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Measurement of carrier envelope offset frequency for a 10 GHz etalon-stabilized semiconductor optical frequency comb

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Abstract: We report Carrier Envelope Offset (CEO) frequency measurements of a 10 GHz harmonically mode-locked, Fabry-Perot etalon-stabilized, semiconductor optical frequency comb source. A modified multi-heterodyne mixing technique with a reference frequency comb was utilized for the measurement. Also, preliminary results from an attempt at f-2f self-referencing measurement are presented. The CEO frequency was found to be ~1.47 GHz for the particular etalon that was used.

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OCIS codes: (140.7090) Ultrafast lasers; (140.5960) Semiconductor lasers; (140.3425) Laser stabilization.

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1. Introduction

Carrier Envelope Offset (CEO) frequency stabilized optical frequency comb sources have emerged lately as powerful tools for frequency metrology [1], spectroscopy [2,3], astronomy [4], remote sensing [5], optical signal processing [6,7], arbitrary waveform generation and measurement [8–11] among many other applications. Commercial CEO stabilized lasers are readily available for ~1 GHz and lower repetition rates in both solid-state and fiber laser platforms. Nevertheless, there is a special effort towards reaching higher repetition rates in order to achieve higher average power per comb line, enable more complex signal generation and processing, and facilitate the usage of standard spectral dispersers for spectral analysis. To the best of our knowledge, state-of-the-art Ti:Sapphire based CEO stabilized comb sources have been demonstrated up to 10 GHz repetition rates [12], while fiber laser based systems have been shown to operate at rates up to 1 GHz [13]. While these fundamentally passively mode-locked sources show remarkable progress, higher repetition rates (>5 GHz) result in very short cavity lengths which are challenging due to component size constraints, reduced gain, and reduced nonlinearities that hinder fundamental mode-locking. Another technique utilizes effective repetition rate multiplication of low repetition rate CEO frequency stabilized lasers with external Fabry-Perot etalon filters [4, 14]. Unfortunately, this technique, which usually requires multiple external etalons, lacks large side-mode suppression, and the laser noise is multiplied with the repetition rate. There are also parametric techniques that utilize microresonators for comb generation with large comb spacing [15]. These techniques are fairly new and promising, however the phase relationships between the comb lines that enable short pulse formation in time-domain needs more study.

We have recently demonstrated a scheme that relies on coupled-cavity harmonic active mode-locking of a semiconductor optical amplifier (SOA) to obtain stabilized frequency combs at high repetition rates [16,17]. In this technique, a stable Fabry-Perot etalon with ~10 GHz free spectral range (FSR) is inserted into a ring laser cavity with ~10 MHz fundamental repetition rate. The longer ring cavity is synchronized to the etalon with an intracavity Pound-Drever-Hall (PDH) locking technique. Due to the coupling of the cavities, both narrow linewidth and frequency-stable optical combs are achieved simultaneously. This scheme is very robust and has demonstrated excellent performance. One unavoidable consequence is that the etalon passbands serve as the passive references for the optical comb frequencies. Therefore, the absolute positions of the optical combs, hence the CEO frequency of these lasers, are not known, and cannot be tuned to an arbitrary value for a fixed, passive etalon. In this paper, we demonstrate the measurement of the CEO frequency for such a laser for the first time through multi-heterodyne beating with another CEO-stabilized comb source. We report observations of the CEO frequency drift over several hours due to environmental factors. We also show preliminary results of an attempt to measure the CEO frequency through the f - $2f$ self-referencing technique.

2. Etalon-stabilized semiconductor optical comb source

A schematic of the etalon-stabilized semiconductor optical comb source is shown in Fig. 1 (top). The gain medium was a commercial fiber-coupled semiconductor optical amplifier (SOA). The SOA had a gain bandwidth of ~ 100 nm around 1550 nm, and a maximum output power of ~ 60 mW. The cavity was constructed in a “coupled ring cavity” laser architecture, where the main ring cavity is formed with fiber-optic and semiconductor components, and the coupled cavity is formed by the Fabry-Perot etalon. SMF-28 single mode fiber constituted the majority of the main cavity, and dispersion compensating fiber (DCF) was utilized to minimize the effective cavity dispersion. The total cavity length was ~ 10 meters yielding a fundamental frequency of ~ 20 MHz. Two independent delay lines were implemented inside the cavity, one coarse delay line for the tunability of the cavity fundamental frequency, and a fine piezoelectrically activated delay line for the PDH lock implementation. Polarization controllers and isolators were distributed throughout the cavity in order to ensure stable, unidirectional operation. Mode-locking was achieved through an electro-optic intensity modulator (EOM) with >13 GHz bandwidth. The EOM was driven by a low-noise sine-wave generator (Agilent E8257) directly at the repetition rate dictated by the Fabry-Perot etalon. The laser cavity was placed in a commercial 19” rackmount enclosure, with simple thermal control and acoustic-isolation, which is placed on top of a vibration isolated optical table in a free-standing manner. The optical output was split into three branches. The first branch was used as the feedback signal for the PDH lock, the second for diagnostics, and the third branch was sent through an erbium-doped fiber amplifier (EDFA) and a grating-based pulse compressor before being utilized for the CEO frequency measurements.

