High-Performance Silicon-Nitride-Based Multiple-Wavelength Source

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***Abstract*— We demonstrate a stable complementary metal-oxide-semiconductor-compatible on-chip multiple-wavelength source by filtering and modulating individual comb lines from a parametric optical frequency comb generated in a silicon nitride microring resonator. We show comb operation in a stable low-noise state. Bit-error rate measurements demonstrate negligible power penalty from six independent frequency comb lines when compared with a tunable diode laser baseline. Open eye diagrams confirm the fidelity of the 10 Gb/s data transmitted at the comb frequencies and the suitability of this device for use as a fully integrated silicon-based wavelength-division-multiplexing source.**

***Index Terms*— Integrated optics, nonlinear optical devices, silicon nitride, wavelength-division multiplexing.**

I. Introduction

SILICON-BASED integrated photonics aims to deliver on-chip optical communications networks with bandwidths orders of magnitude larger than electronic networks. As the microelectronics industry moves to multi-core and multi-processor chips, complementary-metal-oxide-semiconductor (CMOS)-compatible photonics will replace much of the electronic communications backbone. A key benefit of optical communication systems is wavelength-division-multiplexing (WDM) which enables a single waveguide to carry multiple data streams and is essential to reach the full bandwidth potential of photonic integrated circuits. Many components necessary for on-chip optical interconnects such as filters [1], modulators [2], switches [3], and detectors [4] have been demonstrated over the past decade. However, an integrated silicon-based on-chip source capable of generating the many wavelengths necessary to drive the network has been elusive. Since silicon is an indirect band gap material, approaches thus far have focused on integrating III-V active devices by bonding, such as microdisk lasers [5] or a hybrid waveguide [6]. Although both methods can be replicated on-chip to generate multiple wavelengths, scaling to the hundreds of wavelengths envisioned by optical network architectures quickly becomes power hungry and space consuming [7], [8]. All-optical approaches have included utilizing the Raman effect in silicon [9]. Although this process can be cascaded [10], the wavelength separation is determined by the Raman shift which is inadequate for WDM standards.

In contrast, we have recently demonstrated a fully integrated CMOS-compatible frequency comb based on optical parametric oscillation using a silicon nitride microring resonator [11]. The device produces a comb of wavelengths evenly spaced in frequency with a single pump input. The frequency spacing is determined by the resonator free spectral range (FSR). This source could readily be used as an on-chip multiple-wavelength source matched to the telecom WDM standards.

In this letter, we examine the characteristics of the generated comb lines of the Si_3N_4 frequency comb and analyze their fidelity as WDM sources. In principle, the highly nonlinear process used to generate the comb could induce signal noise. Additionally, the large quality factor Q of the resonator leads to high circulating powers, which could also induce instability in the system due to the sensitivities of both the parametric gain and cavity lineshape to power and temperature fluctuations. Given these many sources of noise and instability, a robust measurement of the generated frequencies is required to demonstrate the usefulness of the on-chip source. Note that previous work has shown comb generation using parametric gain in microresonators [11]–[18], but an analysis of the fidelity and stability of encoded data on filtered individual comb lines has yet to be examined.

II. Microresonator Comb Sources

The bit-error rate (BER) measurements are performed on a 116-μm radius Si_3N_4 ring resonator with a 725 by 1550 nm cross-section. The resonator is pumped using a 1541 nm single-frequency cw laser that is amplified with a 1.8-W erbium-doped fiber amplifier (EDFA). The amplifier output is

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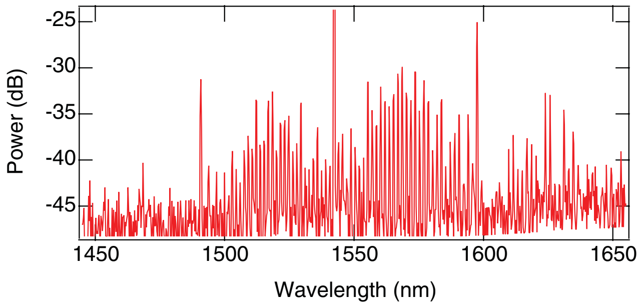

Fig. 1. Optical spectrum of the generated frequency comb at the output of the Si_3N_4 waveguide with a pump wavelength of 1541 nm. The comb is in a stable low-noise state with this spectrum and we are able to manipulate and process the generated frequencies when filtering out the pump.

