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Phase-sensitive optical processing in silicon waveguides

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Abstract: Parametric optical signal processing is reviewed for silicon nano-rib-waveguides with a reverse-biased pin-junction. Phase-sensitive parametric amplification with a phase-sensitive extinction of more than 20 dB has been utilized for the regeneration of DPSK signals.
OCIS codes: (130.3120) Integrated optics devices; (190.4360) Nonlinear optics devices; (190.4975) Parametric processes; (230.7405) Wavelength conversion devices

1. Introduction

The use of parametric processes using the 3rd order optical nonlinearity in optical materials for applications such as low noise amplification, wavelength conversion, signal regeneration and other kinds of optical signal processing has raised considerable interest over the last years [1-3]. In particular, parametric processes also allow for phase-sensitive optical amplification, which may be utilized for signal regeneration [4], even for higher order modulation formats [5]. Most experiments have so far been conducted using highly nonlinear silica fibers (HNLFs), which require a length of typically several hundred meters due to the relatively low optical nonlinearity in silica.

In order to achieve compact modules, 3rd order nonlinearities may also be utilized in photonic integrated circuits (PICs). For this purpose, PICs have been either based on glasses or semiconductor materials. With respect to PICs based on glass materials, nonlinear parametric processing has been demonstrated, e.g. for silicon nitride, Hydex [6] or chalcogenide glasses [7]. Even though the nonlinearities in these waveguides are about two orders of magnitude higher than in silica-HNLFs, they usually still require pump powers in excess of several Watts because of the relatively short interaction lengths in PICs. Nevertheless, it has been possible to achieve a phase-sensitive extinction ratio of around 10 dB in a dual-pump degenerate-idler configuration with planar chalcogenide glass waveguides [8] in pulsed operation.

Much higher nonlinearities are feasible in PICs based on semiconductor materials, where silicon is of particular interest [9]. It combines the advantage of a relatively high 3rd order nonlinearity with the realization of nanowires with tiny effective cross sections down to about 0.1 μm^2 exhibiting nonlinear phase shifts of around 200…300 rad/(W·m), which is about 4 orders of magnitude higher than in silica HNLFs. Even higher effective nonlinearities are possible for photonic crystal Si-nano-waveguides thanks to slow light enhancement, where, for a phase-sensitive amplifier in pulsed operation, a phase-sensitive extinction ratio of 11 dB has been achieved [10].

However, silicon suffers from two-photon-absorption (TPA) and the associated generation of carriers leading to free-carrier absorption (FCA). TPA can be reduced using amorphous instead of crystalline silicon [11] or silicon-slot waveguides employing polymers on a silicon-organic platform [12]. However, both concepts suffer from relatively high linear losses and a limited compatibility with CMOS or BiCMOS micro-electronics. TPA can also be omitted by operating the devices at longer infrared wavelengths [13,14]. The influence of FCA can be reduced for operation with pulsed pump sources, which is, however, not adequate for telecom applications. Alternatively, FCA in crystalline silicon nano-waveguides can be considerably reduced by reducing the effective carrier lifetime down to about 10-20 ps via a reverse biased pin-junction [15-17].

In this paper, we review our recent achievements on the design and fabrication of silicon nanowires using reverse-biased pin junctions and their applications for phase-sensitive all-optical signal processing at telecom wavelengths using cw-pump sources.

2. Silicon nano-waveguide design

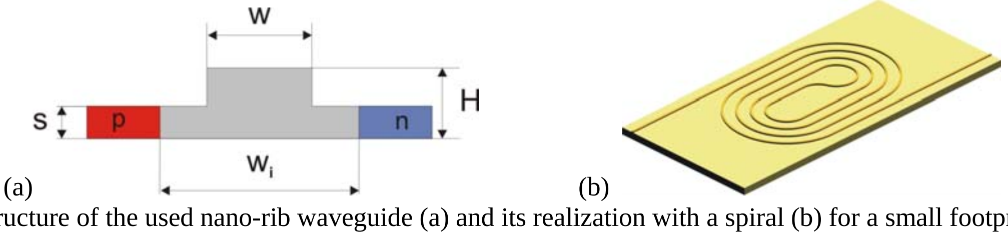

Fig. 1. Structure of the used nano-rib waveguide (a) and its realization with a spiral (b) for a small footprint.

