power. With the current waveguide length, this value is even ~10 dB higher than in the case where neither two-photon nor free-carrier absorption occur. The origin behind this behavior stems from the existence of different optimum waveguide lengths with and without carrier effects, as can be seen from the inset in Fig. 3a), where the signal extinction ratio is plotted as a function of waveguide length, with a total pump power equal to 33 dBm. In the ideal case without either types of nonlinear absorption, a maximum extinction ratio is obtained in a periodic manner.

4. Conclusion

Phase sensitive parametric processes are experimentally measured in a nano-engineered silicon waveguide, and numerically matched. A numerical optimization predicts room for improvement in achieving larger signal phase sensitive extinction ratio for potential applications such as chip-based signal phase and amplitude regeneration. The design of waveguides with reduced propagation loss and reduced carrier lifetime is desired to enable the predicted performance and relevant nonlinear processing functionalities.

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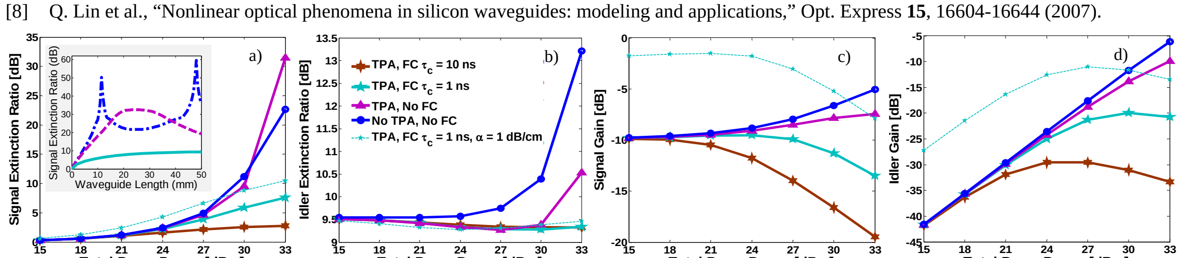

Figure 3 - Phase sensitive gain and extinction ratio optimization of the signal and idlers. Dashed-thin lines correspond to cases when the waveguide propagation loss is reduced from 5.1 dB/cm to 1 dB/cm. Inset in a): solid-line: TPA and FC lifetime 1 ns; dashed-line: TPA only; dotted-dashed: without TPA and FC. Total pump power is 33 dBm.