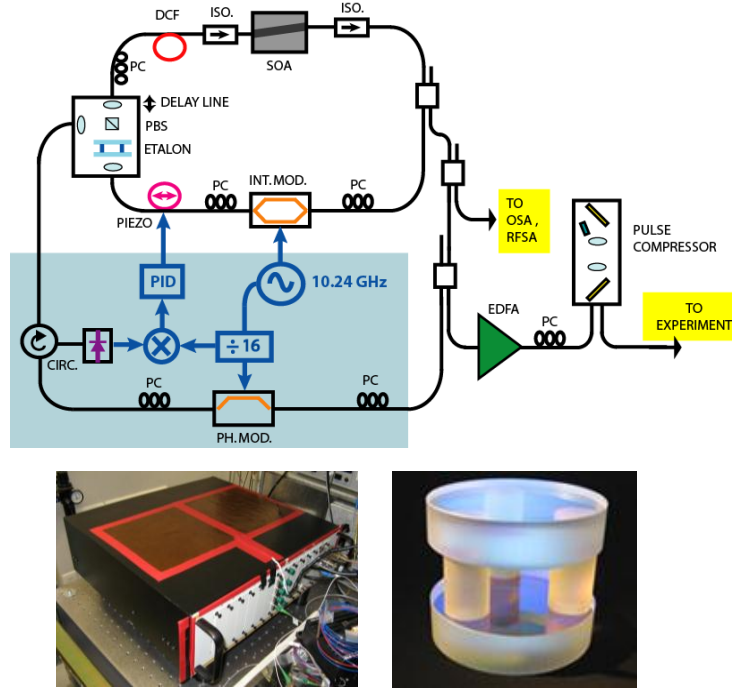


Fig. 1. Schematic of the comb source (top) with the PDH loop shown in the blue rectangle, photograph of the comb source on the optical table (bottom left), and photograph of the etalon (bottom right)

The Fabry-Perot etalon used inside the laser cavity was a commercial unit produced by LightMachinery. (Fig. 1 bottom right). It utilized fixed Zerodur spacers, an unsealed flat-flat mirror configuration, a finesse of ~ 100 , and a FSR of ~ 10.24 GHz. A variant of the PDH

technique described elsewhere [18] was used to measure the free spectral range of the etalon as ~ 10.24263 GHz (to within tens of kHz level accuracy) at ~ 1.55 μm wavelength. Consequently, the sine-wave generator was set at this frequency, and the cavity fundamental rate was tuned to ~ 20.005 MHz in order to mode-lock the laser at exactly the 512th harmonic. This was chosen in order to eliminate possible crosstalk that might arise during pulse picking for the self-referencing experiments (detailed in section 4). The intracavity PDH stabilization scheme was implemented by probing the etalon with a phase modulated version of the laser output in the orthogonal polarization state. The details of this intracavity PDH implementation can be found in [16].

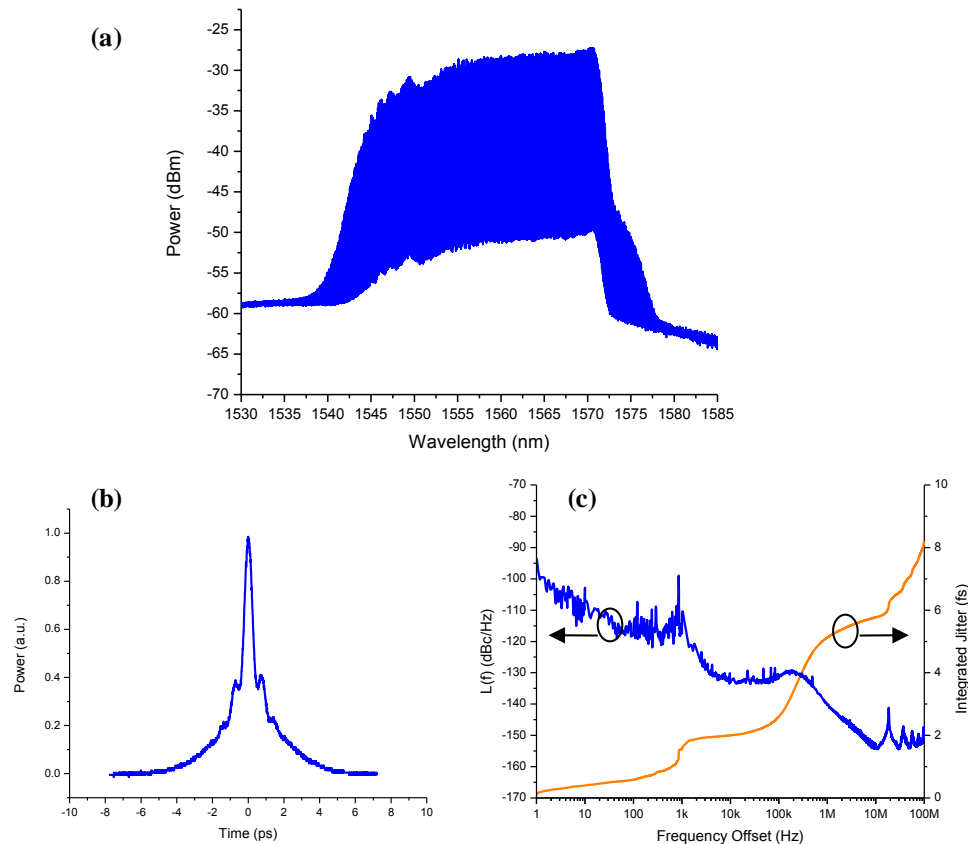


Fig. 2. (a) Optical comb source output showing optical spectrum, (b) autocorrelation, and (c) phase noise (blue trace) and integrated residual jitter (orange trace)