In order to combine Si-nano-waveguides with a pin-junction, nano rib-waveguides have been fabricated according to Fig. 1 on 2 µm thick buried oxide with W=500 nm, H=210 nm, s=50 nm and w_i=1200 nm within the BiCMOS foundry of IHP using a 248 nm lithography with a linear loss of about 1 dB/cm [18]. The waveguide is realized in form of a spiral yielding a small footprint of only 2.5 × 0.6 mm^2 for a waveguide with a length of 4 cm.

3. Wavelength conversion with four-wave mixing

Si rib waveguides with a reverse biased pin-junction allow for very efficient wavelength conversion via four-wave mixing [15,18,19]. As shown in Fig. 2, a record cw conversion efficiency (defined as the ratio between idler and signal power at the waveguide output) of -1 dB has been achieved (best value of -0.7 dB) [18].

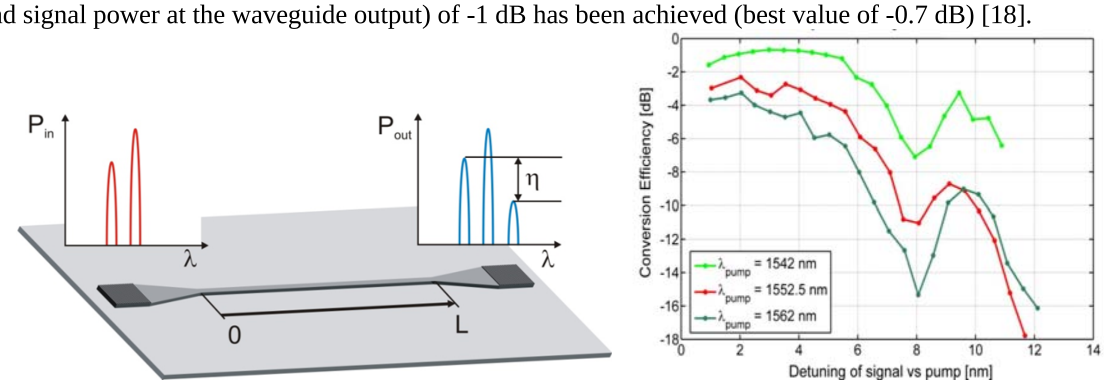

Fig. 2. Schematic of wavelength conversion within a Si-nano-waveguide with grating input/output-couplers and measurement results (length of the waveguide L=4cm, loss per grating coupler ~ 4.5 dB, cw-pump power before the grating 26 dBm, reverse bias voltage 20 V) [18].

This high conversion efficiency was achieved for just 26 dBm of external cw-pump power, corresponding to a pump power inside the waveguide of only about 150 mW. The conversion bandwidth is limited by the relatively high amount of chromatic dispersion, which we estimate to about -2.5 ps/(m·nm) for our specific waveguide [20,21].

These results underline the high efficiency of four-wave mixing processes in Si nano-waveguides, which have also been exploited for error-free wavelength conversion of 40 Gbit/s on-off keying (OOK) modulated signals [21].

4. Phase-sensitive optical signal processing

Based on the high efficiency of four-wave mixing processes in silicon waveguides, it is also very attractive to study phase-sensitive parametric processing in these waveguides with the purpose of signal regeneration of phase modulated signals. We did investigate both phase-sensitive parametric gain as well as the regeneration of 10 Gbit/s differential phase-shift keying (DPSK) signals [22, 23] with a set-up as shown in Fig.3.

