APPLICATION NOTE

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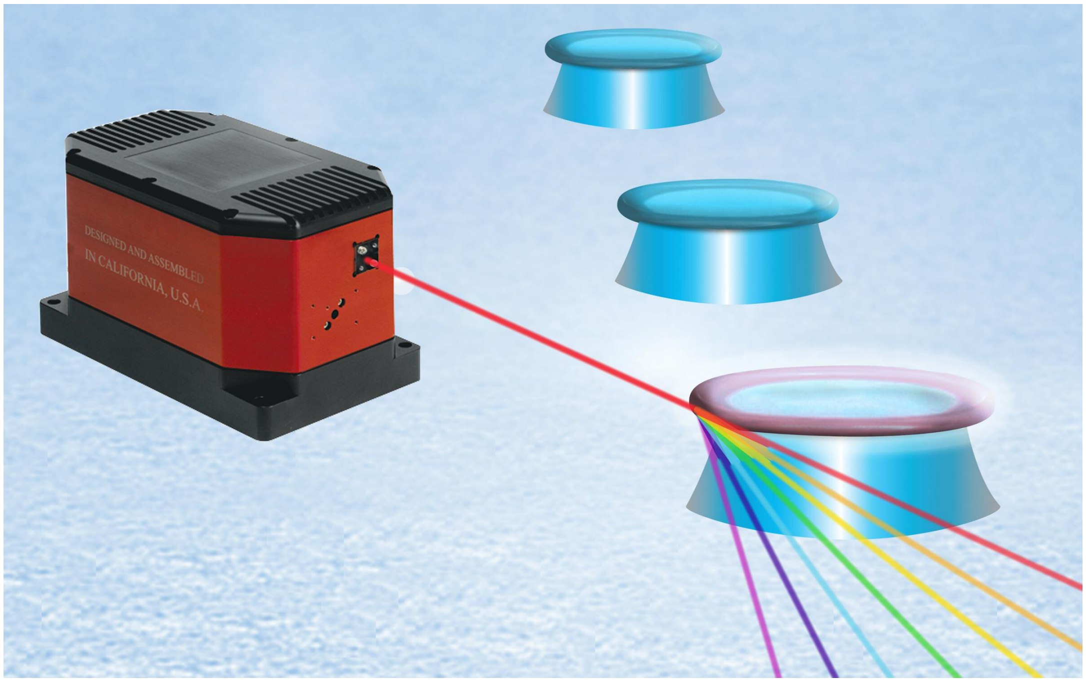
Frequency Comb Research Advances Using Tunable Diode Lasers



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Frequency Comb Research Advances Using Tunable Diode Lasers

The discovery of the optical frequency comb and the breakthrough work of Hänsch and Hall in refining the frequency comb technique have revolutionized the field of scientific metrology. [1] Optical frequency combs now allow for a more precise measurement of frequencies in the optical domain (≈400-800 THz) by permitting for direct, phase-coherent comparison to electronically manageable microwave and radio frequencies (≈3 Hz-300 GHz). The optical frequency comb is also poised to profoundly impact the precise measurement of time as it represents the long sought-after clockwork needed for the all optical atomic clock. Beyond applications in precise frequency and time measurement, frequency combs are also finding application as versatile tools in molecular spectroscopy owing to their high spectral resolution, phase coherence among the comb lines, and broad spectral coverage.

The ideal optical frequency comb is essentially a spectrum in the THz region comprised of equidistant, phase coherent lines. It is obtained from the Fourier decomposition of ultrashort femtosecond pulses, as emitted from say a Ti:sapphire laser, into their component frequencies.

