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# Wavelength Conversion of a 128 Gbit/s DP-QPSK Signal in a Silicon Polarization Diversity Circuit

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**Abstract** – Wavelength conversion of a 128 Gbit/s DP-QPSK signal is demonstrated using FWM in a polarization diversity circuit with silicon nanowires as nonlinear elements. Error-free performances are achieved with a negligible power penalty.

**Index Terms** – Wavelength conversion device, four-wave mixing, dual-polarization signals.

## I. INTRODUCTION

Among various optical signal processing techniques, all-optical wavelength conversion appears as a key functionality to enable reconfigurability and wavelength management in future all-optical networks. Over the past few years dual-polarization quadrature phase-shift keying modulation (DP-QPSK) has become the format of choice for the implementation of optical transmission systems operating at a bit rate of 100 Gbit/s and such systems are now a commercial reality. As a consequence, future wavelength conversion solutions to be deployed should be able to accommodate this modulation format. Wavelength conversion based on four-wave mixing (FWM) is well known to be transparent to the bit rate and phase of the signal and is therefore compatible with high-speed QPSK modulation [1]. However, FWM is inherently polarization sensitive. In order to be able to optically process polarization-multiplexed signals using FWM, a polarization insensitive scheme is required. A number of schemes based on either dual orthogonal pumps [2] or on polarization diversity loops [3] have been investigated when optical fibers are used as the nonlinear medium. However, having an integrated device on the silicon platform is desirable since it would enable ultra-compact, on-chip, all-optical signal processing. In this context, we have recently demonstrated polarization insensitive wavelength conversion using a silicon polarization diversity (Pol-D) circuit [4].

In this paper, all-optical wavelength conversion of a 32 Gbaud DP-QPSK signal (bit rate of 128 Gbit/s) is experimentally demonstrated using FWM in a silicon-on-insulator Pol-D circuit where silicon nanowires are used as nonlinear elements. Wavelength conversion is successfully achieved with a negligible power penalty (less than 0.5 dB) at a quality (Q) factor of 9.8 dB (equivalent to a bit-error-ratio (BER) of  $10^{-3}$ ), resulting in error-free performance at a net bit rate of 120 Gbit/s (assuming 7% forward-error-correction overhead).

To the best of our knowledge, this is the first demonstration of wavelength conversion of DP-QPSK signals using a silicon nanowire as nonlinear element.

## II. POLARIZATION DIVERSITY CIRCUIT

The Pol-D circuit fabricated on a silicon-on-insulator (SOI) wafer consists of two identical polarization splitters and rotators (PSRs) connected by two identical 2 cm long silicon nanowires, with cross sections of  $250 \text{ nm} \times 500 \text{ nm}$ . The input PSR is based on a tapered waveguide  $\text{TM}_0$ -to- $\text{TE}_1$  mode converter [5] followed by a tapered directional coupler (DC)-based  $\text{TE}_0$ & $\text{TE}_1$  mode splitter [6]. In case of  $\text{TE}_0$  input, light propagates through the adiabatic taper without any change, while in case of  $\text{TM}_0$  input, light is converted to the  $\text{TE}_1$  mode during the adiabatic tapering [5]. The two  $\text{TE}_0$  signal beams propagate separately through the Si nanowires and interact nonlinearly with the pump, which is also split equally between the two waveguides in the  $\text{TE}_0$  polarization. At the waveguides outputs, an identical PSR combines back the two  $\text{TE}_0$  beams so that the entire device shows polarization insensitive transmission. Both input and output of the device are equipped with silicon inverse tapers in order to reduce coupling loss to tapered fibers to 1.5 dB/facet. The minimum insertion loss of the device was around 13 dB with about 2.6 dB residual polarization-dependent loss (PDL). A microscope image and schematic structure of the device are shown in Fig. 1. More details about the design and fabrication of the device can be found in [4,5].

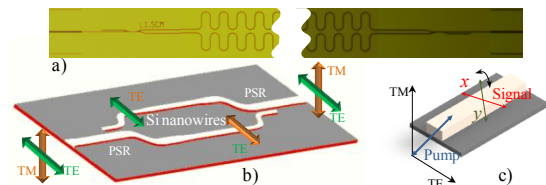


Fig. 1 (a) Microscope image and (b) schematic diagram of the polarization diversity circuit. (c) Polarization configuration at the input of the device.

## III. EXPERIMENTAL SETUP AND RESULTS

Fig. 2 shows the experimental setup used for all-optical wavelength conversion. In order to generate the 32 Gbaud DP-QPSK data signal, light from a continuous wave (CW) external cavity laser (ECL) at 1549.7 nm was modulated in an in-phase/quadrature (IQ) modulator driven by two pseudo-random

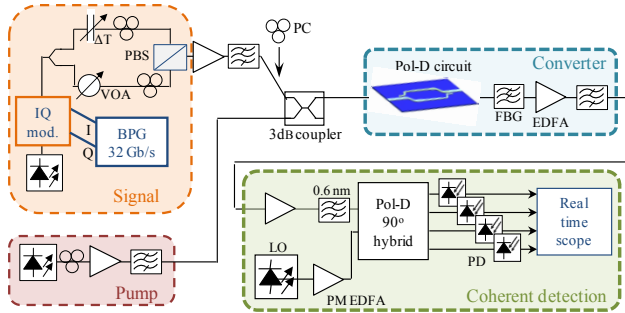


Fig. 2 Experimental setup for wavelength conversion of a 32 Gbaud DP-QPSK signal.

