Increasing the Mode-Spacing of Stabilized Frequency Combs with Optical Filter Cavities

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Abstract: We explore methods and limitations for increasing the mode spacing of a 1 GHz optical frequency comb using a Fabry-Perot filter cavity. Applications to optical and microwave waveform generation are highlighted.

While many applications would benefit from low-noise, frequency-stabilized combs at repetition rates $f_{rep} \geq 10$ GHz, the recent exciting developments in this area have been mostly limited to femtosecond lasers with f_{rep} up to ~1 GHz [1-3]. Mode-locked lasers with repetition rates around 10 GHz (and higher) do exist, but they all produce low-energy picosecond pulses that would require significant amplification, spectral broadening, and pulse compression to reach the necessary powers (~100 pJ in 30 fs at 800 nm or ~1 nJ in 75 fs at 1550 nm) to generate the desired octave spanning spectra. The problem of excess amplitude and frequency noise (10's of dBs in some cases) in nonlinear continuum generation with pulses longer than ~100 fs poses an additional challenge [4,5].

Here we explore the use of a simple Fabry-Perot cavity to filter the output of a mode-locked femtosecond laser, thereby creating a frequency comb with increased mode spacing (see Fig. 1(a)). This is accomplished by matching the nominal free spectral range (FSR) of the Fabry-Perot to a harmonic of the repetition rate of the femtosecond laser, such that FSR=M×f_{rep}, where M is an integer. This straightforward approach has existed for at least a few decades [6], but considerations relevant to broadband frequency combs have not been fully considered. (Related work with femtosecond buildup cavities have been performed, but in that case the emphasis has been on higher finesse cavities with M=1 [7].) Questions to be addressed include maximizing the optical bandwidth over which the filter cavity works, and maximizing the suppression of the unwanted modes. An important issue in this approach is careful control of the dispersion of the filter cavity. While the comb from the mode-locked laser is strictly uniform in spacing, the modes of the filter cavity are not equally spaced (due to dispersion in the cavity). This will result in an eventual spectral walk-off of the filter modes relative to the comb modes. Preliminary results, shown in Fig. 1(c), indicate that it is possible to filter with M=10 over fractional optical bandwidths approaching 10%. This has been achieved with a portion of the spectrum from a

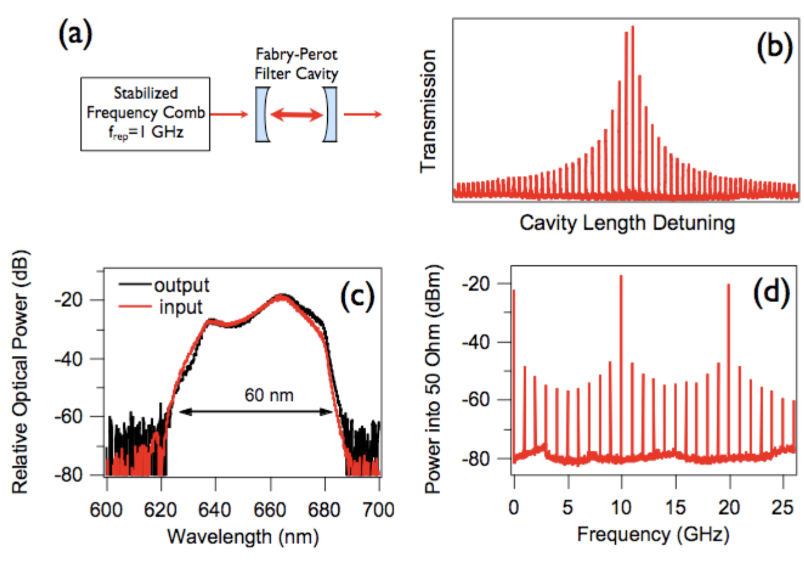

Figure 1: (a) Fabry-Perot filter cavity consisting of two 50 cm ROC mirrors having ~99% reflectivity near 650 nm. (b) Measured transmission through the cavity as its length is changed in the vicinity of L=1.5 cm (10 GHz FSR). The filter cavity length is servo-controlled to maintain the transmission on the highest peak in the center of the pattern. When locked in this position the cavity transmits nearly 100% of the resonant modes (c) Optical spectra input to (red) and output from (black) the 10 GHz filter cavity. (d) Measured RF spectrum of the transmitted light as detected with a 25 GHz photodetector. The original 1 GHz repetition rate harmonics are suppressed by -30dB to as much as -40dB below the 10 GHz carrier.