A simple description starts with the femtosecond pulse circulating inside of the mode-locked laser cavity. With each roundtrip, an attenuated copy of the pulse escapes through the output coupler to give a train of ultrashort pulses (see Fig. 1) separated in time by T, equal to inverse of the pulse repetition rate f_{rep}. Due to dispersion in the cavity, the average carrier and group velocities will differ and the carrier "slips" within the pulse envelope (Fig. 1a), with respect to the pulse envelope frame. This slipping ultimately leads to the frequency comb being shifted by an amount f_0, called the offset frequency. It is common to see the entire frequency comb expressed in terms of just two degrees of freedom, f_{rep} and f_0, both microwave frequencies; the frequency of comb line n is given by

$$\nu_n = n\, f_{\text{rep}} + f_0.$$

Therefore, by controlling only two degrees of freedom, the mode-locking of a femtosecond laser enforces the equidistant spacing of comb lines across the spectrum. Controlling and stabilizing f_{rep} and f_0 is now routine in many labs now and represents a robust method for phase coherence and stability from a reference from anywhere in the electromagnetic spectrum.

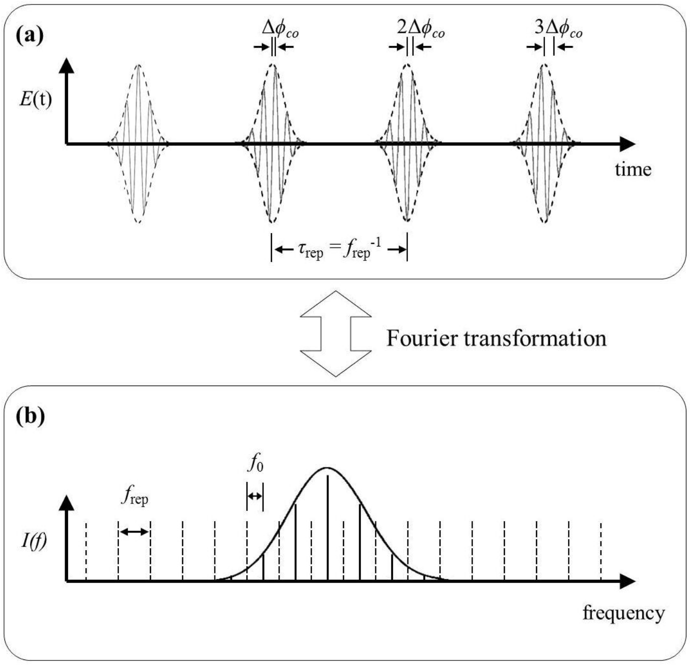

Figure 1. Time and frequency domain pictures of output of mode-locked laser. (a) Train of ultrashort pulses separated in time by T, equal to inverse of the pulse repetition rate f_{rep}. Due to dispersion in the cavity, the average carrier and group velocities, υ_p and υ_g, will differ and the carrier is seen as "slipping" within the pulse envelope. After a round-trip through the cavity, the carrier will pick up in phase an integer multiple of 2π plus some phase offset $\Delta\phi$co due to the mismatch in υ_p and υ_g. (b) Frequency comb resulting from Fourier transform of each pulse's temporal envelope. Comb lines are separated in frequency by f_{rep} and offset from cavity modes by f_0. Dashed lines represent cavity modes.

A more recent, alternative approach [2] to frequency comb generation does not rely on the femtosecond pulses of a mode-locked laser. Instead, a continuous-wave (CW) tunable external cavity diode laser (ECDL) is used to pump a miniaturized, circular high-Q microresonator above some threshold power to give a frequency comb. One of New Focus' areas of expertise is the ECDL, so in the remainder of this application note we will look more closely at how the so-called "microcombs" are generated and what the role of ECDLs, such as the *Velocity*™ laser, is in the microcomb generation process. We will briefly discuss how the microcomb is evolving into a compact, versatile tool with increasing application, for example, in the field of molecular spectroscopy. Although still maturing, the field of microcombs has the potential to transform various other disciplines, leading to compact comb generation platforms with numerous applications.

Microcomb Generation

Many groups are moving towards the generation of microcombs using microresonators, which can be fabricated “on-chip”. Microresonators are compact devices (few hundred nanometers in size), can confine pump photons for long periods of time in resonator modes with extremely small volumes to give large intracavity intensities (GW/cm^2), and can therefore facilitate the nonlinear frequency conversion necessary to generate the comb. In some of the earliest reported devices, thresholds for nonlinear conversion were on the order of only tens of microwatts. [2]

To generate the comb, light from a tunable, single-frequency ECDL pump laser is coupled through a waveguide into the high-Q (up to 10^9) microresonator device by bringing the waveguide into close proximity to the device. Here, a narrow linewidth, widely tunable ECDL source is key as device resonances are narrow (sub-MHz) and may be separated by a free-spectral range of several nanometers. On resonance, light is confined in the device for up to nanoseconds, and the effective power density in the device is increased.

