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Large bandwidth from a tiny device

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Microresonator-based optical frequency comb generators convert a continuous-wave laser into an octave-spanning spectrum covering a wavelength range of 1–2μm.

Since their inception a decade ago, optical frequency combs have transformed the fields of spectroscopy and metrology. In 2005, they were awarded a part of the Nobel Prize in Physics.[1] Their development was triggered by the demand for a technology that can precisely measure optical frequencies and compare them to our present microwave time/frequency standard, the cesium atomic clock. Initially, optical frequency combs were mainly intended for fundamental research, in particular for precise measurements of atomic transitions to test fundamental laws of physics. However, in recent years more and more applications have emerged with high potential for chemical sensing, astrophysical spectrometer calibration, arbitrary waveform generation, and as channel generators for telecommunication. Here the combs are used as rulers in the frequency domain.

An optical frequency comb represents a rainbow of different colors. However, as the name already suggests, the spectrum is not continuous but consists of discrete, comblike frequency 'teeth.' The whole comb is completely defined by two parameters: the spacing between the teeth, f_{rep}, and an overall offset, f_{ceo}, such that the frequency of the n^{th} comb line, f_n, is given by

$$f_n = f_{\mathrm{rep}} + n \cdot f_{\mathrm{ceo}}. \quad (1)$$

Conventional optical frequency combs are generated by mode-locked lasers emitting a train of short laser pulses. Fourier analysis shows that such a train corresponds to a comb spectrum in the frequency domain and that f_{rep} corresponds to the rate at which light pulses are emitted. In contrast, the generation of a microresonator-based frequency comb can be completely described as mixing of lightwaves at different frequencies (colors), resulting from extremely high circulating powers within a tiny resonator.[2–4] Compared to conventional frequency combs, the light emitted by a microresonator comb is not necessarily pulsed. However, the exact temporal behavior of the emitted light is still under investigation. Figure 1(b) shows the basic principle. A continuous-wave pump laser (frequency, f_{pump}) is converted into a pair of symmetric sidebands (referred to as signal, f_s, and idler, f_i). The equidistance of the first pair of sidebands with respect to the pump laser is ensured by energy conservation of the underlying four-wave mixing process, in which two pump photons are converted into one signal and one idler photon:

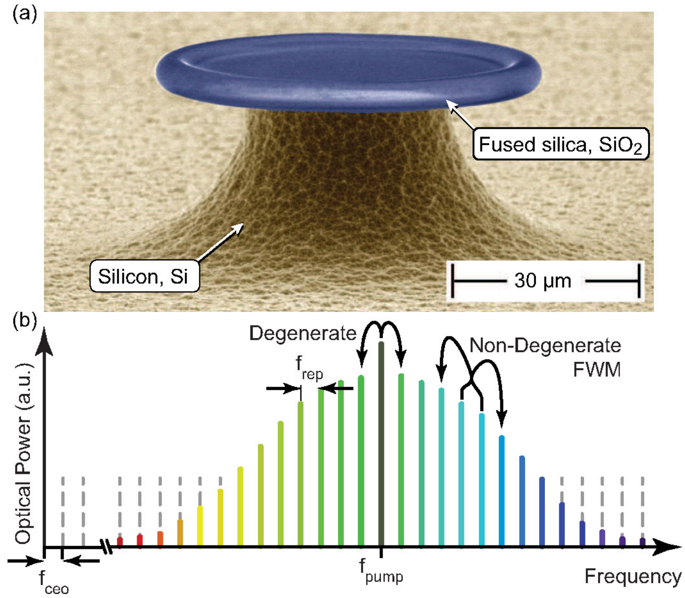

Figure 1. Microresonator-based frequency comb generation. (a) Scanning electron microscope image of a fused silica (SiO_2) microtoroid used to produce nonlinear optical effects for generating frequency combs. Light is coupled into these resonators by way of optical nanofibers and travels around the circumference of the SiO_2 toroid up to one million times before being scattered out of the resonator. (b) The high-power enhancement of the resonator converts a single-frequency pump laser (f_{pump}) into an optical frequency comb through four-wave mixing (FWM). f_{rep}: Spacing between comb teeth. f_{ceo}: Overall offset of the comb. a.u.: Arbitrary units.