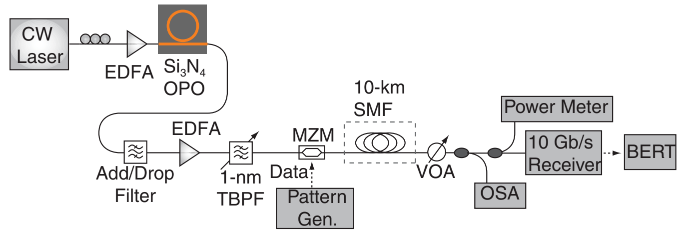

Fig. 2. Experimental setup for frequency comb generation and BER measurement. The comb output is filtered and modulated for bit-error rate (BER) measurements. MZM: Mach-–Zehnder modulator. TBPF: tunable band-pass filter.

sent into a silicon nitride bus waveguide, which is coupled to the resonator using a lensed fiber. The coupling losses are 7 dB. Parametric oscillation in the microring results in comb formation, generating over 100 new wavelengths across a 200 nm span (Fig. 1). The dimensions of the ring are specifically designed to yield anomalous group velocity dispersion at the pump wavelength. The intrinsic Q of the ring is on the order of 10^6 which induces a cavity enhancement of the input pump by a factor 200. Combining the designed dispersion profile, low propagation loss and the nonlinearity of the silicon nitride allows for parametric oscillation. When the pump wavelength is tuned into a cavity resonance, signal and idler wavelengths initially oscillate symmetrically about the pump frequency. The oscillation threshold power level is achieved when the pump-induced parametric gain is greater than the cavity loss at one of the cavity resonances, typically multiple FSRs away, where the phase mismatch for parametric four-wave mixing (FWM) is minimized. Beyond the threshold power, which is approximately 50 mW [11], cascaded FWM generates new frequencies at each cavity resonance with increasing power. Recently, we have shown that the spacings between these frequencies are equidistant to within 3 parts in 10^{15} of the center frequency [16]. Additionally, we have shown generation of spectrally flat and very broad frequency combs spanning an octave [19]. We have observed a transition behavior where the RF amplitude noise reduces by >25 dB indicating phase-locking analogous to mode-locking in a femtosecond laser system.

We achieve stable operation of the comb by tuning the pump wavelength to a spectral point in the microring resonance where the comb intensity noise drops. We tune the pump laser into resonance from the "blue-detuned" side to avoid thermal bistability. As we tune into the resonance the RF amplitude noise drops by >25 dB resulting in a stable, low-noise state. At this point the pump can be further tuned within the resonance to generate and modify the spectral shape of the output comb while maintaining low RF noise. In this low-noise operation state, a stable comb can be maintained for hours.

III. Experimental Setup and Measurements

We filter and modulate individual wavelengths generated in the ring resonator and measure the BER and power penalty at 10-Gb/s (Fig. 2). Once a stable comb is generated, the output of the chip is collimated using a lens and coupled into an optical fiber. The power at each selected wavelength coupled from the ring to the bus waveguide can be as high as 1 mW; however, the inefficiency of our off-chip collection and filtering require amplification for further processing. The fiber output is first transmitted through an add/drop filter in order to remove a 9 nm spectral region surrounding the pump wavelength. We use a low-noise EDFA to increase the power of the remaining comb lines and use a 1 nm tunable filter to select individual wavelengths. We modulate the selected wavelength with a lithium niobate Mach–Zehnder modulator driven by a pattern generator to imprint a $2^{31} - 1$ non-return-to-zero psuedo-random bit sequence (PRBS) at a data rate of 10 Gb/s. The modulated signal is then sent either to a sampling oscilloscope to generate eye diagrams or to a variable optical attenuator (VOA) and then into a 10 Gb/s lightwave receiver and a bit-error-rate tester (BERT). For the baseline measurement of our set-up, we modulate a tunable external cavity diode laser, operating at a wavelength near the filtered comb lines.

In the low-noise phase-locked state, we measure negligible power penalty of the filtered comb lines demonstrating suitability of the source for an on-chip WDM network. The BER as a function of received optical power is plotted in Fig. 3(a). We observe a negligible power penalty for the tested comb lines as compared to the baseline across a 30 nm span, where power penalty is defined as the difference in received power at 10^{-9} errors between the baseline and test data. Additionally, we achieve error-free operation, that is, a BER less than 10^{-12} for at least two of the generated wavelengths. We observe a slight curvature in the BER data. Since the curvature is the same for the baseline and data measurement, we conclude that it originates from our test equipment and is not fundamental to the microring wavelength generator. Additionally, we transmit data from one of the comb lines through a 10 km spool of optical fiber to show suitability for long-haul optical communications. In this case, we incur a very small power-penalty in reference to the same comb line without the added fiber.

