All-Optical Wavelength Conversion of 56 Gbit/s NRZ-DQPSK Signals in Silicon-Organic Hybrid Strip Waveguides

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Abstract: All-optical wavelength conversion of 56 Gbit/s NRZ-DQPSK based on four-wave mixing is demonstrated in a silicon-organic hybrid strip waveguide operated in TM mode.

OCIS codes: (130.7405) Wavelength conversion devices; (190.2620) Harmonic generation and mixing;

1. Introduction

Highly nonlinear waveguides are key components for on-chip integration of all-optical signal processing. Waveguides with ultrafast Kerr nonlinearity enable switching operation and wavelength conversion with virtually unlimited speed. Among the nonlinear effects found in waveguides, four-wave mixing (FWM) is special as it preserves the phase information and allows format-transparent operation [1-3].

However, all pure silicon implementations to date suffer from two-photon absorption (TPA) and free-carrier absorption (FCA) effects which limit the speed for all-optical signal processing [4]. Silicon waveguides with hybridly integrated nonlinear organic cladding materials overcome these speed limitations [5]. Wavelength conversion at 40 Gbit/s has been demonstrated using FWM [6, 7] and recently also using cross-phase modulation (XPM) [8]. For the silicon-organic hybrid (SOH) waveguide technology no fundamental speed limitation has been found, possibly allowing to scale bitrates up to 170 Gbit/s and beyond [9]. Of the basic silicon-organic waveguide geometries [10], strip waveguides operated in TM mode are of particular interest, as they effectively exploit the cladding nonlinearity with nonlinearity parameters of $\gamma = 110\,000\ (\mathrm{W\ km})^{-1}$, and are easy to fabricate [11].

In this paper, we demonstrate for the first time all-optical high-speed wavelength conversion of a phase-encoded signal based on four-wave mixing in a 4 mm long silicon-organic hybrid strip waveguide operated in TM mode. The bitrate of 56 Gbit/s this is the fastest wavelength conversion reported for silicon waveguides, limited only by the available measurement equipment. Compared to previous results reported for waveguides with slot nonlinearity, strip waveguides operated in TM mode exploit the nonlinearity of the cladding material and have the advantage of a greatly reduced complexity in fabrication. Silicon-organic hybrid waveguides provide CMOS compatible nonlinearities for all-optical signal processing at highest bit rates.

2. Sample Structure

The highly nonlinear silicon-organic hybrid slot waveguides are based on silicon-on-insulator (SOI) technology in a 193 nm process offered by ePIXfab [12]. On a buried oxide buffer silicon strip waveguides are formed with a height of 220 nm and width 400 nm. The waveguides are covered with molecular beam deposited DDMEBT (2-[4-(dimethylamino)phenyl]-3-{[4-(dimethylamino)phenyl]ethynyl}buta-1,3-diene-1,1,4,4-tetracarbonitrile), an off-resonant Kerr-type nonlinear organic cladding with a refractive index of $n = 1.8$ [13]. Waveguide facets are as cleaved and no anti-reflection coating is applied, leading to a coupling loss of 8 dB per facet. The linear propagation loss is 1.0 dB/mm. For a device of 4 mm length this amounts to a total fiber-to-fiber loss of 20 dB.

Fig. 1(a) shows the simulated field distribution of the fundamental quasi-TM mode of the investigated structure. Because of the field enhancement at the interface between the silicon strip and the organic cladding material, the light is concentrated in the nonlinear cladding material.

