Fully-integrated silicon wavelength converter with on-chip idler filtering

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Abstract: We demonstrate a fully-integrated silicon wavelength converter utilizing four-wave mixing, featuring tunable idler filtering with >59 dB out-of-band signal suppression. Conversion of a 32-Gbaud 16-QAM signal with around 2 dB power penalty is demonstrated.

1. Introduction

All-optical wavelength conversion is recognized as a key technology to tackle wavelength-contention challenges in routing and switching [1]. Silicon-on-insulator (SOI) devices, with their high optical confinement and high Kerr coefficient, hold promise for the on-chip integration of efficient wavelength converters. However, there are still challenges to be resolved in integrated wavelength converters based on four-wave mixing (FWM), such as the inefficiency of the process exacerbated by the need for off-chip filtering. Such filtering is essential for suppressing residual pump(s) and signal, thereby ensuring the output spectrum predominantly contains the newly generated idler. While on-chip pump filtering has already been demonstrated [2], aspects of idler tunability and system performance when operating with high data rate signals remain unexplored. Our study introduces on-chip tunable filtering, enabling idler extraction with less than 2 dB attenuation and achieving 59.5 dB pump and 61.5 dB signal suppression, respectively. Applying a 32 Gbaud 16-QAM signal, we assessed the quality of the idler, revealing a sensitivity penalty of around 2 dB, confirming the feasibility of on-chip tunable filtering for idler extraction.

2. Device design and measurement results

The device was designed to enable flexible on-chip extraction in the TE_{00} mode of an idler that was generated by degenerate FWM at the output of a PN-junction-equipped silicon rib waveguide on a 220 nm thick Silicon-On-Insulator (SOI) wafer. A conceptual illustration of the device is presented in Figure 1(a). The pump and signal were coupled into a shallow-etched uniform silicon grating coupler optimized for TE_{00} mode operation at 1550 nm. The silicon rib waveguide, designed with a ridge width of 500 nm, a height of 220 nm, and a slab thickness of 100 nm, had a serpentine shape to minimize its footprint. P-doped regions (depicted in blue) and N-doped regions (depicted in red) were incorporated into the silicon slab, with the distance (corresponding to a 0.8 μm gap value) optimized for low electrical power consumption, as detailed in [3]. The PN-junction equipped silicon waveguide was connected to a quadruple Vernier racetrack resonator filter (RRF) via a short section of silicon rib-to-strip waveguide. The RRF was specifically engineered to function as a bandpass-type drop filter, possessing 5:6 perimeter ratio. This resulted in approximately a 0.5 nm 10 dB bandwidth with around 40 nm free spectral range, covering the whole C-band. Each racetrack resonator could be separately controlled through a heater filament (depicted in orange) deposited on top. This ensured that when tuned properly, only the idler wavelength was collected at the drop port, preventing resonance of the pump and signal within the racetrack cavity.

We initiated the characterization of the Vernier filter's through and drop port responses using a broadband ASE source, a polarizer, and an optical spectrum analyzer (OSA). By meticulously adjusting the current applied to the heaters connected to each racetrack resonator, we tuned the overall filter response across various resonance wavelengths. Five example resonant wavelengths, spanning from 1548 nm to 1560nm, are illustrated in Figure 1(b). Note that the drop port response was normalized against that of the through port, revealing an insertion loss ranging between 1 dB and 2 dB. This metric is crucial for understanding the additional loss introduced by integrating the filter to the wavelength converting chip. We argue that this is much less than a solution based on

