Silicon-based monolithic optical frequency comb source

Mark A. Foster, Jacob S. Levy, Onur Kuzucu, Kasturi Saha, Michal Lipson, and Alexander L. Gaeta

1School of Applied and Engineering Physics, 160 Clark Hall, Cornell University, Ithaca, New York 14853, USA
2School of Electrical and Computer Engineering, 428 Phillips Hall, Cornell University, Ithaca, New York 14853, USA
3Kavli Institute at Cornell for Nanoscale Science, Cornell University, Ithaca, New York 14853, USA
*a.gaeta@cornell.edu

Abstract: We demonstrate the generation of broad-bandwidth optical frequency combs from a CMOS-compatible integrated microresonator. We characterize the comb quality using a novel self-referencing method and verify that the comb line frequencies are equidistant over a bandwidth of 115 nm (14.5 THz), which is nearly an order of magnitude larger than previous measurements.

©2011 Optical Society of America

OCIS codes: (190.4380) Four wave mixing; (120.3940) Metrology; (190.4390) Integrated optics.

References and links

1. Th. Udem, R. Holzwarth, and T. W. Hänsch, “Optical frequency metrology,” Nature 416(6877), 233–237 (2002).
2. S. T. Cundiff and J. Ye, “Colloquium: femtosecond optical frequency combs,” Rev. Mod. Phys. 75(1), 325–342 (2003).
3. S. A. Diddams, D. J. Jones, J. Ye, S. T. Cundiff, J. L. Hall, J. K. Ranka, R. S. Windeler, R. Holzwarth, Th. Udem, and T. W. Hänsch, “Direct link between microwave and optical frequencies with a 300 THz femtosecond laser comb,” Phys. Rev. Lett. 84(22), 5102–5105 (2000).
4. P. Del’Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, and T. J. Kippenberg, “Optical frequency comb generation from a monolithic microresonator,” Nature 450(7173), 1214–1217 (2007).
5. P. Del’Haye, O. Arcizet, A. Schliesser, R. Holzwarth, and T. J. Kippenberg, “Full stabilization of a microresonator-based optical frequency comb,” Phys. Rev. Lett. 101(5), 053903 (2008).
6. A. A. Savchenkov, A. B. Matsko, V. S. Ilchenko, I. Solomatine, D. Seidel, and L. Maleki, “Tunable optical frequency comb with a crystalline whispering gallery mode resonator,” Phys. Rev. Lett. 101(9), 093902 (2008).
7. I. S. Grudinin, N. Yu, and L. Maleki, “Generation of optical frequency combs with a CaF$_2$ resonator,” Opt. Lett. 34(7), 878–880 (2009).
8. D. Braje, L. Hollberg, and S. Diddams, “Brillouin-enhanced hyperparametric generation of an optical frequency comb in a monolithic highly nonlinear fiber cavity pumped by a cw laser,” Phys. Rev. Lett. 102(19), 193902 (2009).
9. I. H. Agha, Y. Okawachi, and A. L. Gaeta, “Theoretical and experimental investigation of broadband cascaded four-wave mixing in high-Q microresonators,” Opt. Express 17(18), 16209–16215 (2009), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-17-18-16209.
10. P. Del’Haye, T. Herr, E. Gavartin, R. Holzwarth, and T. J. Kippenberg, “Octave spanning frequency comb on a chip,” arXiv:0912.4990v1 (2009), http://arxiv.org/abs/0912.4990.
11. Y. K. Chembo, D. V. Strekalov, and N. Yu, “Spectrum and dynamics of optical frequency combs generated with monolithic whispering gallery mode resonators,” Phys. Rev. Lett. 104(10), 103902 (2010).
12. Y. K. Chembo and N. Yu, “On the generation of octave-spanning optical frequency combs using monolithic whispering-gallery-mode microresonators,” Opt. Lett. 35(16), 2696–2698 (2010).
13. Y. K. Chembo and N. Yu, “Modal expansion approach to optical-frequency-comb generation with monolithic whispering-gallery-mode resonators,” Phys. Rev. A 82(3), 033801 (2010).
14. T. J. Kippenberg, S. M. Spillane, and K. J. Vahala, “Kerr-nonlinearity optical parametric oscillation in an ultrahigh-Q toroid microcavity,” Phys. Rev. Lett. 93(8), 083904 (2004).
15. I. H. Agha, Y. Okawachi, M. A. Foster, J. E. Sharping, and A. L. Gaeta, “Four-wave-mixing parametric oscillations in dispersion-compensated high-Q optical microresonators,” Phys. Rev. A 76(4), 043837 (2007).
16. A. C. Turner, M. A. Foster, A. L. Gaeta, and M. Lipson, “Ultra-low power parametric frequency conversion in a silicon microring resonator,” Opt. Express 16(7), 4881–4887 (2008), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-16-7-4881.
17. J. S. Levy, A. Gondarenko, M. A. Foster, A. C. Turner-Foster, A. L. Gaeta, and M. Lipson, “CMOS-compatible multiple wavelength oscillator for on-chip optical interconnects,” Nat. Photonics 4(1), 37–40 (2010).
1. Introduction