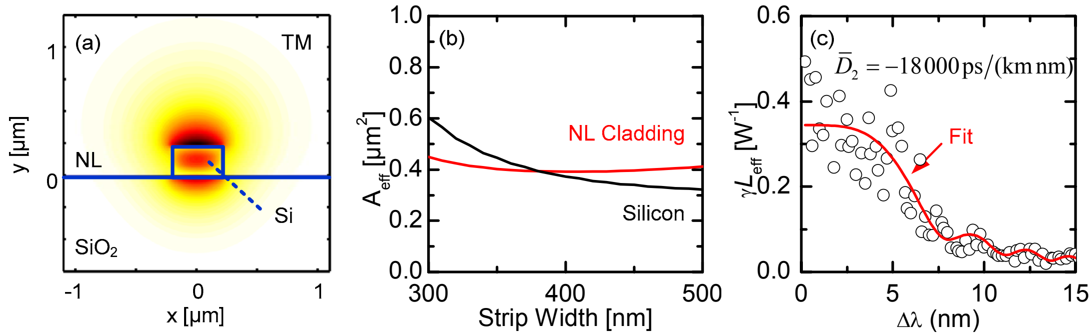

Fig. 1 Silicon-organic hybrid waveguide with cladding nonlinearity. (a) Operated in TM mode, the light is concentrated in the nonlinear cladding material. (b) Effective areas for third order nonlinearities. The contribution of the nonlinear cladding material improves the characteristic figure-of-merit to a value of $FOM_{TPA} = 1.2$ [11]. (c) Dependence of the FWM efficiency on wavelength detuning $\Delta\lambda$, measurement (○) and fit (——).

Fig. 1(b) shows the dependence of silicon and cladding effective areas for third order processes as a function of the strip width. Over a large range of values, both silicon and cladding contribute to the total waveguide nonlinearity, increasing the characteristic two-photon absorption figure of merit to a value of $FOM_{TPA} = 1.2$ [11], which is sufficient for all-optical signal processing [14]. Fig. 1(c) shows the dependence of the four-wave mixing (FWM) efficiency on the wavelength detuning $\Delta\lambda$, measurement (○) and fit (——). Although the dispersion in such strongly confined waveguides can reach high values of $D = -18\ 000$ ps/(km nm), the short device length still enables efficient wavelength conversion up to a detuning of $\Delta\lambda = 5$ nm between pump and signal [11].

3. Wavelength conversion of 28 GBd NRZ-DQPSK signals

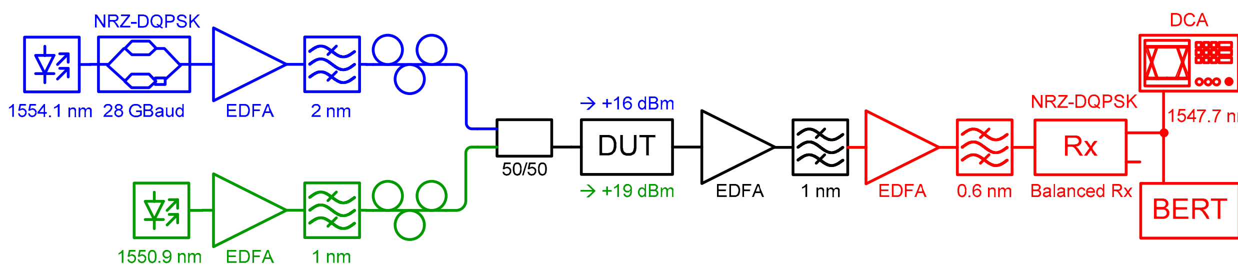

Fig. 2 Experimental setup of the wavelength conversion experiment. Data encoded at 28 GBd NRZ-DQPSK are amplified, bandpass filtered, combined with a strong CW pump, and launched into the device under test (DUT) using polarization-maintaining lensed fibers. The four-wave mixing signal is amplified, bandpass filtered and demodulated in a balanced receiver. The eye opening is monitored with a digital communications analyzer (DCA). The received signal is analyzed using a bit error rate tester (BERT).

