Generation of optical frequency combs with a CaF_2 resonator

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We demonstrate optical frequency combs using the fluorite whispering gallery mode resonator as a nonlinear Kerr medium. Two regimes of generation are observed, giving the record low repetition rate of 13 GHz, equal to the cavity's free spectral range (FSR) or high repetition rates of multiples of cavity FSR. An intermediate regime was also observed. Raman lasing spectrum similar to modulation instability in fibers was observed for the first time to the best of our knowledge. © 2009 Optical Society of America

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Optical frequency combs are new and powerful spectroscopic and metrology tools [1,2]. Conventionally, evenly spaced spectral components of a comb are generated by a mode-locked laser [3]. It was, however, recently demonstrated that combs may also be generated by means of a four-wave-mixing process enhanced in a high-Q whispering gallery mode resonator (WGMR) made of silica [4]. Crystalline WGMRs have a generally higher Q factor [5] and may more easily be fabricated with a larger diameter, providing frequency combs with repetition rates as low as 24 GHz, which are easier to detect [6,7]. It has been possible to control the repetition rate and offset frequency of a WGMR-generated comb through optical power and other experimental parameters [8]. Direct detection of the comb's pulses is thus necessary to realize fine tuning. While commercial frequency combs have repetition rates as low as 0.1 GHz, the high repetition rate of WGMR-based combs complicates implementation of a practical generator.

In this Letter we demonstrate a monolithic optical comb generator with the record low repetition rate of 13 GHz based on an optical resonator with the highest quality factor (as compared to previous combs) of 6×10^9. We also show that the comb may be generated in full, selective, and mixed regimes, where the comb components may have spectral separations of multiples of the cavity free spectral range (FSR). The selection of the generating regime in our experiments appears to be defined by coupling conditions. In addition, we present what we believe to be the first observation of a Raman Stokes spectrum suggestive of modulation instability.

We used an excimer grade calcium fluorite (CaF_2) from Corning to fabricate a WGMR that is 5 mm in diameter and has a 0.1 mm perimeter curvature radius. The resonator axis is coincident with the crystalline [111] direction. We used diamond abrasives to shape and polish the resonator. A very simple setup was used to pump the fluorite resonator with up to 50 mW of optical power at the wavelength of 1560 nm. The Koheras Adjustik fiber laser with kilohertz-range linewidth was used. As schematically shown in Fig. 1, the resonator transmission was monitored by a Thorlabs DET10c photodetector and by a Yokogawa AQ6319 spectrum analyzer. Angle-polished single-mode fiber couplers mounted onto Thorlabs Nanomax stages were used to guide light in and out of the resonator with a coupling efficiency of up to 80%. The setup was enclosed in a dust-free environment that also provided good temperature stability. No direct locking of the laser to a whispering gallery mode (WGM) was employed in this work. Each spectrum was generated by scanning the laser frequency in the vicinity of the WGM having the best coupling efficiency among other modes. The laser frequency was typically scanned through several widths of the WGM resonance by application of a linearly changing voltage to the laser's controller. The WGM profiles were highly nonlinear at the power levels involved in this work. The periodic excitation of a WGM leads to heating of the resonator and to shifting of its spectrum. The laser was manually tuned until the heating of the cavity was balanced by convective and diffusive cooling. This arrangement may be called "thermal lock" and has been successfully used by other researchers [8,9]. To obtain the Q factor of a mode the width of the resonance was measured at low pump power, where the resonator's frequency response is a Lorentzian. The intrinsic Q factor of our resonator was estimated to be $(6\pm1)\times10^9$ and half as much for the measurement conditions where the resonator was close to being critically coupled.

When optical power concentrated in a WGM is high enough, the hyperparametric oscillations mediated by the Kerr nonlinearity [10,11] generate optical

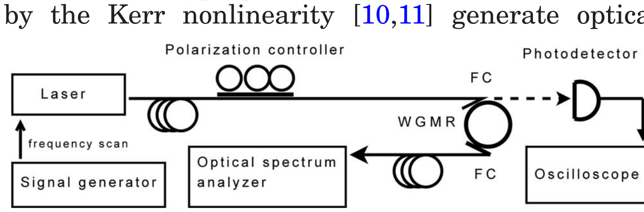

Fig. 1. Experimental scheme. FC, input and output angle polished fiber couplers; WGMR, fluorite resonator.

