Self-referencing a CW laser with efficient nonlinear optics

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Abstract: We present self-referencing of a CW laser via nonlinear pulse broadening of a Kerr microcomb and an electro-optic modulation (EOM) comb. Our experiments demonstrate the first phase-coherent optical-to-microwave link via f-2f self-referencing with such combs.
OCIS codes: (190.4410) Nonlinear optics, parametric processes; (140.3948) Microcavity devices; (190.4380) Nonlinear optics, four-wave mixing.

1. Overview of experimental results

Modelocked-laser frequency combs have revolutionized optical frequency metrology and precision time keeping by providing an equidistant set of absolute reference lines that span in excess of an octave. Their typically sub-GHz repetition frequency and <100 fs optical pulses enable nonlinear broadening for self-referencing, and feature among the highest spectral purity of any oscillator. Such devices have enabled myriad applications from optical clocks (*1*–*6*) to precisely calibrated spectroscopy to quantum information. Moreover, experimental control of carrier-envelope offset phase contributes to ultrafast science.

Frequency combs generated from a CW laser via Kerr parametric nonlinear optics in microcavities (Kerr microcombs) (*7*, *8*) and electro-optic modulation (EOM) (*9*–*13*) are interesting new platforms for experimenters. The 10's of GHz or higher repetition frequency and the offset frequency of such combs are tunable to match a fuller range of comb applications in optical communications, metrology, arbitrary waveform generation, and with quantum-based systems. Furthermore, the physics of comb generation in microcombs and EOM combs offers access to novel regimes of spectral phase apart from requirements of modelocking. Importantly, microcomb and EOM comb generators offer the potential for photonic integration on chip by use of either optical microresonator structures or waveguide-based phase modulators. Despite these advantages, establishing a phase-coherent link between the optical and microwave domains using such frequency combs has remained an outstanding challenge.

Here we report self-referencing and carrier-envelope-offset frequency detection for a 16 GHz microcomb and a 10 GHz EOM comb. Our work leverages efficient pulse broadening in highly nonlinear fiber (HNLF) and low-noise microwave pulse train repetition rates that are possible in the optical domain for theses types of combs. Specifically, the bandwidth initially obtained with the combs is on the order of 10 nm. Hence, we rely on the HNLF to increase the frequency-comb bandwidth by a factor of 100 to approximately 1000 nm, even for the 10+ GHz microwave pulse rates. We will present not only sensitive detection of the carrier-offset frequency (f0) for these combs, but we demonstrate their use for precision optical frequency measurements.

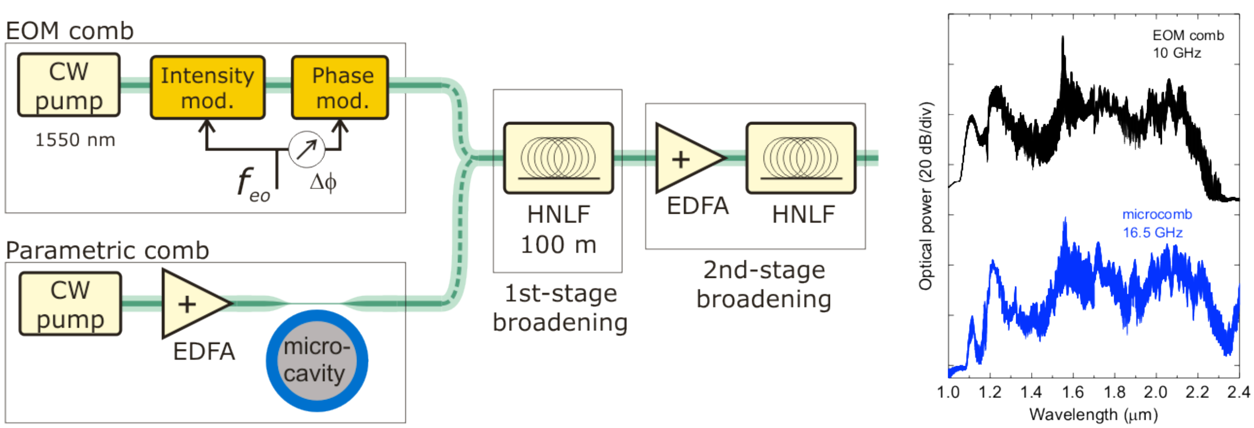

Figure 1: Overview of our experimental apparatus for coherent, octave-span supercontinuum generation and self referencing. At right are example supercontinuum spectra generated using the different comb technologies.

2. Generation of coherent, octave-span microcombs and EOM combs

Our experimental approach for microwave repetition-rate supercontinuum generation is presented in Fig. 1. The frequency combs are generated by way of CW-laser modulation achieved either by parametric nonlinear optics or electro-optic interactions driven by a microwave frequency synthesizer. In both cases the comb spectra are given jointly by the CW-pump-laser frequency and an integer multiple of the comb spacing. Hence, their carrier-offset frequencies are given by the difference of the CW-laser frequency and the commensurate integer multiple of the spacings.