binary sequences (PRBSs) of length  $2^{20}-1$  and  $2^{15}-1$  generated from bit-pattern generators (BPGs). Polarization-multiplexing was emulated by splitting the QPSK signal, delaying one data stream with respect to the other by about 1 ns, and then recombining them with orthogonal polarizations in a polarization beam splitter (PBS). The signal was amplified in an erbium-doped fiber amplifier (EDFA) followed by a 1 nm optical band-pass filter (OBPF) and combined with a pump in a 3 dB coupler. A polarization controller in the signal arm was used to check the polarization insensitivity of the device. The pump was generated from an ECL at 1551.3 nm, amplified by an EDFA and finally filtered by a 1 nm OBPF. The polarization of the pump at the input of the device was controlled by a polarization controller so that the same pump power was coupled into the two nonlinear waveguides, as shown in Fig. 1(c). At the output of the Pol-D circuit, a fiber Bragg grating (FBG) filter was used to block the pump and signal. The filtered idler was amplified and input to a polarization diversity coherent receiver for detection and Q measurements. The coherent receiver consists of an optical 90-degree hybrid circuit, four single-ended photo detectors (PDs) and a tunable ECL as local oscillator (LO). The outputs of the PDs were then input to a 4-channel real-time oscilloscope (Agilent DSOX96204Q) with 80 Gsamples/s sampling rate and 32 GHz electrical bandwidth. The captured data were processed offline through standard steps of digital signal processing (DSP), which include data resampling, polarization recovery (constant modulus algorithm), and phase recovery (Viterbi-Viterbi algorithm). The performance was characterized by evaluating the Q factor from the Cartesian spreads of the constellation as in [7].

The spectra measured at the input and output of the device are shown in Fig. 3. The signal and pump powers at the input of the Pol-D circuit were 15.2 dBm and 18.7 dBm, respectively leading to a conversion efficiency (defined as the ratio between the idler power and signal power at the output of the waveguide) of -27.4 dB. The pump polarization at the input of the device was aligned so that the conversion efficiencies of the two tributaries of the DP-QPSK signal were the same.

Fig. 4 shows the Q performance of the converted signal as a function of the optical signal-to-noise ratio (OSNR, defined in a 0.1 nm noise bandwidth) at the input of the receiver. The back-to-back (B2B) performance was measured directly at the

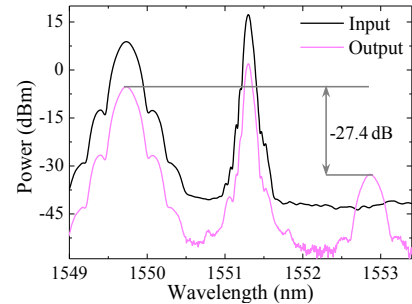


Fig. 3 Input and output spectra of the polarization diversity circuit for DP-QPSK input signal (0.06 nm resolution).

output of the DP-QPSK transmitter, and compared with the performance of the converted signal. Negligible power penalty smaller than 0.5 dB at a Q of 9.8 dB was observed for both polarization tributaries of the converted signal. In order to investigate the origin of the penalty, the performance of a converted signal was characterized in case only one signal polarization was present at the device input (64 Gbit/s QPSK signal). In this case, wavelength conversion was achieved without any power penalty, indicating that the main source of residual penalty in the DP case is caused by imperfections in the PSR, leading to some cross-talk between the two polarization tributaries. Nevertheless, a power penalty of less than 0.5 dB in the dual-polarization case clearly remains within tolerable range.

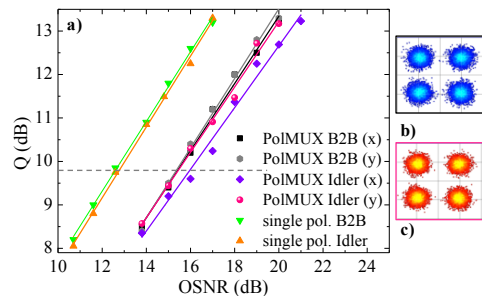


Fig. 4 (a) Q versus OSNR for the B2B and wavelength converted 32 Gbaud DP-QPSK signal at 128 Gbit/s and single polarization QPSK signal at 64 Gbit/s. Constellation diagrams of the converted DP-QPSK signal at 16 dB OSNR for (b) x - polarization (c) y - polarization.

#### IV. CONCLUSION

Using a polarization diversity circuit with nonlinear waveguides fully integrated on the silicon platform, we have successfully demonstrated wavelength conversion of a 128 Gbit/s DP-QPSK signal based on FWM. The performance of the converted signals has been characterized through Q measurements, showing excellent performances. This is the first successful demonstration of wavelength conversion of dual polarization QPSK signals on the silicon platform.

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