Open-eye diagrams confirm the low power penalty of the modulated spectral lines. Figure 3(b) shows the eye diagram for each comb line on which we performed BER measurements. As expected, the 10 Gb/s signal shows up clearly on the oscilloscope with minimal noise and no closing of the pattern eye. Thus, we have independently filtered and modulated all selected comb lines without distortion from generated neighbors.

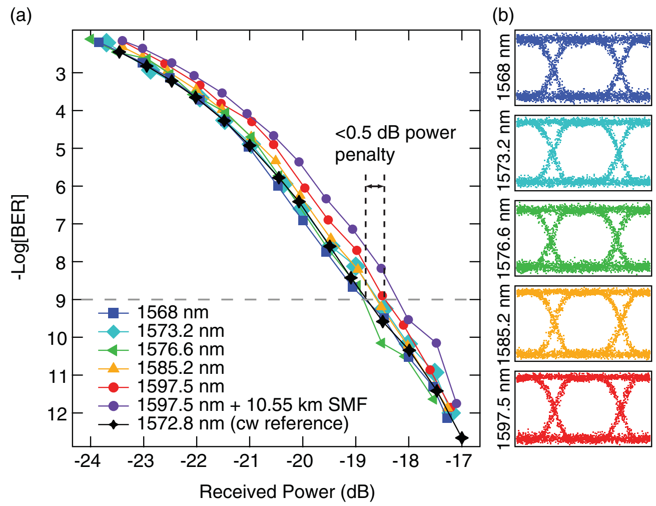

Fig. 3. (a) BERT measurements of the filtered comb lines. The cw reference measurement acts as a back-to-back baseline with which to compare the modulated comb lines. We note error-free operation of the comb lines and a minimal power penalty measured at a bit-error-rate of 10^{-9}. (b) Eye diagrams for the five measured comb lines generated by the microcavity for 1568 nm, 1573.2 nm, 1576.6 nm, 1585.2 nm, and 1597.5 nm. The clean and open eye confirms the BER data showing no power-penalty.

The frequency comb used in this experiment has a line spacing of 200 GHz. This spacing can be precisely tuned by modifying the resonator radius, which allows for great flexibility in channel spacing and the potential to meet standard WDM specifications. The ITU Grid frequency grid used for dense WDM requires 100 GHz spacing between wavelengths 1528.77 and 1563.86 nm, which would require a ring resonator with a radius of 230 μm generating 73 comb lines, which is well within the range of demonstrated operation. While the resonator radius can be accurately designed, the fabrication error in the cross-section can be as high as ±50 nm, which, according to simulations, can result in 0.2 % deviations in the effective index. The FSR can be adjusted post-fabrication through thermal tuning of the resonator. Comb generation depends on the efficiency of the FWM process, which depends largely on the resonator dispersion. In the microring resonator, the FSR and the dispersion are largely uncoupled, allowing for comb spacings as low as 20 GHz [20] and as high as 1.1 THz [11]. Additionally, we have shown that it is possible to achieve low-noise operations in larger resonators (20 GHz FSR) [20]. The experiment performed here is akin to broadcasting a 10 Gb/s signal over 6 wavelengths yielding a total data rate of 60 Gb/s. The speed is not limited to the source; and the comb lines could be modulated at much higher data rates. In our current experiment, the power in the generated comb lines are not uniform over the entire spectrum, limiting the number of usable lines. The number of usable comb lines can be significantly increased by utilizing a frequency comb with equalized amplitudes and low RF noise, which can be achieved by engineering the dispersion and increasing the cavity Q [19].

IV. Conclusion

We characterized the performance of the multiple-wavelength source generated from a microring OPO and show that it is suitable for an on-chip optical communications network. In this letter filtering and modulation are done off-chip, but through the incorporation of cascaded silicon electro-optic ring resonators [21], the same functionality can be performed on-chip for a completely integrated system. In that case, each silicon ring modulator would be aligned to one of the hundreds of generated wavelengths to enable on-chip data transmission rates of over 1 Tb/s.

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