Highly selective terahertz optical frequency comb generator

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Using a 10.5-GHz resonant electro-optic modulator placed inside a resonant optical cavity, we generated an optical frequency comb with a span wider than 3 THz. The optical resonator consists of three mirrors, with the output coupler being a thin Fabry–Perot cavity with a free spectral range of 2 THz and a finesse of 400. Tuning this filter cavity onto resonance with a particular high-order sideband permits efficient output coupling of the desired sideband power from the comb generator, while keeping all other sidebands inside for continued comb generation. This spectrally pure output light was then heterodyne detected by another laser with a frequency offset of the order of 1 THz.

Recently there has been tremendous progress toward the high-resolution spectroscopy of narrow-linewidth lasers and supersharp absorbers. Several high-accuracy optical frequency references in the visible have been proposed and realized.[1–4] This has resulted in parallel development of precise optical frequency measurement techniques. A key step is the ability to bridge wide frequency intervals, usually more than a few terahertz, phase coherently. Several approaches have been developed, including frequency-interval bisections,[5] optical parametric oscillations,[6] optical comb generations,[7,8] and frequency division by three.[9]

An optical frequency comb (OFC) generator is a simple system that uses only one laser. Yet it offers the unique property of supplying a comb of equally spaced spectral lines around the carrier. These lines are modulation sidebands generated by an electro-optic modulator (EOM). To enhance the optical–rf field interactions, one places the EOM inside a low-loss optical cavity in resonance with the carrier and all the sidebands. In other words, the rf modulation frequency equals an integer multiple of the cavity free spectral range (FSR). In principle, the span of the generated comb is limited only by the system dispersion, which one can carefully compensate by following designs used in ultrafast laser systems. A 4-THz-wide OFC was already observed at 1.5 μm,[7] showing the possibility of shifting 2% of the optical frequency in a single step. We note that an appropriately low-noise rf oscillator should be used to drive the EOM so that high-order sidebands do not quickly collapse because of the multiplied phase-noise amplitude.

The power spectrum of the OFC is shown[7] to be proportional to an exponential function. Denoting P_k as the power of the kth sideband, we have

$$P_k \propto \exp\left(-\frac{|k|\pi}{\beta F}\right), \qquad (1)$$

where β is the modulation index of the EOM and F is the finesse of the crystal-loaded cavity. Macfarlane *et al.*[10] added an important partial mirror in the input to recycle rejected carrier light back into the OFC, thereby improving the input coupling efficiency. Although the rich spectrum of their comb is useful in generating short optical pulses, for the purpose of optical frequency metrology it is preferrable to have a single pure spectral line. Hall[11] suggested an efficiency improvement of the comb generator by replacing one of the cavity mirrors with a short filter cavity to output resonantly an individual sideband from the comb. If the FSR of the filter cavity is larger than the comb width, then the filter will be resonance free until one reaches the desired sideband. Therefore the filter cavity will not alter the comb-generation process until a good match occurs between its resonance and a sideband, beyond which the comb spectrum will be cut off sharply. Although the original proposal[11] was to use the filter cavity for in-coupling improvement as well, here we used the extra resonator only as a selective output coupler. The filtered single spectral line can be conveniently detected by use of heterodyne mixing with a tunable laser source. Because we extract the full power of the chosen sideband from out of the comb generator while keeping the carrier and all other sidebands trapped inside, we can expect an important improvement of the detection signal-to-noise ratio (SNR). This is evidenced by a comparison of the resultant power SNR in heterodyne detection of the kth sideband in two configurations, a simple comb generator,

$$\mathrm{SNR}_k(\text{power}) = \frac{\eta T P_k P_{\text{ref}}}{2eB\left(T\sum_{k=-\infty}^{+\infty} P_k + P_{\text{ref}}\right)}, \qquad (2)$$

and a comb generator with a filter cavity,

$$\mathrm{SNR}_k(\text{power}) = \frac{\eta \chi P_k P_{\text{ref}}}{2eB\left(\chi P_k + P_{\text{ref}}\right)} \cdot \qquad (3)$$

Here e is the electron charge, B is the detection bandwidth, and η is the detector's efficiency in amps per watt. P_{ref} denotes the power of the reference laser, and P_k is the power of the kth sideband inside a comb generator. T represents the power-transmission coefficient of the output coupling mirror of a simple comb generator, and χ is the filter cavity's resonant transmission efficiency. Using a filter cavity not only increases the signal size of the heterodyne term by a factor of χ/T (usually $T < 1\%$) but also decreases the noise level determined by dc power, as the larger

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powers distributed among the carrier and lower-order sidebands are not detected.