Sample measurements of the optical output are shown in Fig. 2. The output spectrum spans more than 27 nm (10-dB full width), with >30 dB comb contrast (resolution-limited by the ANDO optical spectrum analyzer (OSA)). Compared to other fiber and semiconductor actively mode-locked sources, to the best of our knowledge, this bandwidth is the widest reported to date directly out of the laser. In order to achieve this, we utilized the unique characteristics of semiconductor gain media. Strong current-injection in a semiconductor optical amplifier results in extension of the optical spectrum towards longer wavelengths due to gain dynamics, as visible by the shoulder on the spectrum in Fig. 2 [6,16]. Unfortunately, this process also adds some nonlinear chirp to the laser output, which was not fully compensated by the grating compressor as seen in the autocorrelation trace. Nevertheless, a full-width at half maximum (FWHM) pulse width of 426 fs was inferred from the autocorrelation trace (FWHM of ~ 650 fs) using a decorrelation factor of ~ 1.5 . This factor was

obtained by simulations to match spectral and temporal measurements of the laser. The relative phase noise of the photodetected optical output (10.24 GHz tone) was also measured using a commercial phase noise test set (Fig. 2c). The integrated residual jitter (1 Hz – 100 MHz) was measured to be ~ 8.2 fs. The linewidth and frequency stability of the optical frequency combs were measured by optical heterodyne mixing with an ultra-stable single-frequency fiber laser (Orbits Eternal) that exhibited <1 kHz linewidth. The measurements yielded <10 kHz optical linewidth of the combs, and ~ 700 kHz optical frequency stability in 30 seconds. These numbers are in agreement with what was reported in [16] for a similar optical comb source. We believe the frequency fluctuations are a result of noise in the PDH loop, and air temperature/pressure fluctuations inside the etalon.

In order to shed insight into the operation of the comb source, we can focus on two parameters as a function of frequency: absolute optical frequencies and separations of the etalon transmission peaks (Fig. 3). Both of these depend on the dispersion curves of the air inside the etalon, and the mirror coatings. Obviously, a perfect etalon with zero dispersion would always have its first transmission peak, and thus the CEO frequency at zero. In contrast, the real mirror coatings of our etalon had close to zero dispersion at only the $1.55 \mu\text{m}$ optical wavelength band (~ 193.5 THz region). This allows for a fixed RF sine-wave modulation (which is carefully tuned to the exact FSR of the etalon in this band) to efficiently generate a large number of optical comb lines, as illustrated in Fig. 3. However, as the combs are traced (in a virtual fashion) to the zero frequency line, the first comb line will not coincide with zero frequency. This difference is what is identified as the CEO frequency of the laser that is locked to the etalon as the optical frequency reference.

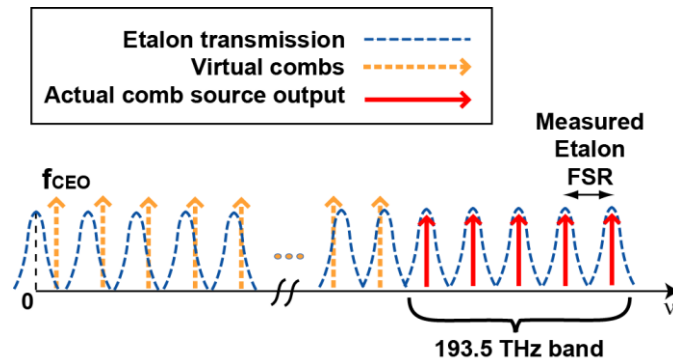


Fig. 3. Illustration of the etalon-stabilization of the optical frequency comb source

The function of the intracavity PDH lock is to ensure that the optical frequency comb lines are locked to the transmission peaks of the etalon (at the $1.55 \mu\text{m}$ optical wavelength band) throughout various environmental fluctuations of both of the coupled cavities. This means that the main cavity FSR is locked to the $1/512^{\text{th}}$ of the etalon FSR, and the main cavity will follow any changes in the etalon absolute optical transmission peaks. It is important to emphasize that the etalon reference for the PDH lock is established in the ~ 193.5 THz optical band, not the $\sim \text{GHz}$ RF band. In this regard, we can claim that our frequency comb source is locked to a secondary optical reference (the etalon), whereas an atomic/molecular resonance would be a primary optical reference. The main motivation of this study was to measure the absolute optical frequencies dictated by this secondary optical reference.

The comb source we present here is not limited to a 10 GHz repetition rate, and can easily be scaled to 40 GHz or higher depending on component availability. The modulation is accomplished with a low-noise commercial RF clock and a LiNbO_3 modulator which are readily available up to 40 GHz. The Fabry-Perot etalon is also available commercially at 40 GHz (and beyond). Moreover, the actual cavity length is not constrained by the repetition rate of the laser due to the harmonic modelocking process.

In our comb source, the longer active ring cavity, and the passive etalon cavity have to be synchronized. The same issue exists for filtering low repetition frequency combs, where the laser cavity and the etalon have to be synchronized to each other for the best performance. The difference is, additional noise is always introduced when an oscillator frequency is multiplied externally. Our laser suppresses this “harmonic” noise due to the coupled-cavity architecture. The free-space section for the etalon and PDH loop in our laser can easily be packaged into a rugged fiber-pigtailed format, and is available from commercial vendors. We did not use these packages due to cost and loss of flexibility in laboratory experimental environment.

3. CEO Frequency measurement through multi-heterodyne mixing

The typical f - $2f$ technique with an octave-spanning spectrum cannot be easily implemented to measure the CEO frequency due to the very low peak power of the pulses at 10 GHz repetition rate. The next section features our initial efforts in this direction. Another technique for measuring the CEO frequency of such a 10 GHz frequency comb source is discussed in this section. We propose to measure the CEO frequency by comparing it against another CEO-stabilized comb source that is well characterized. To illustrate this idea, let’s assume two CEO-stabilized optical comb sources with different repetition rates and CEO frequencies (Fig. 4). Once these two comb sources are optically mixed in a photodetector (multi-heterodyne), the differences of the optical combs are compressed and translated into an RF domain comb. This technique can yield vast amounts of information about the optical frequency comb sources, simply measured with RF equipment [19]. For instance, the RF comb separation frequency will be equal to the difference in the repetition rates of the two optical comb sources. This also indicates that, if one repetition rate is a multiple of the other, the RF comb will collapse into a single beat note. Additionally, the center frequency of the RF comb will be related to the difference in the CEO frequencies of the two optical sources. Through RF measurements, partial knowledge (repetition rate) of one comb source, and the complete knowledge of the other comb source, the missing information about the CEO frequency can be retrieved.

