Continuously Tunable Wavelength Conversion of Data with Record Probe-Idler Separations in a Silicon Nanowire

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Abstract: We demonstrate tunable wavelength conversion of 10-Gb/s data with up to 168-nm probe-idler separation based on four-wave mixing in silicon nanowires. We incorporate an NRZ-to-RZ format change using a pulsed pump and achieve error-free operation.

OCIS codes: (130.7405) Wavelength conversion devices; (190.4380) Nonlinear optics, four-wave mixing.

1. Introduction

The growing demands for optical communication bandwidth are driving optical communication technologies toward increased wavelength channel density, spectrally-efficient modulation formats, higher symbol rates, as well as increased-density spatial parallelism. In addition to these emerging methods, one can also leverage the bandwidth available beyond the currently utilized C and L ITU bands. To enable operation outside of these well-developed bands, gain elements have to become available with either different gain materials (such as thulium) or through parametric amplification, most commonly achieved with highly-nonlinear fibers [1]. As the operational band continues to expand, broadband flexible parametric processing platforms will be required to provide energy-efficient manipulation of light for a variety of communication functionalities such as wavelength conversion, multicasting, temporal demultiplexing, and signal regeneration [2-5].

Recently developed dispersion engineered nanowires offer tremendous potential for four-wave mixing (FWM) over an extensive bandwidth in the silicon platform. In such nanowires, the cross section dimensions are tightly controlled to balance the material dispersion properties with the waveguide-induced dispersion, yielding excellent phase-matching over an unrivaled wavelength range greater than 800 nm [6]. In this work, we leverage this bandwidth to wavelength convert 10-Gb/s optical data over a range scaling from 60 nm up to a record high 168 nm using a high repetition-rate pulsed pump, with near constant conversion efficiency. We make use of a pulsed pump in the FWM process to produce a data format change from a non-return-to-zero (NRZ) format to a return-to-zero (RZ) format, giving rise to improved performance with respect to the receiver. Error-free reception is observed for all converted signals (defined as having a bit-error rate (BER) less than 10^{-12}) with an average power penalty of -2.6 dB (measured at a BER of 10^{-9}). The negative power penalty is mainly attributed to the avalanche-photo-diode's improved sensitivity to pulsed light, which we quantify by BER measurements.

2. Device and Experiments

The nanowire was fabricated at the Cornell Nanofabrication Facility using e-beam lithography followed by reactive-ion etching. The oxide-clad nanowire is 1.1 cm long with a 300-nm by 710-nm cross section surrounded by a 30-nm slab. Inverse tapers on both facets provide efficient coupling to fiber. The nanowire is laid out in a compact spiral occupying less than 1 mm^2 to reduce e-beam stitching-induced losses, resulting in 8.4-dB fiber-to-fiber loss.

The experimental setup (Fig. 1.a) includes a continuous-wave (CW) tunable laser whose output is on-off-keyed modulated by a commercial LiNbO$_3$ mach-zehnder modulator (mod) with a 2^{31}-1pseudo-random-bit-sequence pattern. The modulated light is amplified by a thulium-doped fiber amplifier (TDFA) before being filtered (λ) and

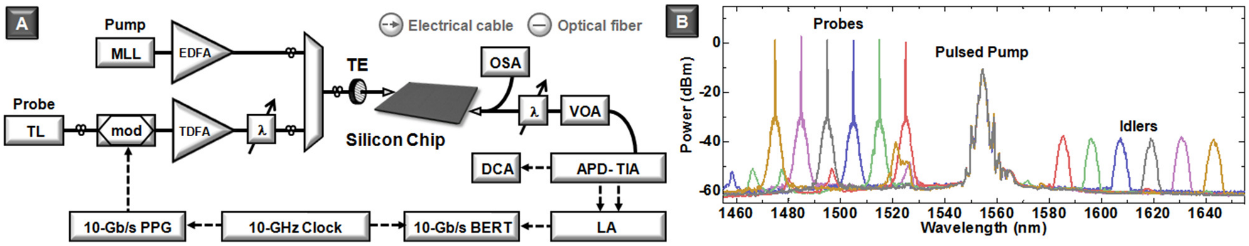

Fig. 1: a. Experimental setup. **b.** Overlaid OSA traces of the wavelength conversion experiments, depicting conversions of 60 nm up to 168 nm.