Optical frequency combs enable the precise measurement of optical frequencies through direct referencing to microwave atomic clocks. Future atomic clockwork is expected to utilize optical frequency combs to transfer the rapid oscillations of optical frequency standards to measurable microwave frequency ranges \[1\text{–}3\]. Combs are traditionally generated using mode-locked ultrafast laser sources. Recently, the generation of optical frequency combs through the nonlinear process of continuous-wave optical-parametric oscillation using micrometer-scale resonators has attracted significant interest \[4\text{–}10\] since these devices have the potential to yield highly compact and frequency agile comb sources. The microring resonator structures include silica microtoroids, silica microspheres, silica-fiber Fabry-Perot cavities, and CaF\(_2\) microresonators \[4\text{–}10\]. These demonstrations have yielded impressive results including the generation of spectral bandwidths up to 150 THz (octave-spanning) with a comb spacing of 850 GHz \[10\], as well as with spacing’s as small as 14 GHz but with a reduced bandwidth of 3.7 THz \[7\]. The frequency spacing of the comb generated in microtoroids was found to be equidistant to \(7 \times 10^{18}\) relative to the optical frequency \[4\]. Additionally, stabilization of a microtoroid comb to a microwave source was demonstrated by controlling the pump laser power and frequency in a feedback loop \[5\].

While the full dynamics of parametric comb generation is highly complex and resonator specific \[9,11\text{–}13\], the fundamental mechanism is shared by all geometries. This mechanism relies on a combination of optical parametric amplification and oscillation as a result of the nonlinear optical process of four-wave mixing (FWM) within the resonator \[14\text{–}16\]. Specifically, a single pump laser is tuned to a cavity resonance, and the resulting parametric amplification provides optical gain for the surrounding spectral modes. With sufficient pump power the amplification exceeds the round-trip loss and some of the modes undergo oscillation. The presence of multiple oscillating frequencies leads to FWM that generates light in additional modes. This frequency conversion combined with parametric amplification can lead to a vast cascading of the oscillating frequencies and due to energy conservation the newly generated frequencies are precisely equidistant.

Here we demonstrate the generation of optical frequency combs from a highly-robust CMOS-compatible integrated microring resonator optical parametric oscillator \[17\text{–}20\]. Both the microring resonator and the coupling waveguide are fabricated monolithically in a single silicon
nitride layer using electron-beam lithography and subsequently clad with silica. Existing microresonator comb sources require coupling with fragile and mechanically sensitive tapered or cleaved optical fibers and operation in sealed environments to avoid contaminants, whereas our system yields a fully-monolithic and sealed device with coupling and operation that is insensitive to the surrounding environment.