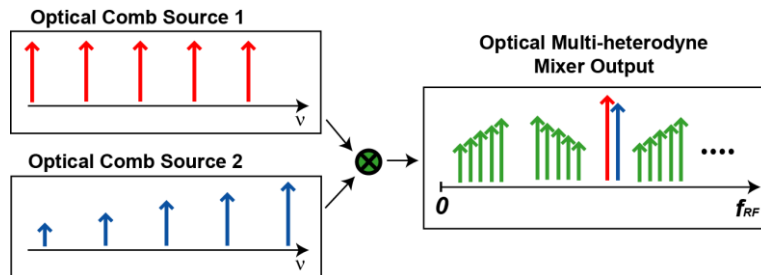


Fig. 4. Illustration of the optical multi-heterodyne mixing of two optical comb sources

For the multi-heterodyne measurement reference, we utilized a commercial optical frequency comb source (Menlo Systems FC1500) (Fig. 5). The direct output of the Menlo comb source spans an optical spectral range of >60 nm FWHM, and was set to operate at a CEO frequency of 20 MHz. The repetition rate of the Menlo comb source was tuned to 249.82 MHz, which is $1/41^{\text{st}}$ of the repetition rate of our 10.24263 GHz comb laser. Consequently, when the two sources are mixed at the photodetector, the resultant multi-heterodyne beats of the optical comb lines collapse to a single frequency. Both lasers were locked to a Cesium atomic clock (10 MHz reference) for long term stability of the RF measurements. This locks the repetition rates to a common reference, but the CEO frequencies were still asynchronous due to the etalon being an optical reference on its own.

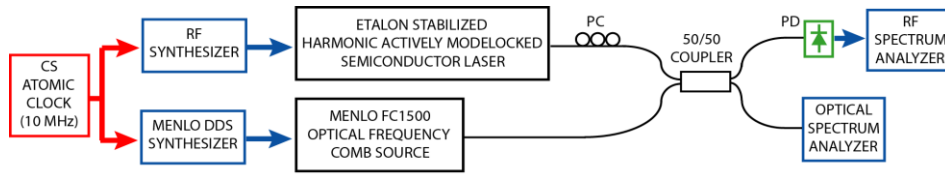


Fig. 5. Experiment Setup for CEO frequency measurement through multi-heterodyne beating

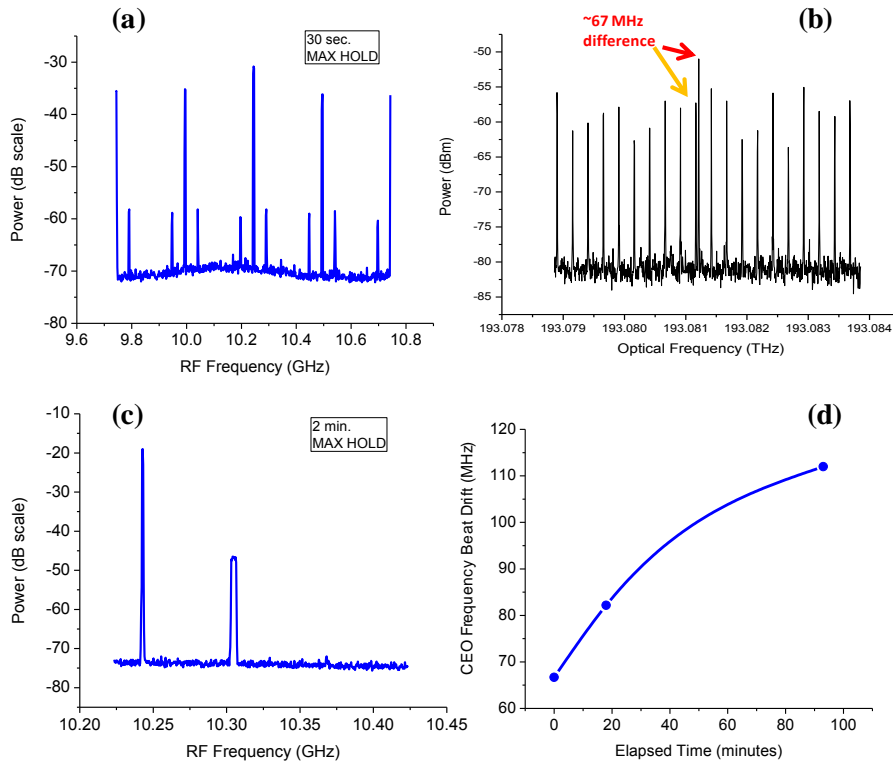


Fig. 6. (a) Multi-heterodyne RF beat tones showing CEO frequency, (b) 17 MHz resolution optical spectrum trace of photodetector input, (c) max-hold for 2 minutes of a single RF beat tone, and (d) RF beat drift over 1.5 hours

