All-Optical Wavelength Conversion Using Cross-Phase Modulation at 42.7 Gbit/s in Silicon-Organic Hybrid (SOH) Waveguides

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Abstract: Error-free wavelength conversion using cross-phase modulation (XPM) is shown in a passive 4 mm long silicon-organic hybrid waveguide. This is the first XPM demonstration in a CMOS compatible chip for bitrates of 42.7 Gbit/s at communication wavelengths.

Keywords: Optical communication, Silicon on insulator technology, Nonlinear optics, Optical Kerr effect, Organic material

1. Introduction

Highly nonlinear waveguides are key components for on-chip integration of all-optical signal processing. Among the nonlinear effects, cross-phase modulation (XPM) is of great importance. It enables switching operation with virtually unlimited speed across a large spectral range, because there is no phase-matching restriction for XPM such as with four-wave mixing (FWM). So far, XPM in silicon has only been studied at low repetition rates, using pump-probe measurements that clearly show speed limitations imposed by two-photon absorption and free carrier effects [1-3]. Very recently, NRZ-OOK to RZ-OOK conversion using XPM at 10 Gbit/s has been demonstrated in a pure silicon waveguide [4]. Silicon waveguides with hybridly integrated nonlinear organic cladding materials offer a way to overcome these speed limitations [5].

In this paper we report for the first time error-free all-optical wavelength conversion at 42.7 Gbit/s based on XPM, using a 4 mm long highly $\chi^{(3)}$-nonlinear silicon-organic hybrid (SOH) slot waveguide for cross-phase modulation, and a tuneable one-bit delay interferometer (DI) for phase-to-amplitude conversion. The measured bit error rate (BER) of BER = $2 \cdot 10^{-10}$ demonstrates error-free operation.

2. Sample structure

The highly nonlinear SOH slot waveguides are based on silicon-on-insulator technology in a 193 nm process [6]. On a buried oxide buffer a 160 nm wide slot waveguide is formed by two silicon ribs of height 220 nm and width 220 nm. The slot is filled and the waveguides are covered with molecular beam deposited DDMEBT, an off-resonant Kerr-type nonlinear organic cladding with a refractive index of n = 1.8 [7, 8].

In a slot-geometry, the nonlinearity of the cladding material is further enhanced [9] up to a record value of $\gamma = 10^5\ \mathrm{W}^{-1}\mathrm{km}^{-1}$ [5] while losses due to two-photon absorption and free-carrier absorption can be avoided [10]. Waveguide facets are cleaved but no anti-reflection coating has been applied, leading to a coupling loss of 6.2 dB per facet. The linear propagation loss is 1.55 dB/mm. For a device of 4 mm length this amounts to a total fiber-to-fiber loss of 18.6 dB. The device is kept at 25°C to stabilize coupling.

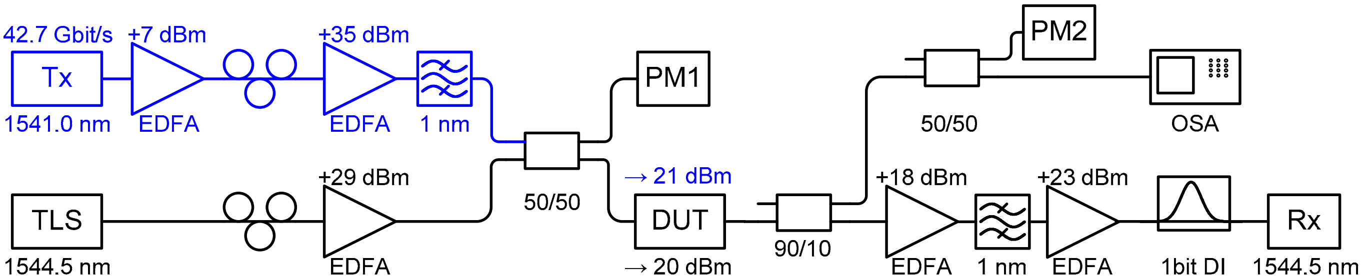

Figure 1 : A pseudo-random bit sequence (PRBS) of 42.7 Gbit/s 33 % RZ pulses is highly amplified, combined with a strong cw wave, and the composite signal is launched into the device under test (DUT) using lensed fibers. The phase of the cw wave is modulated via the intensity of the data stream by means of the $\chi^{(3)}$-nonlinearity of the waveguide. A one-bit delay interferometer (DI) is used for phase-to-amplitude conversion. The signal is detected by a receiver using a pre-amplifier, and the bit error rate is measured. EDFA: Er-doped fiber amplifier, PMx: power meter, OSA: optical spectrum analyzer.