broadband 1 GHz Ti:sapphire laser in the vicinity of 660 nm [8]. Calculations suggest that fractional bandwidths greater than 15% (i.e. 150 nm at 900 nm) should be achievable with a cavity consisting of two low dispersion 99% reflectors. Experimental verification is in progress. The suppression of the unwanted comb modes is shown in Fig. 1(d), where we plot the microwave spectrum of the transmitted light. With ~99% reflectors, a sideband 5 GHz from the 10 GHz carrier is suppressed nearly -40dB, at the level of the expected off-resonance transmission (i.e. T=0.01^2).

An application that benefits from this filtering is the generation of exceptionally low-noise 10 GHz microwaves by photodetection of f_{rep} from an optically-stabilized frequency comb [9]. When a P-I-N photodiode (GaAs in this case) is illuminated by a stable 1 GHz pulse train (spectrum of Fig. 1(c)), the saturation and increased capacitance of the diode degrade the frequency response and achievable signal-to-noise ratio of f_{rep} and its microwave harmonics. For example, the microwave power at 10 GHz saturates, and even decreases, with increasing optical power (see black squares of Fig 2(a)). This situation can be improved by using a Fabry-Perot cavity to remove power from the un-wanted lower frequency harmonics, while increasing the power at the desired 10 GHz. Figure 2 shows results for filter cavities with M=2, 5 and 10. The maximum achievable microwave power in the 10 GHz harmonic is seen to increase proportionately with the filter cavity FSR. The drawback is that only a fraction (1/M) of the incident optical power (~75 mW) is available after the cavity. However, this power could be retrieved using optical circulators and cavity filters in reflection. For M=10, the present experiment provides a maximum of 7 mW for detection, which is not sufficient to saturate the photodiode. Nonetheless, the scaling indicates that 10 GHz microwave powers of -7 dBm are within reach. This would represent nearly a 10x improvement over our previous results [9], and push the white phase noise floor of the generated 10 GHz microwave signal down to below -165 dBc/Hz.

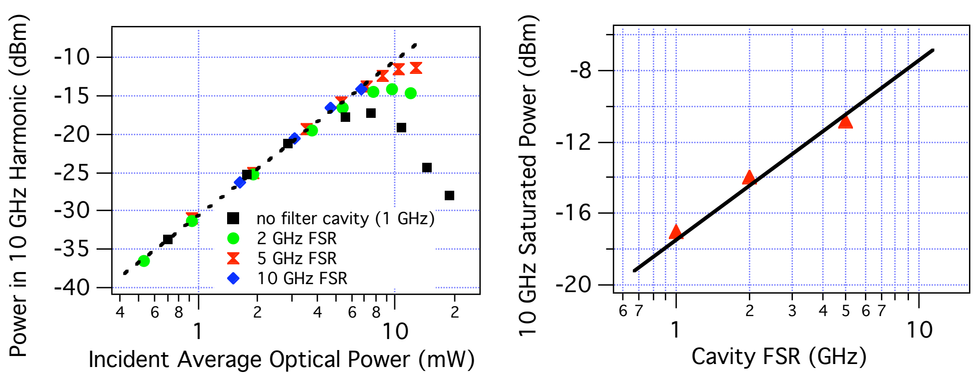

Figure 2: (a) Measured microwave power in the 10 GHz harmonic of the photodetected pulse train from a femtosecond laser. The four different data sets correspond to no cavity filtering (black squares), M=2 (green circles), M=5 (red hourglass), M=10 (blue diamonds). (b) Maximun saturated power in the 10 GHz harmonic as a function of the filter cavity FSR (i.e. M), as determined from (a).

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