The RF spectrum of the multi-heterodyne beat signal is shown in Fig. 6. There are periodic multi-heterodyne comb lines at harmonics of 249.82 MHz from the Menlo laser, and the multi-heterodyne beat can be seen between these harmonics as collapsed to single RF comb lines (Fig. 6a). The corresponding optical spectrum is measured with an Agilent high resolution (~ 17 MHz) OSA (Fig. 6b). It can be seen that, due to the extreme repetition rate difference of the two comb sources, the multi-heterodyne beat frequency was observed modulo half the repetition rate of the slower laser. This could be thought of in a similar manner to Nyquist rate violation and aliasing due to undersampling. Therefore, a direct conclusion about the CEO frequency of the 10 GHz comb source could not be derived from this setup alone. One conclusion that could be derived however is related to the CEO frequency stability of our comb source (since the repetition rate is locked by the stable RF sine-wave drive). Observations of the beat note yielded a ~ 50 MHz drift within 1.5 hours as the laser warmed up and stabilized (Fig. 6c and 6d). We believe this drift was mainly due to the air temperature fluctuations inside the etalon; simulations show that 0.5°C air temperature change would yield a ~ 84 MHz optical frequency shift. In these particular experiments, the

laser enclosure was temperature stabilized to $25 \pm 0.1^\circ\text{C}$, but neither the air in the enclosure nor the etalon had localized temperature stabilization. It is possible to minimize these frequency drifts by utilizing a sealed etalon [17], which can be purged of gases and placed in a tightly temperature controlled chamber with active vibration control. Aside from temperature, we have observed CEO frequency changes from controlled offset changes in PDH lock as expected. The drift due to the intrinsic noise in the PDH electronics was much smaller than what was reported here for temperature fluctuations. The SOA pump current changes yielded small changes in CEO frequency, limited by the finesse of the etalon and laser cavity design. Large SOA current changes can also cause heating and temperature fluctuations inside the etalon that would result in larger fluctuations of the CEO frequency. Small scale tuning of CEO frequency in our comb source is possible with a controlled electronic PDH lock offset, and large scale tuning is possible with a piezo-controlled etalon.

In order to eliminate the ambiguity due to the large repetition rate difference of the comb sources, we modified the experiment setup to include a passive optical filter at the output of the Menlo comb source (Fig. 7). This filter was another Fabry-Perot etalon with an FSR of ~ 10.287 GHz and a finesse of 1000, which was readily available in the laboratory. Accordingly, the Menlo comb repetition rate was tuned to 250.9 MHz ($1/41^{\text{st}}$ of 10.287 GHz). This yielded multi-heterodyne RF combs with a spacing of ~ 44.37 MHz (Fig. 8 bottom). Additionally, a tunable optical bandpass filter with 0.4 nm FWHM was inserted before the photodetector in order to limit the number of optical combs that are mixed. This tunable bandpass filter assisted in noise reduction, as well as aiding in estimation of the CEO frequency difference by comparing optical and RF domains (Fig. 8).

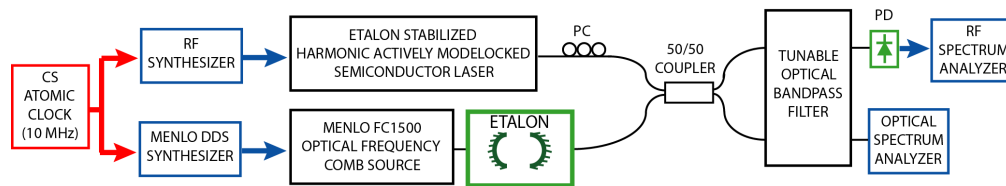


Fig. 7. Modified experimental setup for CEO frequency measurement through multi-heterodyne beating

As expected, compressed replicas of the optical combs appear in the RF domain, similar to the illustration of Fig. 4. The shape of the RF domain signal is very similar to the bandpass filtered optical spectrum of our comb laser. This is due to the Menlo comb source having a relatively flat optical spectrum in the region of interest. The center RF frequency is a function of the CEO frequencies and repetition rates of the individual sources. We should note that, although the repetition rate of the filtered Menlo comb source was 10.287 GHz, the CEO frequency depends on which mode numbers were actually selected by the etalon (which is a function of the CEO frequency of the 10.287 GHz etalon that was used as the passive filter). Assuming mode numbers of 0, 41, 82, etc. being selected by the 10.287 GHz passive etalon filter, a CEO frequency of ~ 9.5 GHz (or 0.74 GHz) can be estimated for the etalon stabilized 10.24263 GHz optical frequency comb source. However, this convenient assumption of mode numbers may not necessarily be valid and is investigated further. In order to eliminate this ambiguity, we observed the multi-heterodyne RF beat notes while tuning the Menlo comb repetition rate by a very small amount in a very short time frame (Fig. 9), similar to [20]. Throughout the experiments the CEO frequency of the Menlo comb source and the optical bandpass filter were fixed. Using this scheme, one of the filtered Menlo mode numbers was calculated as 771816, which yields a base mode number of 32 (modulo 41). Therefore the modified CEO frequency of the filtered Menlo comb would be $(32 \cdot 250.9 \text{ MHz}) + 20 \text{ MHz} = 8.0488 \text{ GHz}$. Thus, if another optical comb source were to be built with this 10.287 GHz etalon, the CEO frequency of that laser would be 8.0488 GHz (or 2.2382 GHz). Using this

number, the corrected CEO frequency of our 10.24263 GHz etalon-stabilized comb source is obtained as $(9.5 \text{ GHz} + 20 \text{ MHz}) - 8.0488 \text{ GHz} = 1.4712 \text{ GHz}$ (or 8.77143 GHz).