Figure 2 depicts the microcomb generation process. Once the threshold power for nonlinear conversion has been reached, signal and idler sidebands (at f_s and f_i) are generated via four-wave mixing (FWM) involving two pump photons: $f_p + f_p = f_s + f_i$. Signal and idler will be separated in frequency from the pump by a distance governed by the cavity modes of the microresonator. Four wave mixing involving the sidebands at f_s and f_i results in the generation of secondary sidebands, f_s' and f_i. The whole comb is formed as the sidebands (by now f_s, f_i, f_s', and f_i') continue to interact with the pump light and among themselves to create even more sidebands. Careful dispersion engineering of the device and choice of ECDL pumping scheme [3] ensures that the generated sidebands are resonant with the mode structure of the microcavity and that a single comb is obtained with evenly spaced lines. Following generation, the microcomb couples from the device into the waveguide, is extracted, filtered, and sometimes further broadened through other nonlinear means.

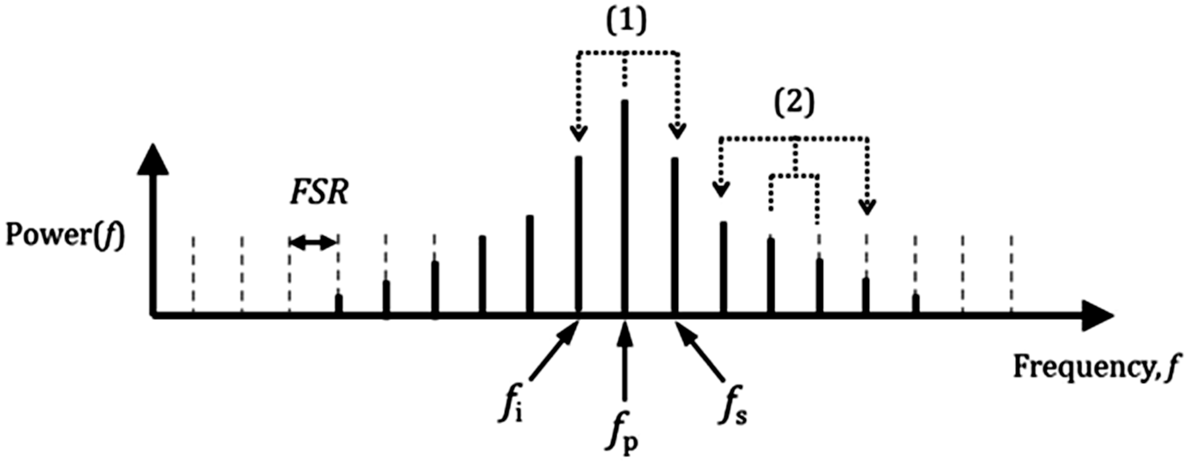

Figure 2. *Four wave mixing leading to microcomb generation. Degenerate* FWM, *labeled* (1), *leads to primary sidebands* f_s *and* f_i. *These interact with the pump and among one another to give more sidebands. One example of non-degenerate* FWM *is labeled* (2). *Dashed lines represent microcavity modes separated by free spectral range* (FSR).

Microcombs Have Potential in Molecular Spectroscopy

The extension of traditional frequency combs and now microcombs into the mid-IR spectral range has attracted much attention because of the presence of numerous gas absorption lines in the "molecular fingerprint" region. Here, most molecules exhibit strong rotational-vibrational signatures which can be used to uniquely identify them, as a fingerprint is used to identify a person. In a molecular spectroscopic measurement, a frequency comb can be used to measure the frequency of a laser used to probe a molecular sample; however, the hundreds to thousands of lines from the comb itself can be used to directly interrogate a sample resulting in highly multiplexed spectra covering a broad spectral bandwidth.

