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Compact optical frequency comb source based on a DFB butt-coupled to a silicon nitride microring

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Abstract—We demonstrate an integrated Kerr frequency comb source based on the butt coupling between a III-V DFB laser and a silicon nitride (Si_3N_4) microresonator. The 30-dB bandwidth of the optical comb is measured to be 148.7 nm (18 THz), centered at 1576 nm, which is, to the best of our knowledge, the largest ever measured on an ultra-compact source. This hybrid compact source can also be used for soliton investigations.

Keywords—Optical frequency comb, photonic integrated circuits, silicon nitride, semiconductor lasers

I. INTRODUCTION

Optical frequency comb sources are key elements in a growing number of applications, such as optical metrology, optical clocks [1], ultra-fast ranging distance [2] or multiplexing in photonic communications [3]. While these demonstrations started on voluminous setups with low efficiency, the rapid progress in integrated photonic platforms has significantly boosted the interest and the research about compact comb sources. Broad spectra can be produced by Kerr-comb generation in high quality whispering gallery mode resonator [4] or microresonator [5], [6]. In this paper, we present a highly compact comb source. Our passive microresonator is pumped with a continuous single mode DFB laser, on a cavity mode which generates a Kerr frequency comb through parametric four-wave mixing [7]. Nonlinear effect is possible at a low power in Si_3N_4 thanks to its significant nonlinear refractive index (compared to silica) and its ultra-low loss allowing very high-quality factor for the microresonator [8]. The silicon nitride circuit used in our experiment are fabricated on 8-inch complementary metal oxide semiconductor (CMOS) pilot lines using a tailored subtractive process [6], [9] ensuring a void-free technology regarding the bus to microring coupling region. Moreover, an annealing step is applied to reduce the propagation losses across the C band occurring due to N-H bonds overtone absorption picking at 1519 nm.

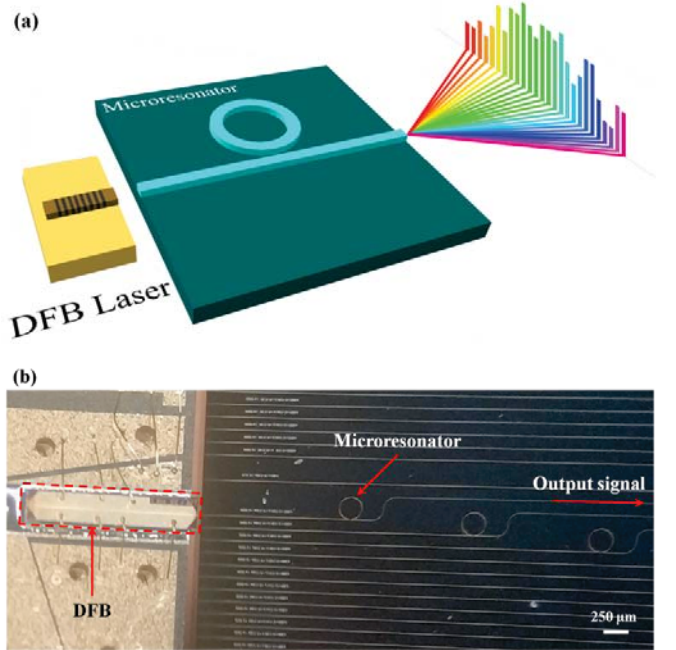


Fig. 1 a) Schematic of optical frequency comb generation by pumping the nonlinear microresonator with the DFB laser. b) Photograph of the butt-coupling. The output signal is extracted with a lens fiber at the right of the passive waveguide (not visible on the picture). The two components are independent, and by the translation of the passive chip, multiple configurations of ring microresonators can be easily tested.

II. HIGH POWER DFB LASER

The InP/InGaAsP DFB laser is designed to guarantee a single-mode lasing able to provide a sufficient pump power (Fig. 2) for the generation of an optical comb in the ring resonator. The DFB laser is fabricated using a dual channel shallow ridge structure as described in [10]. The laser cavity length is 1.75 mm. To ensure maximum output power and an optimal coupling with the passive chip, the back facet of the laser is coated to be highly reflective and the output facet anti-reflective. The lasing threshold is 81 mA and the output power ups to more than 200 mW, as shown in Fig. 2.