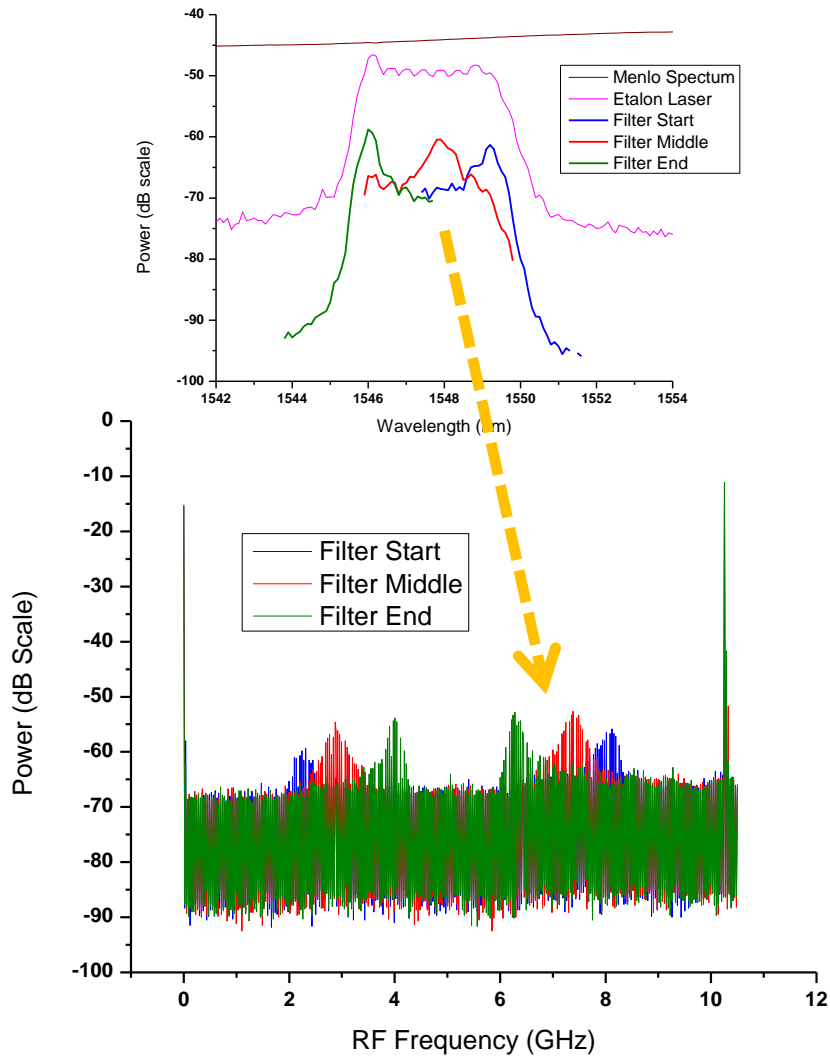


Fig. 8. Optical spectrum of the comb sources of Fig. 7. (top), and multi-heterodyne RF beat tones (bottom) for various tunable optical filter settings. The dashed arrow shows the correlation between optical and RF domains.

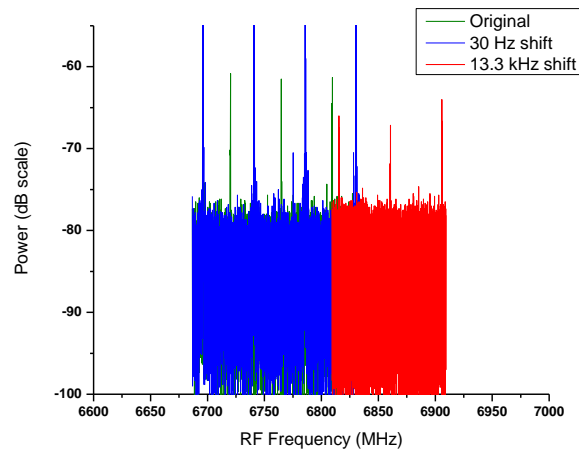


Fig. 9. Multi-heterodyne RF beat notes observed during various shifts of Menlo comb repetition rate

4. CEO frequency measurement through f-2f self-referencing

The standard self-referencing f-2f technique for CEO measurement requires a full coherent optical octave. Two conditions seem critical for a coherent octave: pulse widths below 300 fs, and high peak power with a very short length of nonlinear fiber [1]. These conditions are easily achieved with passively mode-locked, MHz repetition rate Ti:Sapphire and fiber lasers that can generate <150 fs pulses with tens of kilowatts of peak power. However, a ~10 GHz harmonically actively mode-locked semiconductor laser with ~0.4 ps pulsewidth requires significant amplification (>50 W average power) and pulse compression to achieve similar peak power levels. As a first trial, we were able to amplify the comb source output up to 5 W average power (~625 W estimated peak power), and managed to generate an optical octave using a commercial highly nonlinear fiber (HNLF) fabricated by OFS (Fig. 10 top). The octave was measured by a commercial ANDO Optical Spectrum Analyzer (OSA) up to the limit of the instrument of 1750 nm. The remainder of the octave was measured by a custom-built spectrometer with ~3 nm Full Width Half Maximum (FWHM) resolution and ~45 dB dynamic range. The evolution of the octave was also measured by the OSA as a function of estimated peak power of the pulses coupled into the HNLF (Fig. 10 bottom). Unfortunately, due to the low peak power, several meters of HNLF was required to obtain the optical octave. This resulted in excess nonlinear noise, and reduction of the optical comb contrast. In order to characterize the comb contrast in detail, the portion of the octave around 1550 nm wavelength was measured with the ~17 MHz resolution OSA (Fig. 11). As can be seen, the comb visibility (thus the coherency) of the octave is greatly reduced at the laser center frequency as the peak power is increased. This is a clear indication that the coherency at the extremes of the octave will also not be preserved. Therefore, the octave was tagged to be incoherent and not suitable for self-referenced CEO frequency measurement.