What is important for spectral broadening in HNLF is that we can temporally compress the optical pulses generated with these combs to near their transform limit. Here we use line-by-line adaptive spectral phase control for the microcomb (*14*, *15*) and a constant second-order dispersion for the EOM comb. For spectral broadening to octave span, we have refined a two-stage HNLF broadening approach and applied it to both combs. The first stage leverages self-phase modulation to create combs with ~30 nm of bandwidth that we amplify and recompress to realize intensity autocorrelations less than 300 fs. The second stage utilizes a step-wise optimized length of dispersion decreasing HNLF. The pulse energy entering the second HNLF for both combs is approximately 250 pJ. Examples of the supercontinuum spectra that we generate following this two-stage system are shown in Fig. 1. Here the second HNLF dispersion is optimized to extend the high and low frequency ends of the supercontinuum such that f-2f self-referencing is possible. For both frequency combs, the supercontinuum is coherent across the entire comb span as evidenced by the prominence of the lines in these 4 GHz-resolution optical spectrum analyzer traces and by subsequent measurements presented below.

3. Carrier-offset frequency detection and phase locking

We self-reference the 16 GHz microcomb and the 10 GHz EOM comb using a standard f-2f setup with bulk PPLN. A photodetector spectrum of the free-running microcomb (EOM comb) offset frequency is presented in Fig. 2a (Fig. 2c). For optimized signal-noise ratio (SNR) of better than 25 dB, we align the polarization, spatial mode, and arrival time of the f and 2f components. Importantly, these signals directly determine the CW laser frequency for each comb with respect to their electronically measureable comb spacings.

Frequency-comb applications depend on frequency control and phase locking of f0. Here we demonstrate a phase lock of the microcomb f0 signal to a hydrogen maser reference; see Fig. 2b. Feedback is applied to the CW-laser frequency, and a simultaneous phase lock of the microcomb spacing achieves full stabilization of the microcomb spectrum. In the case of the EOM comb, the CW laser that we use is pre-stabilized to an optical reference cavity, and the spacing is given by the output of the microwave synthesizer that excites the EOMs. Hence, no post-generation frequency control is required and counting the mean frequency of f0 determines the CW-laser frequency. Figure 2d presents a time record of 1 sec duration digital frequency counter measurements of the CW laser via f0. The short-term scatter of the data indicate the fluctuations in the maser reference, while the approximately 65 mHz/s drift rate of the CW laser's reference cavity is apparent for longer averaging times.

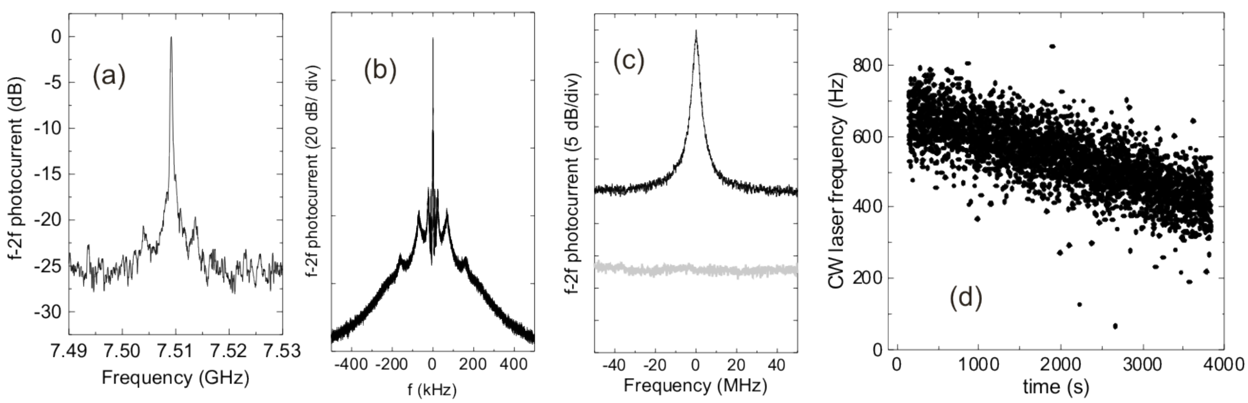

Figure 2: Detection and application of f0. (a) Offset frequency for the 16.5 GHz microcomb. (b) Idem with phase lock enabled to stabilize f0. (c) Offset frequency for a 10 GHz spacing EOM comb. For reference, the detection noise floor is shown in gray. (d) Demonstration of precision optical frequency counting over 4000 s with the EOM comb.

4. Conclusion and Outlook

In this talk, we will present recent experimental results on self-referencing a microcomb and an EOM comb. These types of frequency combs offer unique advantages, including wide tuning capabilities, large mode spacings in the

10's of GHz to THz range, and the capability for photonic integration. Self-referencing these combs, which are fundamentally based on optical-phase modulation, has been an outstanding goal. Indeed, a key characteristic of their offset frequency signals is the contribution from very-high-order frequency multiplication of the mode spacings. Our work opens the door for ultraportable frequency comb application that leverage precise measurement and synthesis of light.

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