Degenerate four-wave mixing is a parametric process frequently exploited for format-transparent wavelength conversion. Fig. 2 shows the setup of the wavelength conversion experiment. A pseudorandom data stream is encoded at 1554.1 nm using the 28 GBd NRZ-DQPSK format, amplified and band-pass filtered in order to suppress the out-of-band spontaneous emission noise. The signal is combined with a strong CW pump, and launched into the device under test (DUT) in quasi-TM (dominant electric field component parallel to the growth direction) using polarization-maintaining lensed fibers. The on-chip power levels are +19 dBm for the pump and +16 dBm for the signal, respectively. The temperature of the device is controlled to 25°C in order to stabilize the fiber-to-chip coupling. The four-wave mixing signal is amplified, band-pass filtered and demodulated in a DQPSK receiver, consisting of delay interferometers and balanced detectors. The eye opening is monitored with a digital communications analyzer (DCA). The received signal is analyzed using a bit error rate tester (BERT).

In NRZ-DQPSK the information is differentially encoded, using phase shifts of $\{0, \pi/2, \pi, -\pi/2\}$ [15]. While NRZ-DQPSK ideally is a constant-envelope signal, for most practical implementations some state transitions in the constellation diagram cause residual amplitude modulation. Compared to 33% RZ OOK signals of the same average power, the peak power of NRZ-DQPSK is reduced by 8 dB. However, patterning effects are significantly suppressed, as no long sequences of marks and spaces are possible. In the absence of patterning effects, TPA and FCA only act as additional loss mechanisms and limit the achievable conversion efficiency.

The measurement results for the wavelength-converted signal are shown in Fig. 3. The optical spectrum at the output of the nonlinear waveguide shown in Fig. 3(a) shows the up-converted and down-converted FWM products.

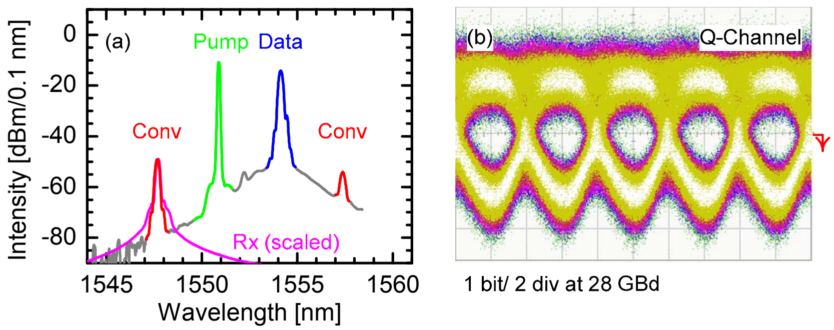

Fig. 3 (a) Optical spectra of the four-wave mixing (FWM) experiment, measured at the output of the nonlinear waveguide and in the receiver (Rx, scaled) after both band-pass filters. No crosstalk is observed. (b) Eye diagram of the Q-component of the four-wave mixing signal at 1547.7 nm, corresponding to a bit error rate of BER = 10^{-5}. The signal quality is limited only by the OSNR degradations due to amplifier noise.

The FWM product at 1547.7 nm is selected for detection in the receiver. No crosstalk is observed. Fig. 3(b) shows the demodulated data of the Q-channel corresponding to a bit error probability of 10^{-5} measured for a pattern length of 2^7-1, showing no distortions from patterning effects. No influence of the pattern length on the performance is found up to 2^{31}-1. Compared to back-to-back measurements, the signal quality is only limited by OSNR degradations due to amplifier noise. This limitation could be easily overcome by reducing the coupling loss or by increasing the input power to the nonlinear waveguide.

4. Summary

All-optical wavelength conversion of a 56 Gbit/s NRZ-DQPSK signal based on four-wave mixing in a 4 mm long silicon-organic hybrid (SOH) strip waveguide is demonstrated. The device is operated in TM mode and exploits the nonlinearity of the organic cladding material. Compared to previous results reported for waveguides with slot nonlinearity, strip waveguides operated in TM mode provide high nonlinearity at a greatly reduced complexity in fabrication. By reducing the coupling loss, error free operation will become possible. This allows scaling nonlinear applications to highest bit rates.

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