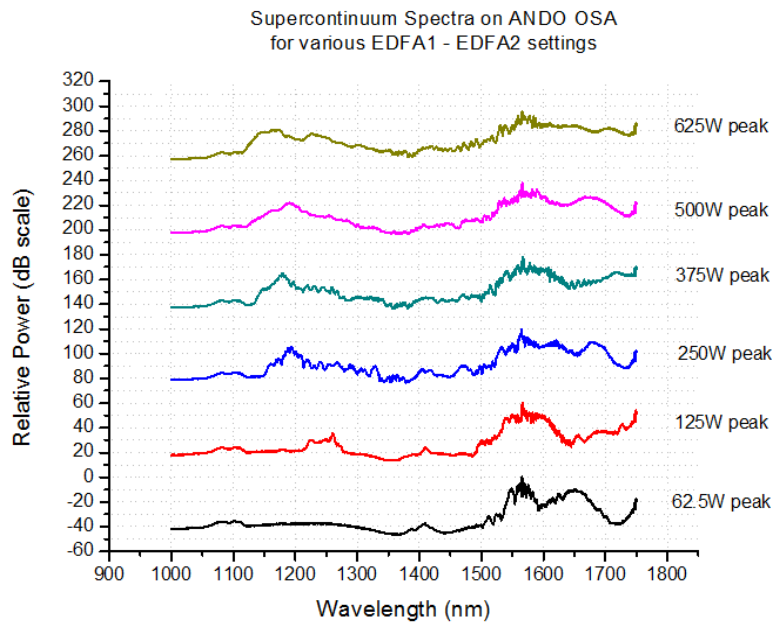
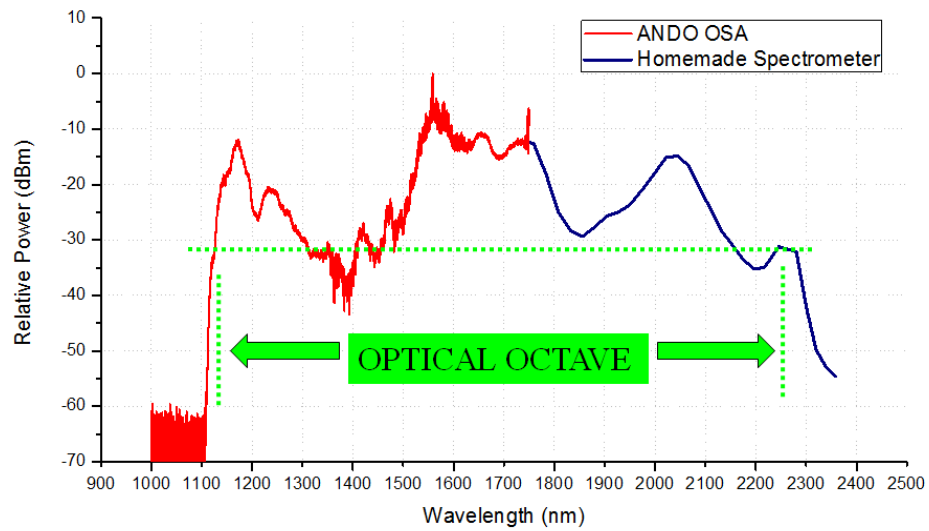


Fig. 10. Optical octave generation at 10 GHz by direct amplification of comb source (top), and evolution of the octave as a function of peak power (bottom)

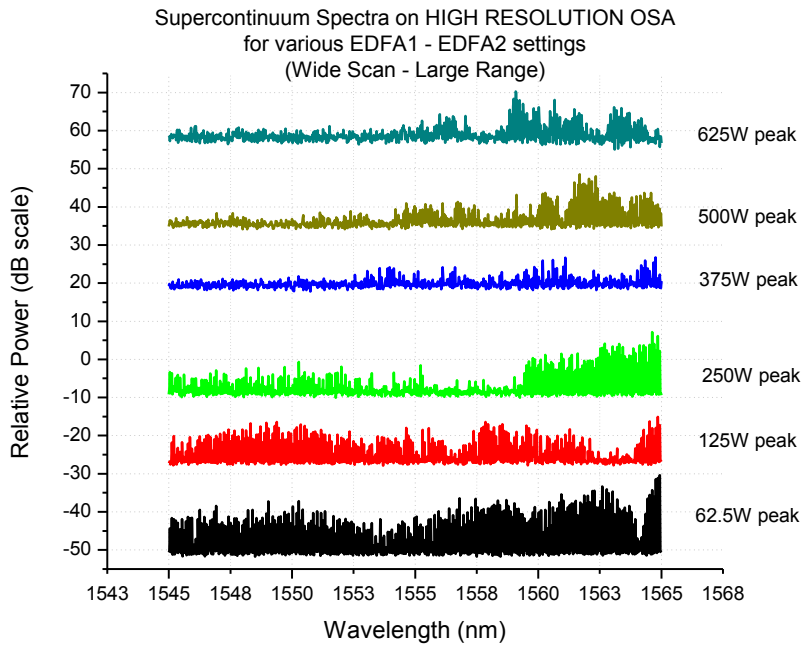
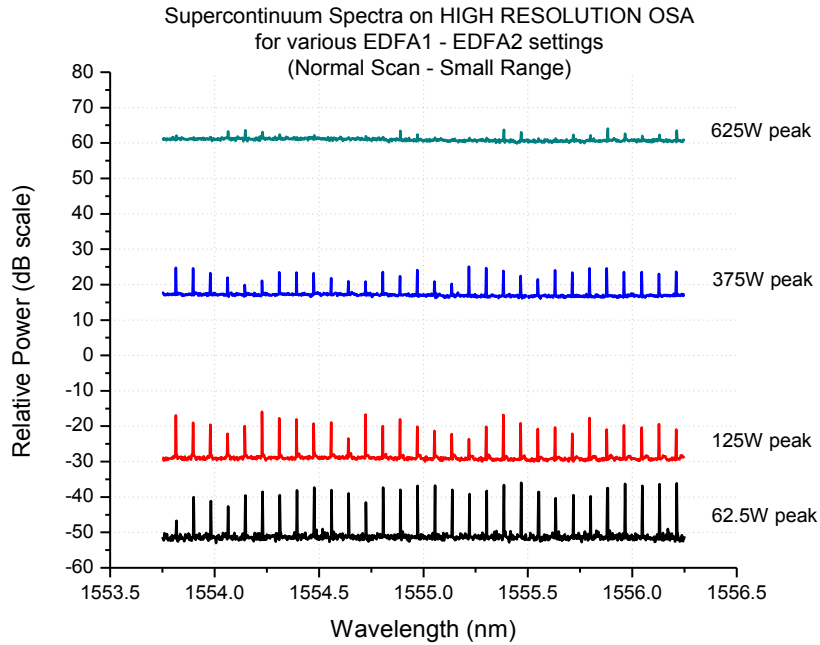