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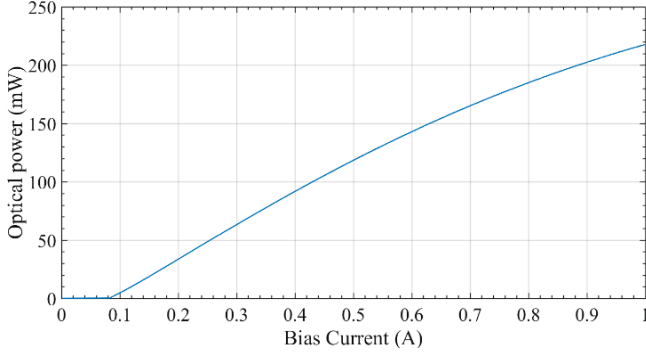


Fig. 2 Optical power measurement at 25°C from the DFB laser.

The laser output mode has an asymmetric shape: we measured a total angle at $1/e^2$ of $20^\circ \times 60^\circ$ (horizontal \times vertical). This non-circular form is due to the specific design of the laser [10]. So as to minimize the coupling loss between the laser and the passive chip, we point out that the laser divergence should be as close as possible to the divergence of the passive chip input.

The lasing wavelength can be precisely tuned by changing the bias current (1.5 pm/mA for a temperature set around 25°C), which allows an easy scan of the resonance of the microring. In Fig. 3, the measured spectrum of the laser exhibits a good side mode suppression ratio (SMSR) of 57 dB, which circumvent possible perturbations of the frequency comb generation during the pumping of the microresonator.

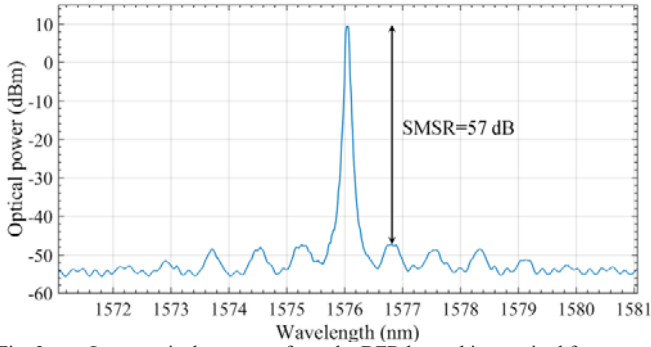


Fig. 3 Laser optical spectrum from the DFB laser chip acquired for a 823 mA bias current and a 25.6°C temperature.

III. HIGH CONFINEMENT, LOW LOSS SILICON NITRIDE RING RESONATORS

A. $\text{Si}_3\text{N}_4/\text{SiO}_2$ passive waveguide fabrication

We start the fabrication process with a 3- μm -thick thermal oxidation of the 200 mm diameter silicon substrate to isolate the optical mode and avoid the leakage to the substrate. Then, following a tailored deposition method [6], [9], 800-nm-thick silicon nitride film (Si_3N_4) is deposited by low pressure chemical vapor deposition (LPCVD). A 248-nm lithography on an ASML-300 stepper is performed using 820-nm-thick resist mask with a bottom anti-reflection coating (BARC). An inductively coupled plasma (ICP) reactor is used to etch the silicon nitride film. In order to increase the photoresist selectivity, the resist is cured by applying an HBr plasma [11]. We used an $\text{Ar}/\text{Cl}_2/\text{O}_2$ plasma process to open the BARC and

the Si_3N_4 is then etched with a $\text{CF}_4/\text{CHF}_3/\text{Ar}$ plasma. The photoresist/BARC layers are removed using an O_2 plasma, and 1% HF dip. The silicon nitride circuits are encapsulated by a 2- μm -thick silica cladding layer deposited at 400°C using high-density plasma-enhanced chemical vapor deposition (HDP-PECVD) technique to avoid voids formation, which is one of the main causes known for devices failure. After the encapsulation, a 3-hour annealing at 1200 °C in nitrogen atmosphere is applied on the wafer to reduce the hydrogen content in the film. The propagation losses of 1.5 μm -wide \times 800 nm-thick waveguides are then reduced from 0.8 dB/cm to 0.3 dB/cm thanks to the annealing.