Fig. 1. CMOS-Compatible Optical Frequency Comb Source. (a) A single pump laser is coupled into the CMOS-compatible silicon nitride microresonator (µOPO) shown in the optical micrograph. A highly nonlinear interaction resulting in four-wave mixing and optical parametric oscillation leads to a vast multiplication of the oscillating frequencies and the generation of an optical frequency comb. (b) Simulated group-velocity dispersion (GVD) of the 750-nm tall by 1500-nm wide silicon nitride waveguide that forms the microresonator. (c) Experimentally measured optical frequency comb generated in this device. The comb spans 75 THz and has a line spacing of 204 GHz, which corresponds to more than 350 lines that are generated.

2. Frequency Comb Generation

An example of the type of structures we employ is the 112-µm-radius microring resonator shown in Fig. 1(a). The free-spectral range of the resonator is 204 GHz, and the loaded quality factor Q of the resonator is measured to be $3 \times 10^5$. The cross-sectional dimensions of the coupling waveguide and the ring are both given by 750-nm tall by 1500-nm wide. As shown in Fig. 1(b), these dimensions are carefully designed to produce anomalous group-velocity dispersion at the pump wavelength of 1550 nm [21,22], and the microring is fabricated as previously described [17]. We inject 300 mW from a tunable diode laser amplified by an erbium-doped fiber amplifier into the coupling waveguide. The polarization of this pump laser is set to the quasi-TE mode of the waveguide, and the laser is tuned onto resonance such that a
stable “thermal-lock” is achieved [5]. As the pump laser is tuned into resonance, the parametric oscillation threshold is reached and cascaded FWM generates an array of new frequencies. Further increase of the pump power within the resonator yields a greater spectral extent and density of comb, and an example spectrum is shown in Fig. 1(c). We observe the generation of more than 350 comb lines spanning over 75 THz (1375 nm to 2100 nm) and spaced by 204 GHz.

For precision measurement, it is desirable to stabilize the DC-offset frequency of the optical frequency comb. The most common method by which to stabilize this parameter is to implement a self-referencing scheme in the form of an $f$-$2f$ interferometer. This method requires the frequency comb to span an octave in bandwidth, an extent which was recently observed in silica microtoroids [10]. The current 75-THz span of our comb is sufficient to implement a $2f$-$3f$ interferometer [23], and we expect to achieve octave-spanning bandwidth in future CMOS-compatible devices by a combination of improved dispersion engineering [22] and increased pump power.

3. Characterization of Comb Quality

For applications in metrology, the generated optical frequencies must be precisely equidistant. Lines generated through cascaded FWM obey this spacing. However, components can also arise from independent oscillations and may not lie on this equidistant comb. Therefore, it is critical to verify that the generated lines represent an equidistant optical frequency comb.

Fig. 2. Multi-Heterodyne Beat Note Detection. (a) Six consecutive comb lines from 1555 nm to 1564 nm are used to perform multi-heterodyne beat-note detection with a 38-MHz reference comb from a mode-locked fiber laser. (b) The six heterodyne beat notes are measured simultaneously with an RF spectrum analyzer. The equidistance of the RF beat notes verifies the equidistance of the six comb modes to within the measurement accuracy of 10 kHz.

3.1 Multi-Heterodyne Beat-Note Detection

To test for this equidistance, we first implement multi-heterodyne beat-note detection with a 38-MHz reference comb from a mode-locked laser. This technique was previously used to characterize the equidistance of silica microtoroid combs [4]. We implement multi-heterodyne beat note detection as follows. The pump laser is tuned onto resonance such that a dense
optical frequency comb is generated, and the pump laser is then locked to a single comb line of the 38-MHz reference comb. We filter out six consecutive generated lines from the microresonator comb in the range of 1555 nm to 1564 nm as shown in Fig. 2(a). These six lines are combined with the reference comb and the beat notes are detected using a 10-GHz-bandwidth photodetector. If the spacing of the microresonator comb is nearly but not exactly an integer multiple of the reference comb spacing, then the RF spectrum measured from the photodetector will show a series of six beat-notes. These tones correspond to the difference in frequency between each of the microresonator comb lines and a nearby tooth of the reference comb. Therefore, the equidistance of the observed RF tones verifies that the comb lines are uniformly spaced in frequency.