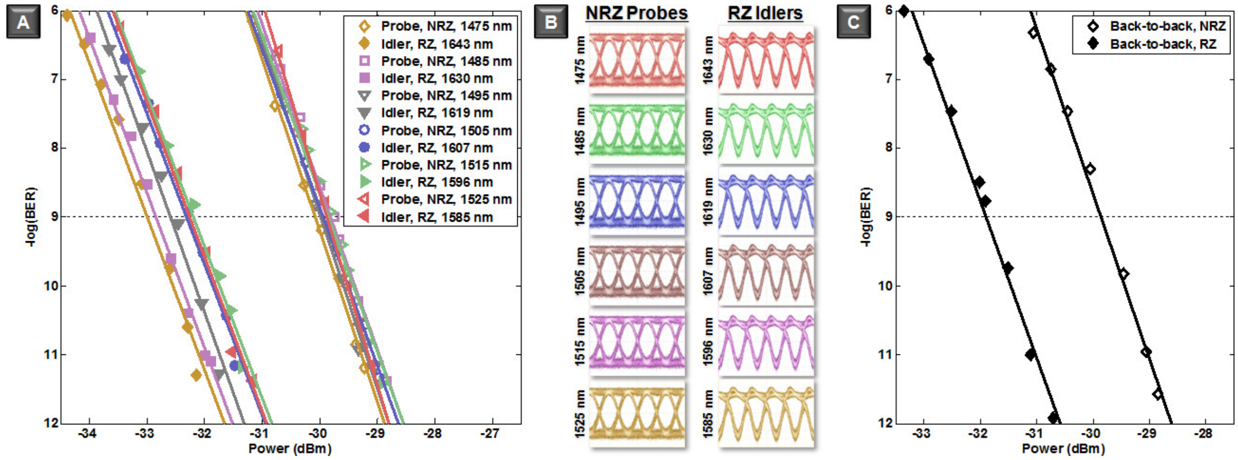

Fig. 2: a. Recorded BER curves for all probe and idler signals indicating an average -2.6 dB power penalty. **b.** Eye diagrams recorded at the APD's output for the probes and the idlers. **c.** Directly modulated RZ and NRZ back-to-back showing a -2 dB sensitivity difference of the APD with regard to RZ data vs. NRZ data.

combined with a pulsed pump using a band combiner. The 1.5-ps, 10-GHz repetition-rate, 16.5-dBm pump (at 1555 nm) is obtained by amplifying the output of a mode-locked-laser (MLL) by an erbium-doped fiber amplifier (EDFA). The combined signals are set to TE polarization and launched into the nanowire. The nanowire's output is filtered to allow reception of the converted signal on a 10.7-GHz bandwidth avalanche-photo-diode (APD-TIA). A variable optical attenuator is included before the receiver to facilitate measurement of BER curves. The output of the receiver is electrically amplified by a limiting amplifier (LA) before being evaluated on a bit-error-rate tester (BERT). A digital communications analyzer (DCA) is used to record the eye diagrams from the photodetector's output, and an optical spectrum analyzer (OSA) is used to record the spectrum at the nanowire's output.

In order to validate the wavelength converter's broadband operation, we vary the probe wavelength between 1475 nm and 1525 nm (Fig 1.b), spanning the respective probe-idler separations of 168 nm down to 60 nm, and yielding a near constant -22.85-dB conversion efficiency (probe-to-idler average-power ratio at the nanowire's output). Error-free transmission (Fig 2.a) and open eye diagrams (Fig 2.b) are observed on all signals. The BER curves are adjusted according to the specified receiver sensitivity curve. The measured average power penalty resulting from the conversion process is -2.6 dB, which is attributed mainly to the APD's improved response to pulsed light. In order to quantify this difference in APD sensitivity, BER curves of the receiver's response to directly modulated NRZ and RZ data at a wavelength of 1555 nm are recorded, using the same pulse characteristics as the pump (Fig 2.c). The resulting -2 dB penalty between RZ reception and NRZ reception accounts for most of the negative power penalty observed from the wavelength-conversion process. The residual power penalty of -0.6 dB is accounted for by the differences between the directly generated RZ signal and the wavelength-converted RZ signal, i.e., shorter pulsewidth of the wavelength-converted signal due to the quadratic pump-idler amplitude relation, as well as improved extinction ratio on the wavelength-converted signal (as the directly modulated RZ signal has limited extinction ratio due to phase instability of the MLL).

3. Conclusions

We have presented the broadest wavelength conversion of data in a silicon platform to date at up to 168-nm probe-idler detuning, accompanied with error-free detection of all converted signals. Additionally, we validate the broadband properties of the silicon-based parametric-processing platform by varying the probe-idler separation, showing near constant conversion efficiencies and consistent negative power penalty.

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4. References

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