10-GHz Self-Referenced Optical Frequency Comb

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A mode-locked femtosecond laser emits an evenly spaced grid of frequencies that can be phase-coherently linked to a primary frequency standard, that is, to a cesium atomic clock. Such frequency combs can cover the entire visible and near-infrared spectral regions and have become invaluable as precise frequency rulers for modern optical frequency metrology (*1*). However, the teeth of the combs have been too densely spaced (0.1 to 1 GHz) to be spectrally resolved in a straightforward manner and are thus not accessible for individual use. Combs with large mode spacings (i.e., greater than 10 GHz) have required compromises both in terms of bandwidth and average power, resulting in pulses that are too weak and too long in duration for efficient nonlinear spectral broadening. By taking advantage of a combination of laser and fiber optic technology, we overcame these limitations of power and bandwidth to directly make a 10-GHz frequency comb. The result is more than 50,000 modes spanning a wavelength range from 470 to 1130 nm that can be directly resolved with a diffraction grating, a result that should accelerate progress in diverse applications including precision spectroscopy with individual comb teeth (*2*); calibration of high-resolution astronomical spectrographs (*3*, *4*); and synthesis of optical, terahertz, and microwave waveforms via line-by-line pulse shaping (*5*).

Our frequency comb is based on a Ti:sapphire laser with a 30-mm-long ring cavity (Fig. 1) (*6*, *7*). The roundtrip period is only 100 ps, resulting in a repetition rate and thus a frequency comb spacing of f_R = 10 GHz. For a femtosecond laser, the 1.2-W average output power is relatively high; however, this translates to a pulse energy of merely 120 pJ at the output and only ~6 nJ circulating inside the cavity. At such low pulse energies, care must be taken to maintain a high peak intensity in the Ti:sapphire crystal in order to support stable pulsed operation via Kerr-lens-mode-locking. We account for this requirement by using tight focusing into the gain crystal and appropriately balancing the intracavity dispersion to support pulses with a duration below 40 fs. The direct output spectrum of the laser (Fig. 1) shows that, for the ~1200 modes within the full width at half maximum, 0.5 mW per individual 10 GHz mode is exceeded, an impressive combination of power and bandwidth among existing frequency comb sources.

Absolute frequency stabilization of the comb requires measurement and control of both the repetition rate (f_R) and the comb's offset frequency (f_0). f_R is easily measured with a fast photodiode, whereas f_0 is measured with a nonlinear f-2f interferometer after spectral broadening of the laser output to more than an octave (*1*). In our case, spectral broadening is achieved in a microstructured fiber with a 1.5-μm core and negative group velocity dispersion at the wavelength of the laser (*7*). A key feature of the fiber is its sealed input, which allows us to achieve coupling efficiency of 50%, yielding more than 500 mW of average power at its output. We achieve spectral coverage from about 470 to 1130 nm (Fig. 1). Common servo techniques are used to phase-lock f_0 and f_R to frequency references that are calibrated by a Cs atomic clock or a more readily accessible representation of the second, for example, a quartz oscillator disciplined by the global positioning system.

Because of the large mode spacing of the comb, a simple grating spectrometer with a resolving power of $\lambda/\Delta\lambda = 6 \times 10^4$ is sufficient to resolve and spatially separate the individual comb elements. Real-color images of the resolved modes were acquired at wavelengths of 490 nm, 540 nm, 583 nm, and 632 nm, through a microscope with a digital camera (Fig. 1). Although the modes at the longest three wavelengths are clearly resolved, we are approaching the resolution limit at 490 nm. Once resolved, the modes are available as precise frequency markers, for example, in astronomic spectrograph calibration. This application should specifically benefit from the wide spectral coverage of our source extending over ~350 THz at a power level exceeding 1 nW per mode, a performance currently unachievable with existing mode-filtering approaches. Selection of individual modes via simple spatial filters or even manipulation in amplitude and phase by use of spatial light modulators is straightforward and can provide a freely programmable array of precisely defined light sources with an inherently high degree of mutual coherence. Such a device would be highly valuable for spectroscopy or Fourier synthesis of arbitrary waveforms via linear superposition and nonlinear mixing and frequency conversion.

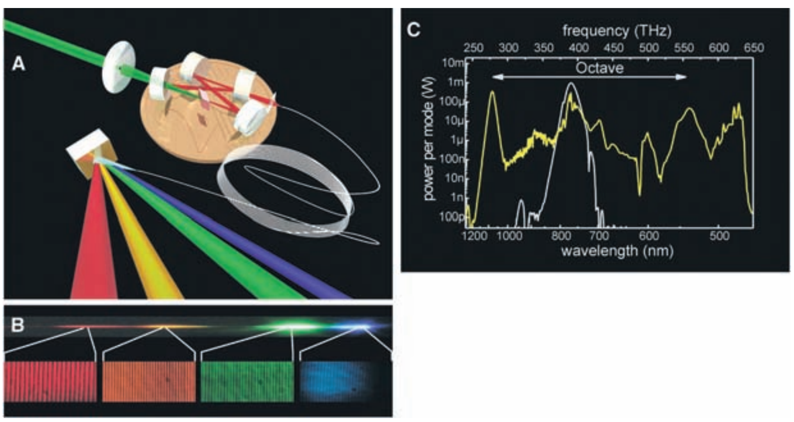

Fig. 1. (**A**) Illustration of the 10-GHz laser cavity. A 0.02-€ coin is shown for size comparison. The nonlinear fiber and diffraction grating dispersing the white light are also illustrated. (**B**) Real-color image of the spectrally dispersed visible part of the continuum and a magnified view of the individually resolved frequency comb modes at wavelengths of 490 nm, 540 nm, 583 nm, and 632 nm. (**C**) Low-resolution measurements of the direct laser output spectrum (gray line) and quasi-continuum output after broadening in nonlinear fiber (yellow line) on a power-per-mode scale.

References and Notes

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7. Materials and methods are available as supporting material on *Science* Online.
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Supporting Online Material

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Materials and Methods
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Fig. S1
References and Notes

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