In this experiment we used a prototype EOM.[12] It consists of a broadband antireflection-coated Mg:Li-NbO_3 crystal (2 mm × 1 mm × 35.4 mm) embedded in a resonant microwave cavity. The cavity design uses a waveguide geometry to force the match between the microwave phase velocity and the optical group velocity through the crystal. The microwave resonance at 10.5 GHz has a bandwidth of ~0.3 GHz and a Q factor of 230. A modulation index of ~0.8 was obtained with a microwave power of 0.6 W. This EOM is placed inside our three-mirror cavity, as shown in Fig. 1. All three mirrors are identical lens substrates with an effective focal length of 25 cm. The convex faces were antireflection coated at 633 nm, and the flat faces were coated to have high reflectivity, ~99.6%. With two such mirrors (M1 and M2) we built a cavity with a finesse of 680 and a transmission efficiency of 20%, implying a transmission coefficient (T) of 0.2% for each mirror. The cavity FSR was 1/16 of the EOM rf frequency. When the cavity was loaded with the cold crystal, the finesse and the efficiency dropped to 200 and 2%, respectively, corresponding to a 1.1% one-way loss through the modulator. Turning on the rf power to the EOM decreased the cavity efficiency further to 0.15% for the overall modulated output, owing to the increased mismatch of input coupling when sideband generations enhanced the carrier loss. The filter cavity formed by mirrors M2 and M3 had a finesse of 400, a FSR of ~2 THz, and an efficiency of ~30%, and increased the output power of the selected sideband by a factor of $\chi/T \sim 0.3/0.2\% = 150$. To lock the cavity onto the input laser frequency, we dithered the input mirror M1 of the generator cavity by use of a PZT. The dither amplitude was ~1/10 of the cavity linewidth and should cause only a slight amplitude modulation of the sidebands. The reflected light was then phase sensitively detected against the dither frequency to provide the cavity-discriminator signal. Another PZT, mounted upon the filter-cavity output mirror M3, was used to tune the filter bandpass frequency. Approximately 150 μW of a polarization-stabilized He–Ne laser was incident upon the comb generator. Part of the output light from the OFC generator was monitored with a DC photodetector, and the other part was sent to an avalanche photodiode for heterodyne mixing with an external-cavity tunable diode laser at 633 nm.

Figure 2 shows the dc-monitored output spectrum of our OFC generator as we continuously tuned the filter-cavity resonance over part of the comb spectrum. A comb span wider than 1 THz is clearly visible from one side of the carrier frequency. The filter cavity had a FWHM of ~5 GHz. This gave just enough resolution to resolve individual sidebands spaced 10.5 GHz apart. As the filter-cavity resonance was tuned close to the carrier frequency, it started to perturb the comb-generation cavity and affect the laser–cavity locking. This is manifested in the glitches shown on the comb spectrum to the right of the carrier (~ 1.25 THz). However, the locking system recovered after the filter cavity resonance passed through the carrier. Based on the observation that high-order (~100th) sidebands still have a good SNR, we expect to see a much wider comb with a filter cavity having a larger FSR. (It will also need a higher finesse to maintain its resolution.) The slope on this comb spectrum is roughly 16 dB/THz.

Approximately 15-μW power from an external-cavity tunable 633-nm diode laser was used for the heterodyne detection of the OFC sideband. Figure 3 shows the resulting beat spectrum. Figure 3(a) shows a beat between the diode laser and the 96th sideband of the He–Ne carrier, corresponding to a 1-THz frequency gap. A 26-dB SNR was obtained with a resolution bandwidth of 100 kHz. The filter-cavity resonance subsequently was also tuned to the 48th (505-GHz) and 144th (1.515-THz) sidebands. The resulting beat spectra are shown in Fig. 3(b). In a 100-kHz bandwidth we obtained a SNR's of 35 and 20 dB, respectively, for the 48th and 144th sidebands. The noise floor is fixed by the shot noise of the detected light power, multiplied by the avalanche photodiode's excessive noise factor. These beat signals can be easily counted with a tracking filter composed of a voltage-controlled rf oscillator phase locked onto the beat signal.

As the filter cavity selects out a particular sideband, it has little effect on the lower-order sidebands that are being generated inside the comb generator. Once the energy in a sideband is coupled out, the comb generation beyond that sideband is strongly reduced. This mechanism is clearly shown in Fig. 4. We parked the filter-cavity resonance on top of the 48th sideband but positioned the diode laser frequency successively to be in line with the 47th, 48th, and 49th sidebands. Het-

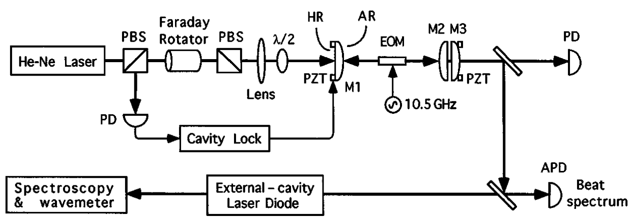

Fig. 1. Experimental setup for our comb generator at 633 nm. Mirrors M1–M2 form the comb-generation cavity, and M2–M3 form a short filter cavity. PBS's, polarized beam splitters; $\lambda/2$, half-wave plate; HR, highly reflective; AR, antireflection; PD's, photodiodes; APD, avalanche photodiode; PZT's, piezoelectric transducers.