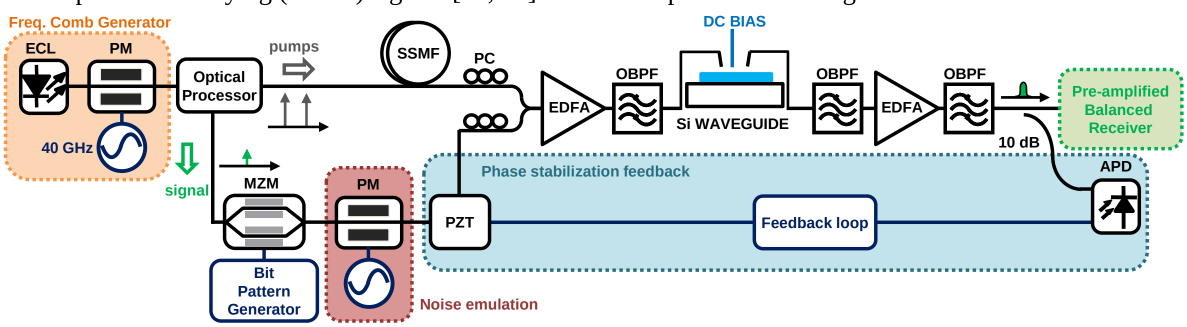

Fig. 3 Experimental set-up for the dynamic phase regeneration of a 10 Gbit/s DPSK-signal [23].

A frequency comb is being synthesized with a phase-modulator (PM) with a 40 GHz sinusoidal drive signal. The optical processor selects three neighboring comb lines. The two outer comb lines act as phase synchronized pumps and the central line serves as the signal. Fig. 4a shows the measured signal power at the output of the waveguide as a function of the signal phase. For a total cw-pump power P_T of 24 dBm before the grating (corresponding to ~50 mW per pump inside the waveguide) and a reverse bias of 20 V, one obtains a phase-sensitive extinction ratio of 11 dB, which can be improved by increasing the pump power to P_T=28 dBm (~110 mW per pump inside the waveguide) and by increasing the reverse bias voltage to 25 V (for reducing the effective carrier lifetime) to a record extinction ratio up to 20 dB [23]. This phase-sensitive gain has been used for the regeneration of 10 Gbit/s DPSK signals. As shown in Fig. 3, the DPSK signal is first generated with a Mach-Zehnder modulator (MZM) and is subsequently distorted by a harmonically driven (f=5 GHz) phase modulator. Excellent regeneration results have been obtained for a cw-pump power of 24 dBm and a reverse bias voltage of 25 V, as shown in Fig. 4b.

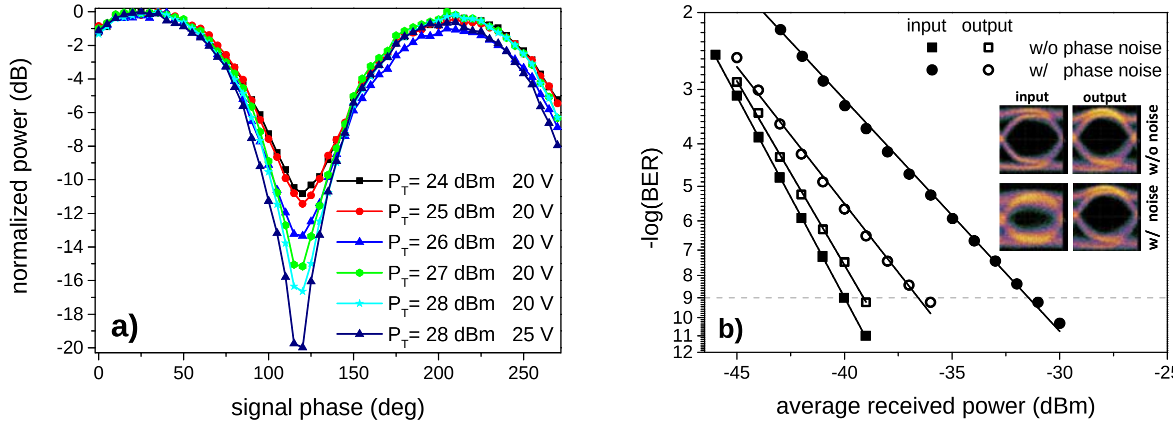

Fig. 4. Phase-sensitive output power (a) and BER curves for a regenerated 10 Gbit/s DPSK signal (b) [23]

5. Conclusion

Nano-rib-waveguides with a reverse biased pin-junction are very suitable for advanced parametric signal processing with relatively low cw-pump powers in the order of 100 mW despite the existence of TPA in silicon at telecommunications wavelengths. Further improvement is expected by suitably tailoring the chromatic dispersion and further reducing the linear losses in the nano-rib-waveguides.

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