Generation of an optical frequency comb in the green with silicon nitride microresonators

Nicolas Volet[1,*], Lin Chang[1], Leiran Wang[1,2], Martin H. P. Pfeiffer[3], Michael Zervas[3], Hairun Guo[3], Tobias J. Kippenberg[3], and John E. Bowers[1]

[1] *Department of Electrical and Computer Engineering, University of California, Santa Barbara (UCSB), CA 93106, USA*
[2] *State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China*
[3] *ÉcolePolytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland*
**volet@ece.ucsb.edu*

Abstract: The first realization of a green-light frequency comb is reported in a silicon nitride ring microresonator, from third-order non-linear interaction of a near-infrared 1-THz spacing Kerr comb spanning 2/3 of an octave.
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1. Introduction

Optical frequency combs (OFCs) have revolutionized the field of frequency metrology and have found numerous applications *e.g.* in astronomy, spectroscopy, the generation of low-noise microwave signals and precision ranging [1]. In recent years, the generation of OFCs has been demonstrated in integrated microresonators [2]. Research was primarily focused on the infrared (IR) and progress has been achieved, including high repetition rate pulse generation [3-5] and coherent terabit communications [6]. The extension into the visible is appealing for biological imaging [7], optical coherence tomography, as well as comb locking to optical atomic transitions that are essential for optical atomic clocks.

Octave-spanning OFCs pumped in the IR have been reported beyond 2 μm (149.9 THz), but failed to extend the short-wavelength side into the visible [8]. Recently, 7 red and green comb lines were observed with a high-Q aluminum nitride (AlN) ring microresonator and attributed to second-harmonic (SH), sum-frequency (SF) and third-harmonic (TH) generations [9]. On the silicon (Si) platform that leverages the cost-effective and excellent compatibility with the widespread complementary metal–oxide–semiconductor (CMOS) fabrication infrastructures, close-to-visible comb operation was achieved with a silicon nitride (Si_3N_4) ring microresonator, where 17 comb lines were observed near 770 nm (389 THz) and attributed to SHG and SFG [7]. In the green spectral range, THG-induced frequency conversion into a single spectral line near 520 nm (577 THz) was observed [10], but no comb has been reported thus far. Using only third-order non-linear processes (*i.e.* no second-order process), here we report, to our knowledge, the first generation of a green-light comb (GLC) in a Si_3N_4 ring microresonator.

2. Device description

The devices are fabricated by low-pressure chemical vapor deposition (LPCVD) on a Si substrate. The photonic Damascene process is used [11], which effectively prevents crack formation that causes high scattering losses in the waveguide. An 850-nm thick nearly stoichiometric Si_3N_4 waveguide is cladded to the bottom and to the top by a 3-μm thick SiO_2 layer. A top view schematic of the investigated device is shown in Fig. 1(a). The microresonator waveguide width H is set to 1.6 μm, and the ring radius R is 22.85 μm, corresponding to a free spectral range (FSR) of ~1 THz. The bus waveguide width $W = 100$ nm and the gap $G = 750$ nm between the bus and the ring waveguides is chosen near critical coupling. A loaded Q factor near $1.1 \cdot 10^6$ is extracted at the designed wavelength of 1555 nm (192.8 THz).

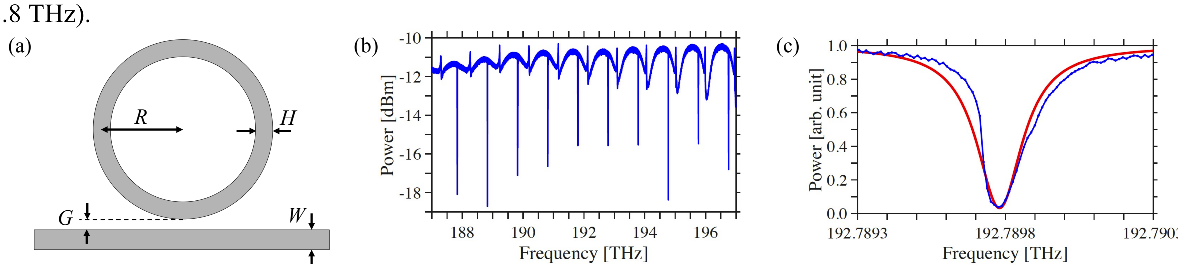

Fig. 1. (a) Top-view schematic of the ring microresonator. (b) Transmission spectrum and (c) fitting (in red) of the resonance near 192.8 THz.