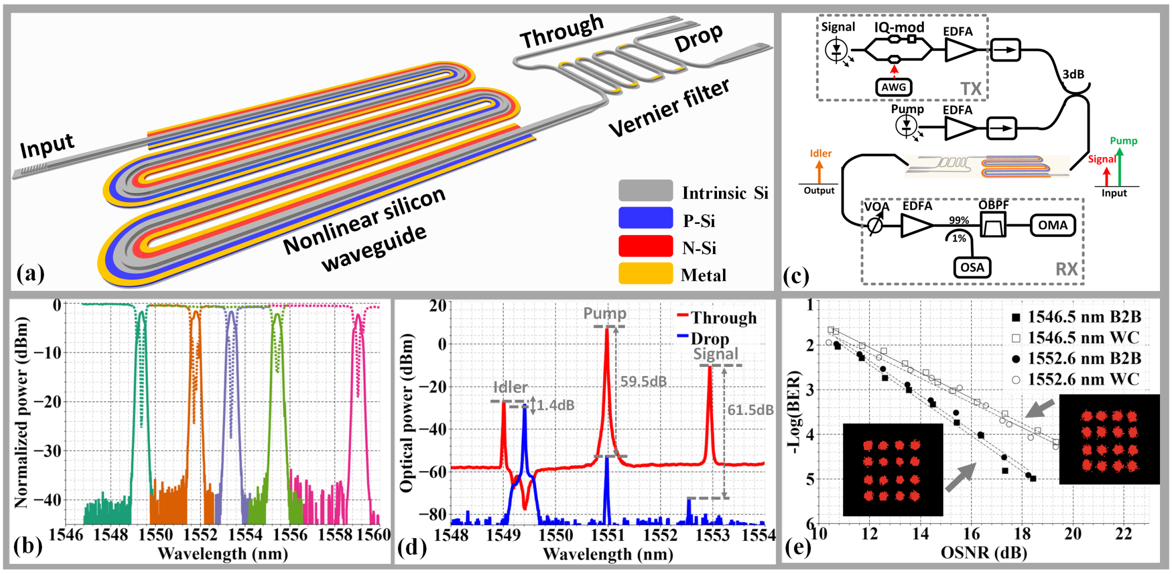

Fig. 1: (a) Layout of the FWM-based wavelength converter; (b) Response of the quadruple vernier RRF at the through and drop ports; (c) Experimental setup for the wavelength conversion and transmission experiments; (d) FWM spectrum at the through port (red - idler out of resonance) and drop port (blue - idler at resonance); (e) Bit Error Rate (BER) as a function of receiver OSNR for signal wavelengths at 1546.5 nm and 1552.6 nm, respectively, under two different scenarios: back-to-back (B2B) signals and wavelength-converted (WC) idlers.

bulk components. The figure 1(b) also shows that the extinction ratio of the filtering action at the drop port is at least 40 dB (constrained by the OSA sensitivity).

We next carried out wavelength conversion experiments, including on-chip idler extraction with and without a modulated signal, using the setup shown in Figure 1(c). Two continuous-wave (CW) lasers were used, one as the pump and the other as the signal source. To generate a 32 Gbaud single-polarization signal with 16-QAM modulation, a CW signal was modulated using an IQ modulator, driven by a $2^{15} - 1$ pseudo-random binary bit sequence (PRBS) generated by an arbitrary waveform generator (AWG). Both lasers underwent amplification via separate Erbium-Doped Fiber Amplifiers (EDFAs), and their outputs were coupled through a 3dB coupler and sent into the chip. Following propagation in the chip, the idler was collected at the drop port and routed to a receiver block enabling Bit Error Rate (BER) measurements and spectral analysis. We first measured the scenario without data modulation to evaluate the conversion efficiency, yielding an output idler to output signal power ratio of approximately -16.4 dB, as shown in Figure 1(d) (red curve). The pump and signal suppression were 59.5 dB and 61.5 dB, respectively, whereas the insertion loss suffered by the idler during filtering is 1.4 dB. Additionally, we evaluated the performance of the modulated data signal. By varying the Variable Optical Attenuator (VOA) at the receiver side and obtaining the Optical Signal-to-Noise Ratio (OSNR) through the OSA, we measured the BER as a function of OSNR for both back-to-back and wavelength-converted scenarios for 1546.5 nm and 1552.6 nm signal wavelengths (and a constant pump wavelength of 1551.0 nm). A receiver sensitivity penalty of around 2 dB OSNR was measured at the HD-FEC limit (BER equals to 3.8×10^{-3}) (see Figure 1 (e)).

3. Conclusions

We demonstrated a fully integrated silicon wavelength converter with on-chip tunable idler filtering, exhibiting less than 2 dB attenuation relative to its counterpart at the through port and approximately 60 dB suppression of out-of-band signals. BER measurements with a 32 Gbaud 16-QAM signal for two different signal wavelengths showed an OSNR penalty at the receiver of approximately 2 dB.

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References

1. C. A.,Brackett et al., "Dense wavelength division multiplexing networks: Principles and applications,"IEEE Journal on Selected areas in Communications. (1990).
2. J. R. Ong, et al., "Silicon microring-based wavelength converter with integrated pump and signal suppression," Optics letter. (2014).
3. V. Vitali, et al., "Design Rules for Low Electrical Power Consumption in Nonlinear Silicon Waveguides with Active Carrier Removal," in CLEO, JTh3A–7 (Optica Publishing Group, 2021).