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sidebands in the resonator. These sidebands are generally located at multiples of cavity FSR away from the pump frequency. A cascaded four-wave-mixing process leads to generation of the wide spectrum of evenly spaced components, as shown in Fig. 2. We also changed the pump power level and the coupling conditions, which led to observation of three intermediate regimes of spectral comb generation. It was previously observed [6] that a comb may be generated at frequency intervals corresponding to multiples of the FSR. Here we observe combs with repetition rates of $m\times$FSR, where m can be 1 or some whole number, but also a combination when two combs are generated simultaneously. Figure 2 shows generation for $m=1$. The comb spacing was used to estimate the resonator diameter D from FSR$=c/\pi nD$. Figure 3 is an example of the regime where the system selects specific multiples of FSR as preferential for sideband generation. The spectrum's energy distribution around the carrier is uneven. Weak, asymmetrical generation at the FSR offset is still present around the pump and sidebands. This regime is interesting, as it provides a single repetition rate comb with frequencies extending into hundreds of gigahertz. Finally, Fig. 4 shows an example of mixed generation, where the frequency comb is generated for $m=1$ and 26 simultaneously. Recent work [6] has emphasized that it is possible to lock the laser to the cavity mode and control selective generation of combs for different multiples of FSR by changing the laser detuning from the cavity WGM center. However, no direct lock was implemented in this work, and the only difference between the circumstances under which the spectra were obtained were the coupling conditions and small variations in the pump power level. It is unclear why these particular offsets are enhanced and what defines them. We speculate that in this regime coupling to more than one WGM is realized, leading to interference of various comb components. A monolithic comb generator based on a single-

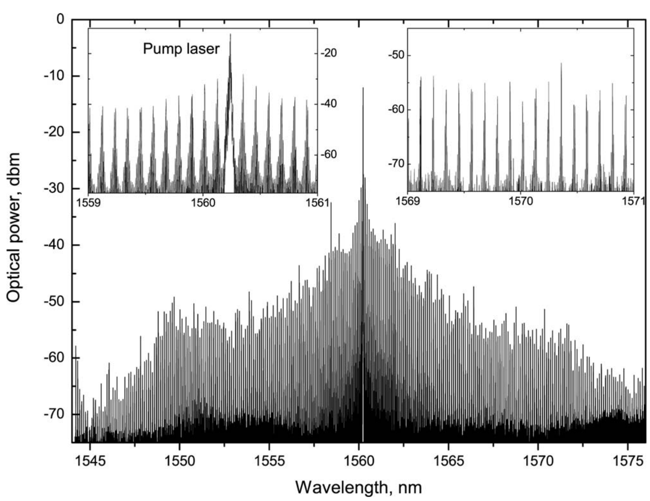

Fig. 2. Optical frequency comb generated in a fluorite resonator. Comb lines are spaced 0.112 nm apart, which translates into cavity FSR of 13.81 GHz and resonator diameter of 4.85 mm. The input optical power at 1560 nm is 25 mW.

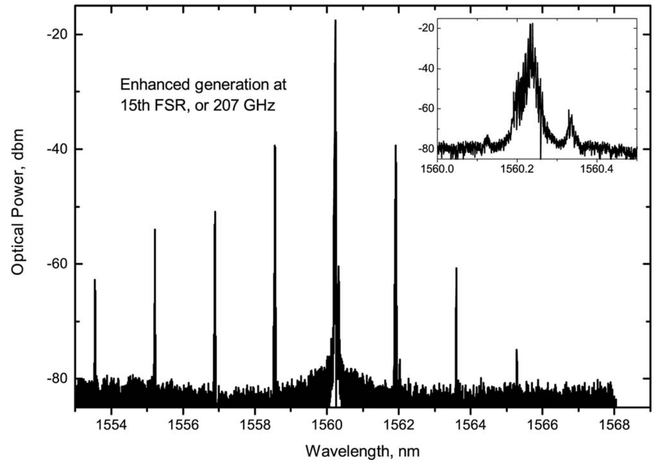

Fig. 3. Frequency comb generated by a fluorite resonator in a selective regime. Generation is enhanced at frequency offsets equal to 15 cavity FSRs.

mode resonator geometry [12] may resolve these complications.