To generate a broadband OFC, the normal material dispersion of Si_3N_4 at 1.55-μm wavelength should be compensated by an anomalous waveguide dispersion, provided by tailoring the waveguide geometry [2]. In the present case, the waveguide dispersion of the Si_3N_4 ring microresonator is also designed to simultaneously phase-match the IR comb and its frequency-tripled GLC.

3. Experiments and Results

A tunable single-frequency CW laser is used as the seed laser to pump the ring microresonator and an erbium-doped fiber amplifier (EDFA) boosts the pump power. The light is passed through a polarization controller to selectively couple into the fundamental TE or TM mode of the waveguide. Tapered lensed fibers are used to couple the light in and out of the device. The signals in the IR and in the green are monitored respectively by a high-speed 1550-nm power sensor and by a silicon-PIN photo-detector for visible light. Two optical spectrum analyzers (Yokogawa AQ6375 for 1200-2400 nm and AQ6373B for 350-1200 nm) measure their respective spectra. Using the thermal-locking technique [12], an IR Kerr comb can be obtained when the pump frequency is tuned into the resonance, with an input power larger than the threshold for parametric oscillations.

Fig. 2 shows our results with a TM pump, where 30 lines are detected for the GLC, with frequencies ranging from 517 THz to 597 THz (502-580 nm). The output power of the GLC measured with the photo-detector is about –19.6 dBm (11 μW), and its intracavity power is estimated to –9.1 dBm (123 μW). The intracavity pump power is estimated to 25 dBm (316 mW), thus yielding an intracavity conversion efficiency of –34 dB ($4\cdot10^{-4}$). The net efficiency is –53 dB ($6\cdot10^{-6}$), which is more than 3 orders of magnitude larger than recently reported with AlN ring microresonators [9].

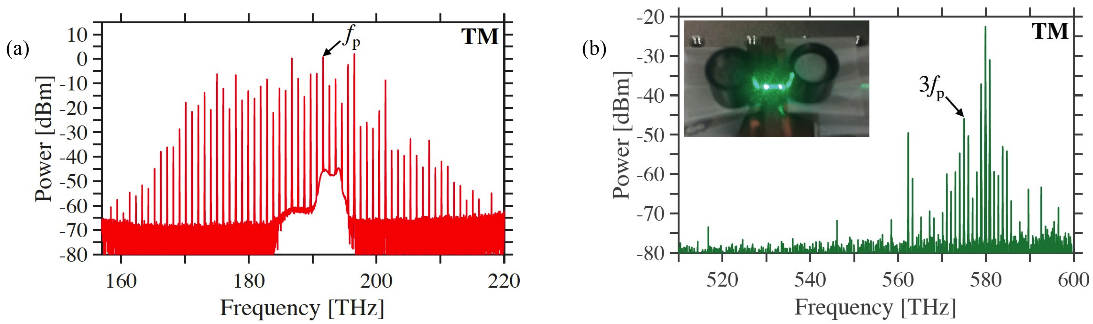

Fig. 2. (a) IR Kerr comb generated with a TM pump and (b) the corresponding GLC with 30 spectral lines. In (b), the inset shows a photograph of the probed device. The pump frequency f_p = 191.6 THz and both IR and green combs have FSR = 977.2 GHz.

Detailed investigations revealed that the first (central) emitted line of the GLC is formed by the THG process, where the interaction of three photons with frequency f_p from the IR pump laser results in the creation of a photon with the tripled frequency $3f_p$. The additional lines of the GLC are created by the third-order SFG process, where the interaction of three photons from the IR Kerr comb, results in the creation of a photon in the green. For this excitation pathway, it is noted that the combs are in the high-noise regime [3]. While not attempted or observed in this work, low-noise comb states can be attained by techniques, such as δ-Δ matching or parametric seeding, or via the soliton regime [4].

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