At the end of the process, a deep etch step has been used to form the chip facets, thus no additional facet polishing steps are required. With an atomic force microscopy (AFM), we measured a 4.5 nm line edge roughness (LER) on a tilted sample (Fig. 4).

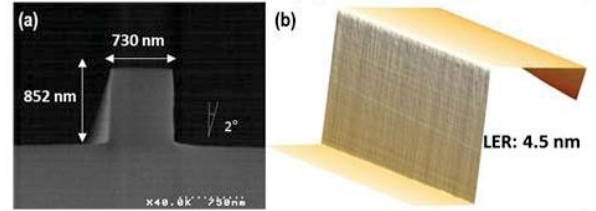


Fig. 4 a) SEM image of a Si_3N_4 waveguide profile after subtractive patterning and b) the corresponding AFM image of the Si_3N_4 sidewalls and the measured LER.

B. $\text{Si}_3\text{N}_4/\text{SiO}_2$ chip measurements

The microresonator used is a Si_3N_4 ring with a 56 μm radius placed at 600 nm of the bus waveguide, which should result in a coupling close to critical. The cross-sectional dimensions of the ring waveguide (1.5 μm -wide \times 800 nm-thick) ensure that the dispersion is anomalous at the pump across the C band, which greatly eases frequency comb generation [6]. The bus waveguide is 20 mm long. The chip dimension is 20.0 \times 21.3 mm. We measured the reflectivity and the transmission spectrum of the ring by using a high-resolution optical spectrum analyzer (OSA) from APEX Technologies (AP2043B model) with an integrated tunable laser source. We looked only for transverse electric (TE) resonance since the DFB laser used as pump in the next part is TE.

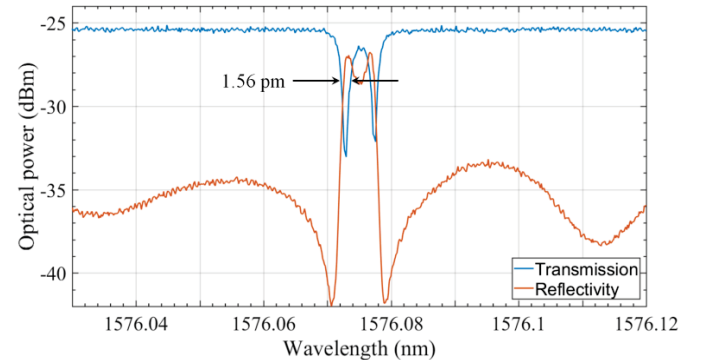


Fig. 5 Spectral response of the 56 μm radius microring, measured by a 1.12 pm resolution OSA.

The measured resonance shows a mode splitting that has been observed by other groups on this type of resonators highly confined with high quality factor [8]. Any small fabrication imperfections can easily induced a backscattering mode, leading to a splitting of the resonance as shown in Fig. 5 [12]. Both resonances have a 1.56 pm (188 MHz) bandwidth, meaning a loaded quality factor Q_l of $\sim 1 \times 10^6$ (thus representing an intrinsic Q_i of 2×10^6). Note that the measured bandwidth could be overestimated (i.e., the Q underestimated) due to limited resolution of the OSA. The 33 pm local oscillation measured on the reflectivity spectrum is due to the back-end facet of the waveguide forming a parasite cavity.

By scanning widely the wavelength, we measured a 3.38 nm (408 GHz) free spectral range (FSR) of the microresonator, which determines the space between the lines generated in the frequency comb.

By injecting a test signal at the end of the passive waveguide, we measure the far-field of the passive waveguide before the microresonator. The full angle at $1/e^2$ is $22^\circ \times 34^\circ$ (horizontal \times vertical).