The Raman-active phonon branch of fluorite has a wave vector $k=2\pi\times 322\ \mathrm{cm}^{-1}$, which for the 1560 nm pump corresponds to the Stokes component at 1643 nm and the anti-Stokes at 1485 nm. While the Stokes components have been extensively observed [13,14], to our knowledge no evidence of the anti-Stokes lasing has ever been seen in WGMRs. In thermal equilibrium the population of the excited vibrational level responsible for Raman transition is less than the ground level population by a Boltzmann factor of $\exp(-\hbar\omega_R/kT)\simeq 0.21$, where ω_R is the Raman frequency shift in fluorite. As long as there is no population inversion between the levels involved in Raman transition, the anti-Stokes beam will experience damping. In our experiments, generation of a comb was accompanied by Raman Stokes generation. Under high pump power, some weak anti-Stokes components are visible, which may be explained by nonlinear four-wave mixing between pump and Raman beams. Under high pump power the Raman spectrum has developed the sidebands that were not previously observed in WGMRs. One possible expla-

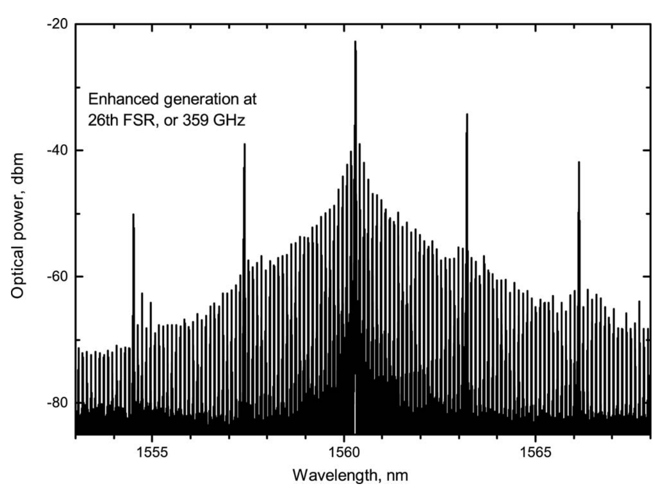

Fig. 4. Frequency comb generated in a mixed regime. Besides components regularly spaced by cavity FSR, selectively enhanced generation is observed at 26 cavity FSRs.

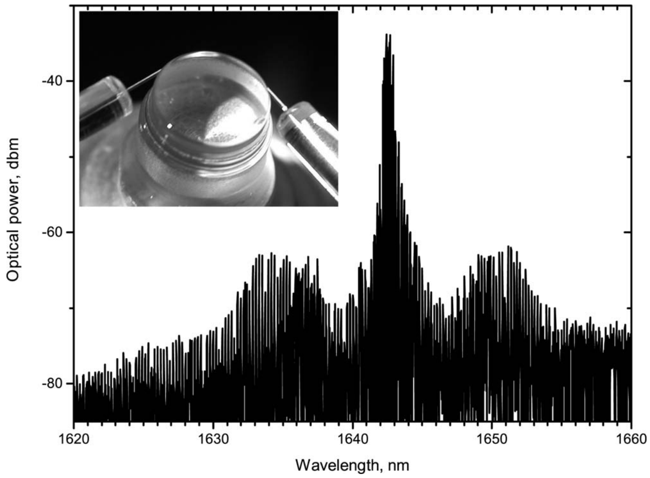

Fig. 5. Intensity envelope spectrum recorded by the periodic excitation of the WGM. Raman lasing Stokes intensity spectrum exhibits two sidebands at 1635 and 1650 nm. Pump power is 20 mW. The inset shows the resonator with two fiber couplers. The sidebands may be explained by modulation instability.

nation for the spectrum presented in Fig. 5 is that the intensity of Stokes components was strong enough to generate its own spectral comb. However, the intensity envelope of this comb is significantly different from that generated by the pump laser. The spectrum resembles that of modulation instability [15], which appears because of the cross-phase modulation between the pump and the Raman beams [16].