$$2f_{\mathrm{pump}} = f_s + f_i. \quad (2)$$

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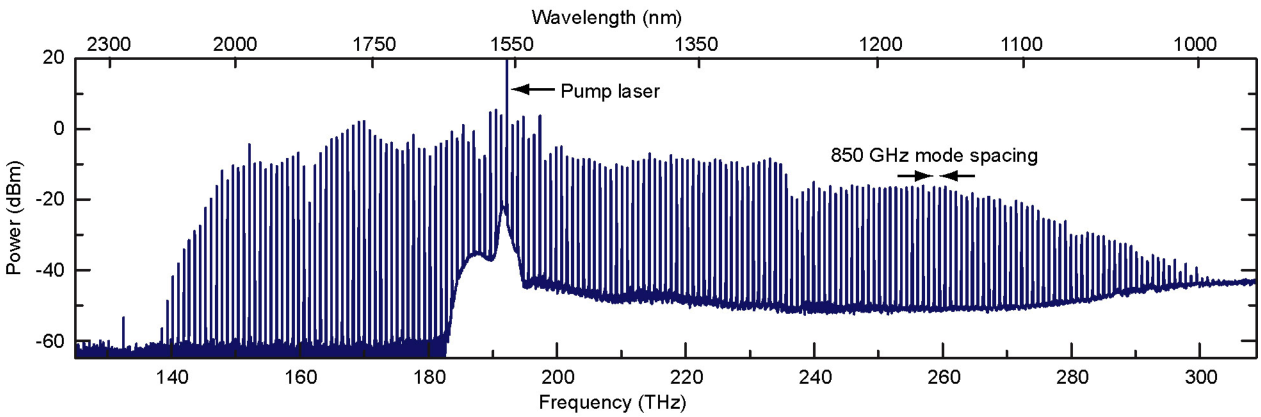

Figure 2. *Octave-spanning spectrum generated from a continuous-wave pump laser in a microresonator.*

Further cascading of the process through non-degenerate four-wave mixing leads to the production of more and more higher-order sidebands forming an optical frequency comb (see Figure 2). A major difference compared with conventional mode-locked lasers is that the pump laser is part of the comb, and thus can be used to control and stabilize the comb modes.[5]

The field of microcombs has grown rapidly since they appeared in 2007. Meanwhile, others have reported a number of different microresonator systems showing frequency comb generation, including hand-polished crystalline resonators[6] for direct frequency combs in the mid-IR[7] (which is of high interest for molecular spectroscopy). A further step toward full CMOS-compatible integration of microresonator combs has been achieved using silicon nitride ring resonators that are directly combined with on-chip waveguides.[8] These devices can be sealed with a protection layer and have huge potential in the design of novel microphotonic circuits.

In summary, we have shown that optical microresonators are viable tools for generating optical frequency combs. Future steps in microresonator comb research include further integration of microresonator comb generators with on-chip waveguides, dispersion engineering for combs in new wavelength regions, and investigation of noise processes within the resonators.

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References

1. T. W. Hansch, *Nobel lecture: passion for precision*, **Rev. Mod. Phys. 78** (4), pp. 1297–1309, 2006.
2. 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), pp. 1214–1217, 2007.
3. P. Del'Haye, T. Herr, E. Gavartin, M. L. Gorodetsky, R. Holzwarth, and T. J. Kippenberg, *Octave spanning tunable frequency comb from a microresonator*, **Phys. Rev. Lett. 107** (6), p. 063901, 2011. doi:10.1103/PhysRevLett.107.063901
4. T. J. Kippenberg, R. Holzwarth, and S. A. Diddams, *Microresonator-based optical frequency combs*, **Science 332** (6029), pp. 555–559, 2011.

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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), p. 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), p. 093902, 2008.
7. C. Y. Wang, T. Herr, P. Del'Haye, A. Schliesser, J. Hofer, R. Holzwarth, T. W. Hänsch, N. Picqué, and T. J. Kippenberg, *Mid-infrared optical frequency combs based on crystalline microresonators*, **eprint arXiv:1109.2716**, 2011.
8. 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. Photon. 4** (1), pp. 37–40, 2010.