A Broadband 1850-nm 40-Gb/s Receiver Based on Four-Wave Mixing in Silicon Waveguides

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Abstract: We experimentally demonstrate a FWM-based receiver operating at long wavelengths. The scheme successfully demultiplexes a 1866-nm 40-Gb/s NRZ signal into 10-Gb/s tributaries while simultaneously wavelength-converting it to 1320 nm for photodetection.
OCIS codes: (130.7405) Wavelength conversion devices; (190.4380) Nonlinear optics, four-wave mixing.

1. Introduction

The increasing bandwidth demands from telecom and metro-area optical networks necessitate the introduction of new technologies to provide higher bandwidth links. While newly introduced techniques allow for improved spectral efficiency [1,2], communication bandwidth may also potentially be increased by expanding the communication bands beyond the 100 nm of spectrum currently utilized for telecom around 1550 nm. The notion of extending the operational wavelength bands is further supported by the emergence of Raman, semiconductor, rare-earth doped fiber, and parametric amplifiers [3-4] which can provide gain at broad regions outside the C- and L-bands. However, devices operating outside the standard bands typically have lower performance compared to their telecom counterparts. In particular, commercially available photodetectors operating at wavelengths longer than 1700 nm do not exceed a 10 GHz bandwidth and exhibit much lower sensitivities than equivalent telecom components. All-optical processing can assist in overcoming receiver bandwidth limitations in such wavelength domains by utilizing optical sampling as well as converting signals to wavelengths more favorable for detection.

Dispersion engineered silicon nanowaveguides developed in recent years have been shown to enable exceedingly broad four-wave mixing (FWM) with greater than 800 nm of continuous 3-dB bandwidth [5]. Furthermore, such nanowaveguides also support processing of Tbaud/sec symbol rates [6] due to the minimal walk off between the mixed signals in the short interaction length (< 2 cm). As such, these FWM devices are uniquely suitable for extremely broad wavelength converters for high bit-rate signals where wavelength-agnostic performance is required.

In this manuscript we report a first demonstration of such an operational concept where a silicon nanowaveguide is used to wavelength convert as well as down-sample a 40-Gb/s data signal for detection on an InGaAs photodetector. We show equal-performance error-free reception of all four 10-Gb/s tributaries (defined as bit-error rate lower than 10^{-12}) and also utilize the optical sampling to reconstruct an eye-diagram of the 1866-nm signal.

2. Device and Experimental Setup

The nanowaveguide used in this experiment (Fig. 1.b) was fabricated at the Cornell Nanofabrication Facility using e-beam lithography followed by reactive ion etching. The oxide-clad nanowaveguide is 1.1 cm long with a 300-nm by 710-nm cross section and is surrounded by a 30-nm thick slab. The device has a linear insertion loss of 7.8 dB (for a 1550-nm signal) and ~1 dB of additional nonlinear loss when a 17-dBm optical pump is present.

The experimental setup (Fig. 1.a) includes an external cavity laser (ECL) which generates continuous wave (CW) light at 1866 nm. A LiNbO3 Mach-Zehnder modulator (MZM) imprints a 40-Gb/s 2^{15}-1 pseudo-random bit

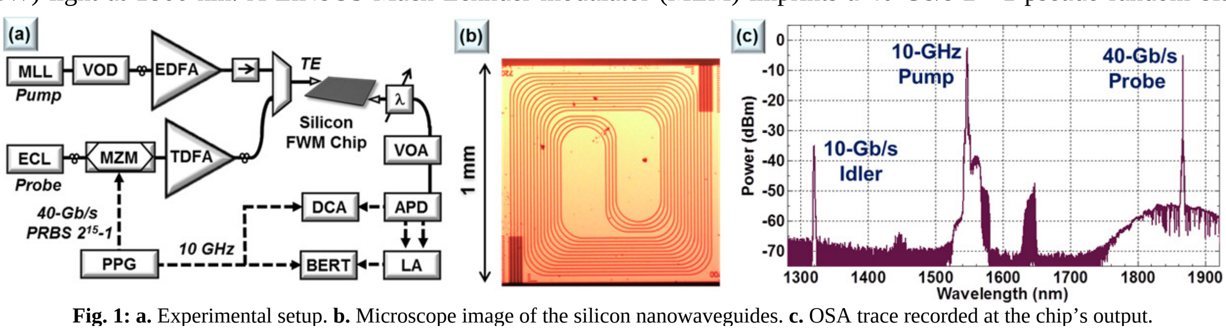

Fig. 1: a. Experimental setup. **b.** Microscope image of the silicon nanowaveguides. **c.** OSA trace recorded at the chip's output.