The generated RF-spectrum for our measurement is shown in Fig. 2(b), and we find the beat notes equidistant to within the measurement accuracy of 10 kHz. This corresponds to better than $9.7 \times 10^{-9}$ relative to the spectral range of the measurement and better than $5.2 \times 10^{-11}$ relative to the optical frequency. The results of this measurement are comparable to the results of the same measurement carried out on silica-microtoroids [4].

3.2 Parametric Comb Folding

To increase the precision of the measurements, we implement a frequency counter, as was previously implemented with silica-microtoroids by comparing 3 comb lines individually with a locked reference comb [4]. Here we develop a new self-referencing technique, which we term parametric comb folding. This method alleviates the need for a locked reference comb and facilitates the characterization of a large number of lines (70 lines here) over a substantially greater bandwidth (> 100 nm) to a level of precision comparable to previous techniques.

![Experimental diagram of parametric comb folding](image)

Fig. 3. Experimental diagram of parametric comb folding. A frequency counter is used to measure the ratio of the offset lock frequency and the beat note between the original and folded comb lines generated through FWM in a HNLF.

Parametric comb folding is implemented as follows (see Fig. 3). A continuous-wave transfer laser is offset-locked to one of the lines of the microresonator comb under test. This transfer laser is amplified and combined with the comb under test in a highly nonlinear fiber. The strong transfer laser serves as a degenerate pump for four-wave-mixing frequency conversion in the nonlinear fiber. This process converts all the comb lines from one side of the transfer laser to the other side (and vice-versa) such that the newly generated lines are symmetric about the transfer laser (see Fig. 3a). In this way, the transfer laser effectively folds the comb in half about the transfer laser frequency. If the comb under test is symmetric about this frequency then the beat notes measured between the original lines and the generated lines will be twice the beat note between the transfer laser and the comb line it is locked with. Comparing these frequencies using a frequency counter in ratio mode allows for the precise measurement of the comb symmetry about this frequency. The deviation from symmetry is defined as the how far each folded comb line is from the ideal symmetric position. This
deviation is calculated by taking the difference between the measured frequency ratio and the expected value of two and multiplying by the comb line offset lock frequency (5 MHz in this work). To determine that the comb not simply symmetric but is in fact equidistant, we measure the symmetry about two more frequencies (7 and 10 comb lines away from this initial frequency). Three measurement points with no common factors in the separation is critical to eliminate the possibility of periodic symmetry.

The results of this measurement are shown in Fig. 4. The deviation from symmetry across the 115-nm bandwidth is shown for three different symmetry wavelengths. The center of the comb (1545 nm) and 7 and 10 comb lines away (1557 nm and 1562 nm). In all cases, the deviation from symmetry is less than 0.5 Hz over the 115-nm (14.5 THz) span of the measurement. This corresponds to a comb equidistance of $3 \times 10^{-14}$ relative to the measurement range and $3 \times 10^{-15}$ relative to the optical frequency.

4. Conclusions

We have demonstrated the generation of broad-bandwidth (75-THz) optical frequency combs from a highly-robust and compact CMOS-compatible microresonator. We developed a new technique to precisely characterize the generated comb and verified the mode equidistance of...
a 115-nm (14.5 THz) span to better than \(3 \times 10^{-15}\) relative to the optical frequency. Based on these results and the compatibility with CMOS electronics, this extremely compact source can serve as a fully chip-scale replacement for relatively bulky mode-locked lasers in many precision frequency metrology and ultrafast photonic applications. In particular, this robust source is ideal for applications where large comb tooth separation are desired such as the calibration of astronomical spectrographs [24–26], line-by-line pulse shaping [20,27], and ultra-high-speed communications systems.

Acknowledgments

This work was supported by DARPA under the POPS and OAWG programs and by the Center for Nanoscale Systems, supported by the NSF and the New York State Office of Science, Technology and Academic Research. This work was performed in part at the Cornell NanoScale Facility, a member of the National Nanotechnology Infrastructure Network, which is supported by the National Science Foundation (Grant ECS-0335765).