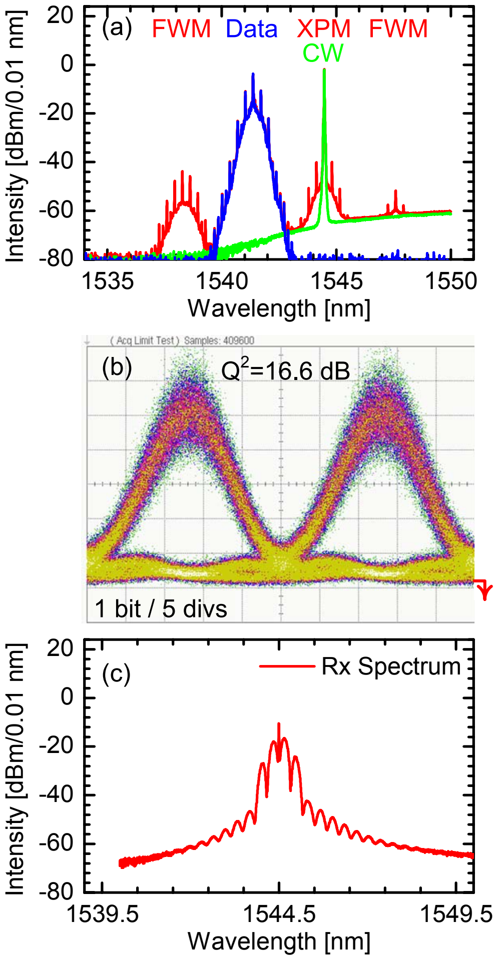

Figure 2 : Result of wavelength conversion experiment using cross-phase modulation (XPM). (a) Signal spectrum at the output of the nonlinear SOH waveguide. When data (blue) and cw (green) are launched together, the total spectrum (red) clearly shows the XPM signal as well as up and down-converted FWM signals. (b) Received eye diagram in the pre-amplifier receiver (Rx) at the destructive port of the delay interferometer. The eye has a good quality factor of Q^2 = 16.6 dB and a bit error rate of BER = $2{\cdot}10^{-10}$. (c) Receiver spectrum showing the strongly suppressed carrier and the expected alternate mark inversion signal spectrum.

3. Cross-phase modulation experiment

The experimental setup is shown in Figure 1. A pseudo-random bit sequence (PRBS) of 42.7 Gbit/s 33% RZ pulses are highly amplified and band-pass filtered to suppress the out-of-band amplifier noise. Using a 3 dB coupler and short lensed fibers, the data stream is combined with a strong cw laser, and then launched into the nonlinear SOH waveguide. On-chip power levels for data and cw are 21 dBm and 20 dBm, respectively. The phase of the cw wave is modulated via the intensity of the data stream by means of the $\chi^{(3)}$-nonlinearity of the waveguide. After amplification, the cross-phase modulated cw wave is band-pass filtered, amplified and launched into a tuneable one-bit delay interferometer (DI) for phase-to-amplitude conversion. A pre-amplifier receiver is used to detect the signal in an optical bandwidth of 50 GHz or 70 GHz using a digital communications analyzer or a bit error tester, respectively.

Figure 2(a) shows the spectrum of the data, the cw, and the total signal at the output of the nonlinear waveguide. The XPM spectrum and the up and down-converted FWM spectra (plotted in red) are clearly visible.

Figure 2(b) shows the eye diagram in the pre-amplifier receiver connected to the destructive port of the delay interferometer. The eye has a good quality factor of Q^2 = 16.6 dB and a bit error rate of BER = $2{\cdot}10^{-10}$. No dependence on PRBS length $2^7 - 1$ to $2^{31} - 1$ has been observed. Figure 2(c) shows the received optical spectrum that has a strongly suppressed carrier and the expected shape of an alternate mark inversion signal.

4. Conclusions

Error-free operation and a wide eye opening demonstrate the absence of strong patterning effects. This proves the suitability of silicon-organic hybrid waveguides for XPM-based all-optical switching applications.

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6. References

[1] O. Boyraz *et al.*, "All optical switching via XPM in silicon waveguides," in *Lasers and Electro-Optics Society, 2004. LEOS 2004. The 17th Annual Meeting of the IEEE*, 2004, pp. 973-974 Vol.2.

[2] I.-W. Hsieh *et al.*, "Cross-phase modulation-induced spectral and temporal effects on co-propagating femtosecond pulses in silicon photonic wires," *Opt. Express,* vol. 15, pp. 1135--1146, 2007.

[3] R. Dekker *et al.*, "Ultrafast Kerr-induced all-optical wavelength conversion in silicon waveguides using 1.55µm femtosecond pulses," *Opt. Express,* vol. 14, pp. 8336-8346, 2006.

[4] W. Astar *et al.*, "Conversion of 10 Gb/s NRZ-OOK to RZ-OOK utilizing XPM in a Si nanowire," *Opt. Express,* vol. 17, pp. 12987--12999, 2009.

[5] C. Koos *et al.*, "All-optical high-speed signal processing with silicon-organic hybrid slot waveguides," *Nat. Photon.,* vol. 3, pp. 216-219, 2009.

[6] W. Bogaerts *et al.*, "Nanophotonic waveguides in silicon-on-insulator fabricated with CMOS technology," *J. Lightwave Technol.,* vol. 23, pp. 401-412, 2005.

[7] T. Michinobu *et al.*, "A new class of organic donor-acceptor molecules with large third-order optical nonlinearities," in *Chem. Commun.*, 2005, pp. 737-739.

[8] B. Esembeson *et al.*, "A high optical quality supramolecular assembly for third- order integrated nonlinear optics," *Adv. Mater.,* vol. 20, pp. 4584-4587, 2008.

[9] T. Baehr-Jones *et al.*, "Optical modulation and detection in slotted Silicon waveguides," *Opt. Express,* vol. 13, pp. 5216-5226, 2005.

[10] T. Vallaitis *et al.*, "Highly nonlinear silicon photonics slot waveguides without free carrier absorption related apeed-limitations," in *Proc. European Conference on Optical Communications*, ECOC 2008, Paper Th.2.D.6.