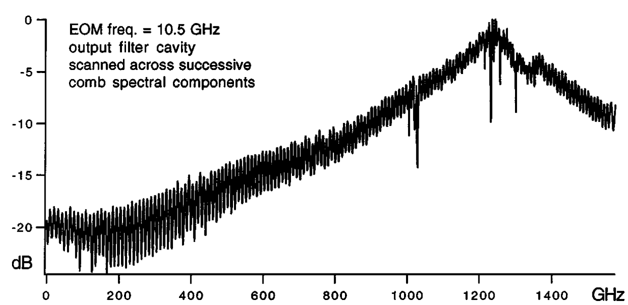

Fig. 2. OFC generator output spectrum as the filter-cavity resonance is scanned through the comb spectrum. The comb-line spacing is 10.5 GHz. The adjacent order of the filter cavity leads to overlapping spectra below ~200 GHz.

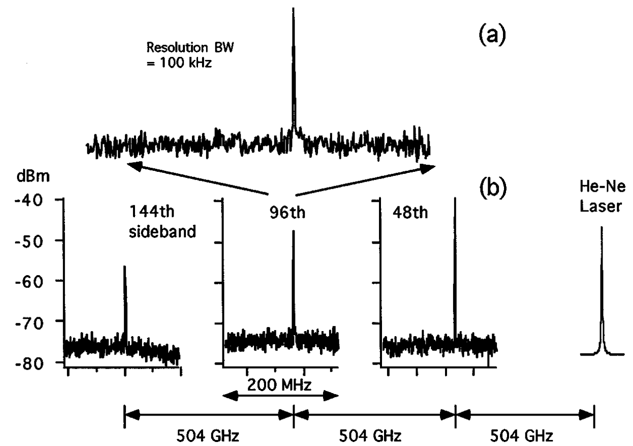

Fig. 3. (a) Beat between the 96th (1-THz) sideband of the He–Ne laser and the diode laser. (b) Beats between the 48th (505-GHz), 96th, and 144th (1.515-THz) sidebands and the diode laser. Incident power, 150 μW.

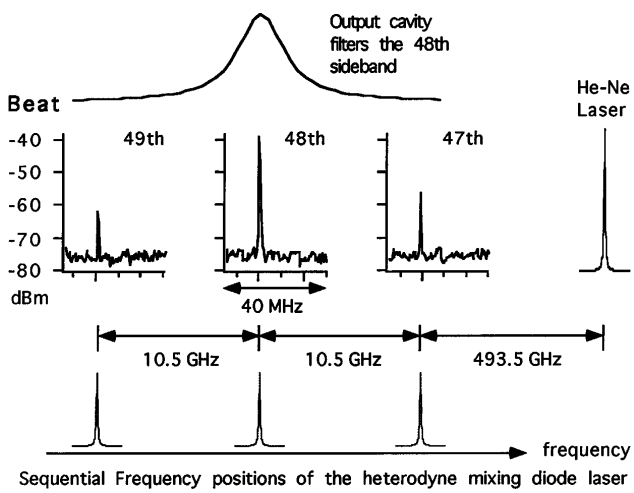

Fig. 4. Filter-cavity mechanism showing its sideband selection and comb-spectrum cutoff.

erodyne detection showed that a fraction of the 47th-sideband power leaked out owing to the finite width of the pass filter (–17.7 dB less than the 48th sideband). The 49th sideband magnitude was lower by 5.6 dB, i.e., –23.3 dB relative to the desired 48th sideband. This good spectral purity will improve further with a filter cavity of higher efficiency or better finesse.

We have realized a wide span (>3 THz) optical frequency comb generator at 633 nm. We improved the comb-generator efficiency by replacing the output mirror with a short filter cavity to permit efficient escape of the selected comb component. With limited power available from a He–Ne laser, we were able to demonstrate a 1.5-THz heterodyne beat signal with a SNR of 20 dB at a 100-kHz bandwidth. We intend to use this OFC generator to bridge gaps between stronger and spectrally narrower iodine molecule absorption lines around 633 nm and the $R(127)$ transition at which the He–Ne laser is traditionally stabilized. An interesting Ne transition ($1S_5 \rightarrow 2P_8$) at 633.6 nm can also be measured in its absolute frequency. We are also planning to revisit our frequency chain for measuring the green iodine transitions at 532 nm.[2] Previously we had to use Ti:sapphire lasers in the chain because of the power demand of the Schottky diode that was used to measure a 1-THz gap. With the OFC generator we can surely take a more direct approach and use diode lasers instead.

Recently we have developed a new, sensitive technique for detection of weak molecular overtone transitions in the visible with what we believe to be record high sensitivities. Excellent laser frequency stabilization that results when these sharp and yet high SNR resonances are used has also been clearly demonstrated.[13] We are in the process of establishing grids of molecular rovibrational lines as high-quality optical frequency references over the red part of the visible spectrum. As the spacing between adjacent rotational lines usually lies anywhere between a few hundred gigahertz and a few terahertz, the OFC generator presented here, which covers a frequency gap of a few terahertz, becomes an essential part of our phase-coherent frequency chains.

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