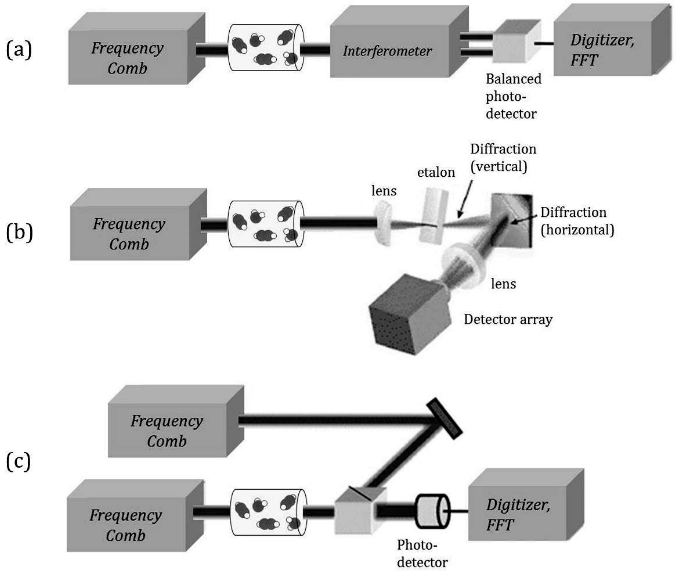

Figure 3. *Frequency comb absorption molecular spectroscopy. (a) Frequency comb Fourier spectroscopy, (b) dispersive, cavity-enhanced comb spectroscopy, (c) dual-comb spectroscopy.*

Traditional frequency combs have been used in absorption molecular spectroscopy employing a number of successful configurations: by starting with a single comb Fourier and dispersive cavity ringdown spectroscopy have been used to successfully measure the overtone or combination band spectra of molecules such as C_2H_2 [4, 5] O_2, H_2O, and NH_3 [5]. Dual-comb spectroscopy is another approach in which the sample is interrogated by a frequency comb and a heterodyne beat of this comb is measured against a second reference comb. [6] This approach works in any spectral region and only requires a single detector, as opposed to the dispersive-cavity enhanced method. Moreover, it does not require any moving parts as is the case for Michelson-based techniques. The output signal is a comb of radio frequencies resulting from the interference of the two combs. Therefore, it is possible to adopt the same configuration using a microcomb source.

There are few reports of microcomb-based molecular spectra, however, as the field is in its infancy. In fact, it was only until recently that microcomb generation in the mid-IR was reported [7, 8] after pumping a microresonator with hundreds of milliwatts of power from a CW-OPO. In proof of concept experiments, microcombs were used to measure the spectra of gas-phase C_2H_2 from 2.1 to 3.5 µm [7] and liquid acetone at wavelengths below 2.5 µm [8]. Thus, the sharp lines of a comb prove very useful not only in recording high-resolution molecular spectra, but also in the measurement of broadband features (here, liquid acetone).

As the field continues to develop, microcomb-based molecular spectroscopic studies will push forward into the fingerprint region and be increasingly quantitative. Many distinguished groups around the world continue to study microcombs and advances in CW laser technology, including new ECDL sources in the IR [9] and even the UV [10], will certainly facilitate microcomb generation in new wavelength regions.

Summary

Microcomb research continues to advance as the miniaturized comb offers many of the same advantages of traditional frequency combs, with wider mode spacing, a much smaller, micrometer-size platform, and the potential for on-chip compatibility. As on-chip microresonator engineering and frequency comb techniques continue to evolve, microcombs will become increasingly accessible tools and novel applications will come within reach. Microcomb-based molecular spectroscopy shows great promise though several challenges remain, one of which is the limited choice of comb sources in the mid-IR and UV spectral ranges. With the first microcomb demonstrated using New Focus ECDL technology, however, a recent push into new wavelength regimes may help advance microcomb research and bring it even closer to new cutting-edge applications.

References

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9. Model TLB-6736 *Velocity* laser, approximate tuning range 1975-2075 nm.
10. Model TLB-6704 *Velocity* laser, approximate tuning range 405-410 nm.

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