Cavity dispersion, or change in FSR over adjacent optical modes, has two contributions [4,17]. Geometrical dispersion is normal and for our cavity is $\Delta\mathrm{FSR}=(\nu_{m+1}-\nu_m)-(\nu_m-\nu_{m-1})\simeq-600$ Hz at 1550 nm. The material dispersion changes sign near 1550 nm, as can be found from a four-term Sellmeier equation. The total cavity dispersion remains smaller than optical mode bandwidth (64 kHz) allowing for generation of a spectral comb. It is worth noting, however, that under strong optical pump conditions, the cavity dispersion will be modified by "mode pulling" effects owing to cross- and self-phase modulation. In addition, studies of dispersion in real fluorite cavities [18] show that significant deviations from theory may take place owing to impurities.

In conclusion, we have demonstrated generation of optical frequency combs in a fluorite WGMR in selective and nonselective regimes and also in a combined regime. We have demonstrated the lowest repetition rate of a WGMR-based comb of 13 GHz generated with the WGMs having the highest Q factor of 6×10^9 ever used for this purpose. Our observations suggest that selection of generation regimes is determined by coupling conditions and pump power values. The low repetition rate of our comb in the nonselective regime (13 GHz) makes it easier to measure and control in practical applications, and represents an important step toward a compact monolithic frequency comb generator. Higher frequencies generated in the selective regime may also be useful for optical generations of microwave beatnotes. We have also observed the Raman Stokes spectrum suggestive of a modulation instability process.

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References

1. Th. Udem, R. Holzwarth, and T. W. Haensch, Nature **416**, 233 (2002).
2. S. T. Cundiff and J. Ye, Rev. Mod. Phys. **75**, 325 (2003).
3. J. D. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, Science **288**, 635 (2000).
4. P. Del'Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, and T. J. Kippenberg, Nature **450**, 1214 (2007).
5. A. A. Savchenkov, A. B. Matsko, V. S. Ilchenko, and L. Maleki, Opt. Express **15**, 6768 (2007).
6. A. A. Savchenkov, A. B. Matsko, V. S. Ilchenko, I. Solomatine, D. Seidel, and L. Maleki, Phys. Rev. Lett. **101**, 093902 (2008).
7. D. V. Strekalov and N. Yu, arXiv:0807.1909v1.
8. P. Del'Haye, O. Arcizet, A. Schliesser, R. Holzwarth, and T. J. Kippenberg, Phys. Rev. Lett. **101**, 053903 (2008).
9. T. Carmon, L. Yang, and K. J. Vahala, Opt. Express **12**, 4742 (2004).
10. T. J. Kippenberg, S. M. Spillane, and K. J. Vahala, Phys. Rev. Lett. **93**, 083904 (2004).
11. A. A. Savchenkov, A. B. Matsko, D. Strekalov, M. Mohageg, V. S. Ilchenko, and L. Maleki, Phys. Rev. Lett. **93**, 243905 (2004).
12. A. A. Savchenkov, I. S. Grudinin, A. B. Matsko, D. Strekalov, M. Mohageg, V. S. Ilchenko, and L. Maleki, Opt. Lett. **31**, 1313 (2006).
13. S. M. Spillane, T. J. Kippenberg, and K. J. Vahala, Nature **415**, 621 (2002).
14. I. S. Grudinin and L. Maleki, Opt. Lett. **32**, 166 (2007).
15. S. Pitois and G. Millot, Opt. Commun. **226**, 415 (2003).
16. G. P. Agrawal, P. L. Baldeck, and R. R. Alfano, Phys. Rev. A **39**, 3406 (1989).
17. L. Maleki, A. A. Savchenkov, V. S. Ilchenko, and A. B. Matsko, Proc. SPIE **5104**, 1 (2003).
18. A. A. Savchenkov, E. Rubiola, A. B. Matsko, V. S. Ilchenko, and L. Maleki, Opt. Express **16**, 4130 (2008).