IV. HYBRID INTEGRATED OPTICAL COMB SOURCE

A. Hybrid InP-Si₃N₄/SiO₂ setup

To perform the butt-coupling between the DFB laser and the passive chip (Fig. 1), we use a dynamical alignment system with micrometric translation stages. Consequently, mechanical vibrations slightly affect the performance of our device. The advantage is the possibility to easily different ring configurations.

By computing the overlap of the measured far-field from the DFB laser and the microresonator, the minimum coupling loss achievable on our setup is estimated around 0.6 dB to which 0.5 dB should be added due to the reflection at the Si₃N₄ chip input.

B. Optical comb generation

The operating output power of the DFB laser was set at 187 mW. However, if we subtract the coupling loss due to the mode mismatch and the propagation losses in the bus waveguide, we estimate a maximum injection power of 133 mW. The actual injection power is lower due to alignment imperfection. By pumping the microresonator near a cavity mode, we generated an optical comb through cascaded parametric Four Wave Mixing (FWM) [7], as shown in Fig. 6.

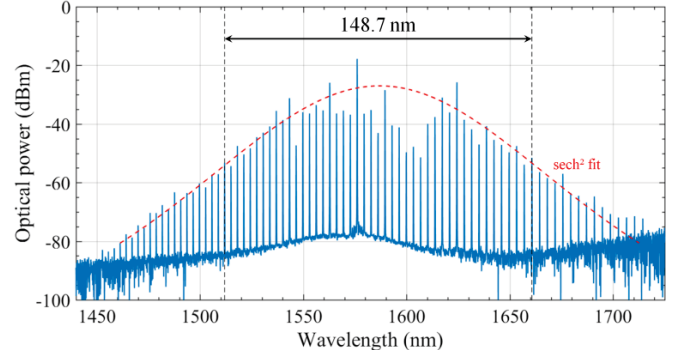


Fig. 6 Spectral measurement of an optical frequency comb generated by the pumped microresonator. The bias current of the DFB laser was 813 mA, meaning a 187-mW output power at 1576.08 nm lasing wavelength.

Here the wavelength pump laser is set at 1576.08 nm to match a resonance of the microresonator. The microresonator design provides anomalous group velocity dispersion [6], which greatly facilitates Kerr comb generation. As shown on Fig. 6, the 30-dB bandwidth of the Kerr comb is measured to 148.7 nm (18 THz), which is the largest value for a fully compact system to the best of our knowledge. In detail, when comparing to previous solutions, where a Fabry-Perot InP laser is butt-coupled to the silicon nitride microresonator [13], the silicon nitride circuit is air-cladded due to dispersion constraints limited by available Si₃N₄ thickness. As a consequence, the system is harder to package and its reliability may be affected. Furthermore, in the case of the RSOA butt-coupled to the silicon nitride microresonator [14], the heater complicates the integration, while increasing the optical circuit footprint.

Our comb spectrum has a *sech*² shape (see Fig. 6) that is characteristic of a single dissipative Kerr soliton (DKS) state. Others measurements [14], [15] are still necessary to prove the existence of solitons. For instance, autocorrelation and amplitude noise measurements could confirm the soliton regime.

V. CONCLUSION

We have developed a Si₃N₄/SiO₂ on silicon fabrication platform that allows the fabrication of high quality microresonator. We have demonstrated a compact optical frequency comb source formed by butt-coupling between an InP DFB laser and a Si₃N₄/SiO₂ microresonator. We succeed to measure a 148.7 nm (18 THz) broadband frequency comb, which is, to the best of our knowledge, the largest ever measured on an ultra-compact source. Such performance on portable systems offers the potential for a wide variety of applications relying on precise frequency comb such as metrology, communications [3] or waveform generation.

Further works will investigate the conditions of soliton's appearance by measuring different parameters such as power threshold, pump detuning, FSR frequency comb variations etc. This should enable a full control of the soliton regimes, which in turn will enable to target a large number of applications such as ultra-fast ranging distance [2] or even calibrations of astronomical spectrographs [16].

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