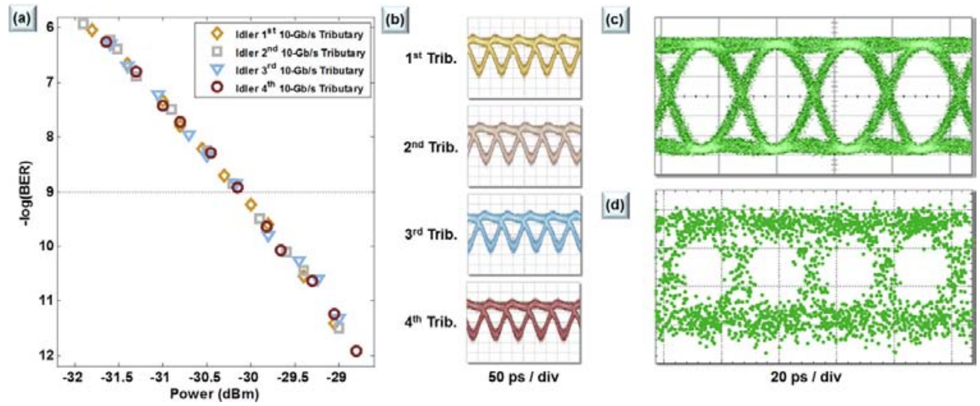

Fig. 2: a. BER measurements of the 10-Gb/s tributaries. **b.** Idler eye diagrams recorded at the inverted-data differential output port of the APD. **c.** 40-Gb/s Electrical eye diagram recorded directly from the PPG. **d.** 40-Gb/s eye diagram reconstructed from the optical sampling process by sweeping the pump pulse timing (recorded at the APD's output).

sequence NRZ pattern on the CW light. The signal is then amplified by a Thulium-doped fiber amplifier (TDFA) and combined with the pump. The 1546-nm 17.3-dBm pump is comprised of a 10-GHz pulse train with 1.5-ps wide pulses generated by a mode-locked laser which is passed through a variable optical delay (VOD) and amplified by an Erbium-doped fiber amplifier (EDFA). The combined signals are launched into the nanowaveguide in quasi-TE polarization using tapered fibers. The nanowaveguide's output is inspected on an optical spectrum analyzer (OSA) and is then sent to a band filter in order to recover the idler. The idler signal passes through a variable optical attenuator (VOA) before it is received on an InGaAs avalanche photodiode (APD). The APD's output is sent either to a digital communications analyzer (DCA) or to a limiting amplifier (LA) followed by a bit-error-rate tester (BERT). The MLL, DCA, and BERT are triggered by a 10-GHz distributed electrical clock generated by the PPG.

3. Results

The FWM process results in the creation of a 1320-nm data-carrying idler (Fig. 1.b) with a -30.5 dB conversion efficiency (ratio of output idler average power to input probe average power). The use of a 10-GHz pulsed pump serves to both improve the conversion efficiency (compared to a CW pump) as well as demultiplex the 40-Gb/s into its 10-Gb/s tributaries. The 10-Gb/s tributaries at this stage can be received on a 10-GHz APD which allows inspection of eye diagrams (Fig. 2.b) and BER-based data-integrity verification (Fig. 2.a). As expected, all 10-Gb/s tributaries are received error-free with equal sensitivity. By temporally sweeping the pump pulses across the fixed probe signal we are able to reconstruct the probe eye-diagram from recorded DCA traces of the idler. The reconstructed eye-diagram (Fig. 2.d) shows an open 40-Gb/s eye comparable to the recorded electrical eye recorded directly from the PPG's output (Fig. 2.c).

4. Conclusions

We have experimentally demonstrated a FWM-based high-bandwidth (> 40GHz) receiver capable of receiving signals at wavelengths at which standard high-bandwidth receivers are not available. Additionally, we leverage the FWM process to temporally demultiplex the 40-Gb/s signal into its 10-Gb/s tributaries and show the process allows error free reception of all tributaries with equal performance across the tributaries.

As silicon nanowaveguides have been shown to allow a continuous conversion-efficiency bandwidth greater than 815 nm [5], this receiver configuration should be capable of receiving high-speed signals in wavelengths ranging from the C-band up to 2050 nm with performance independent of the signal wavelength. Furthermore, such a receiver does not require any knowledge regarding the signal wavelength.

This work was supported by DARPA MTO under the CIPhER program, grant number HR0011-10-10080.

5. References

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