Fig. 11. High resolution optical spectrum showing optical comb contrast as a function of output peak power

In order to achieve higher peak powers required for self-referencing, the comb source output was demultiplexed (pulse picked) by a factor of 512 to the cavity fundamental frequency of ~ 20 MHz. This frequency was chosen to avoid any potential ambiguities arising from the harmonic mode-locking process. The etalon-stabilized comb source behaves mostly

like a fundamentally passively mode-locked laser due to suppression of optical supermodes (a byproduct of harmonic mode-locking), and pulse-picking to cavity fundamental of ~ 20 MHz should eliminate all remaining supermode noise. In theory, demultiplexing should not change the CEO frequency, but rather translate it modulo the new repetition rate.

The two main challenges for high contrast pulse picking from GHz rates to MHz rates are the generation of a high-fidelity and high-bandwidth electrical gate signal with sufficiently high voltage, and the extinction ratio of the LiNbO_3 intensity modulator used for the gating process. In order to pick a single pulse out of a ~ 10 GHz pulse train every ~ 50 ns, the intensity modulator has to be gated with an electrical pulse that has a maximum duration of ~ 150 ps, and a repetition rate of ~ 20 MHz. Additionally, the electrical pulse should have a very clean “zero” level, and should have at least 3-4 Volts amplitude (0-peak) to enable full modulation depth of a generic commercial intensity modulator. Such high-fidelity and high-bandwidth electrical pulses are hard to generate, and are usually obtained from high-end commercial 10-40 Gbit/s Bit-Error Rate Testing (BERT) systems. Even in this case, the amplitude of the electrical pulses is usually limited to 1.8-2.5 Volts. We did not possess such a high-end high-speed BERT system, thus we opted to use another commercial electrical pulse generator to drive the pulse picker. This device could produce ~ 120 ps electrical pulses with amplitudes up to 5 Volts, however there was ripple existing on the zero level of the pulses (Fig. 12 top).

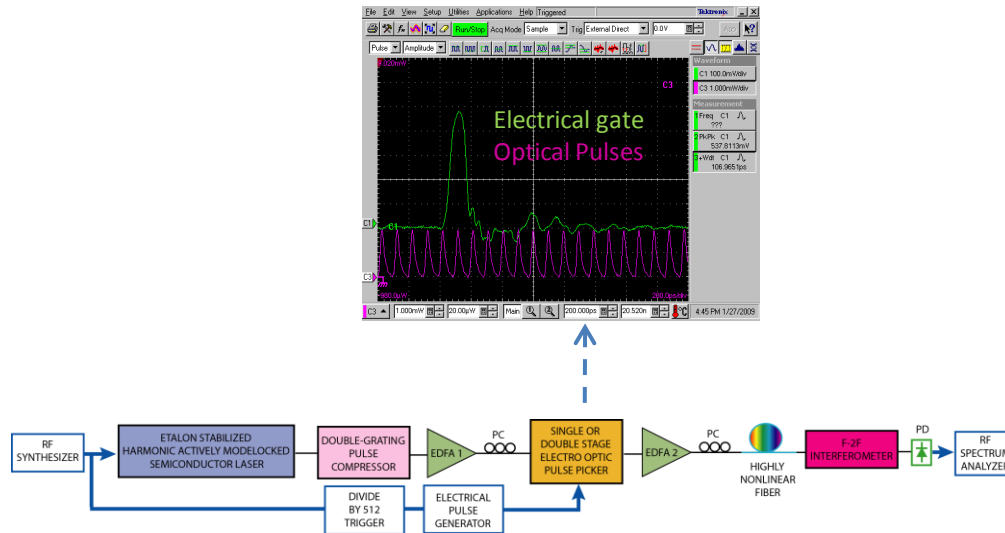


Fig. 12. Measurement of the electrical gate use for multiplexing showing non-ideal zero level (top), and experiment setup for f-2f CEO frequency measurement

The experimental setup for the f-2f self-referenced CEO frequency measurement is shown in Fig. 12 (bottom). The output of the optical comb source after the pulse compressor is fed into a commercial EDFA (EDFA1) and amplified up to 400 mW. Since a significant amount of power is discarded in the pulse picking process, pre-amplification helps to saturate the amplifiers better after the pulse picker. A portion of the RF sine-wave drive of the comb source was divided by 512 and used to trigger the electrical pulse generator for pulse picking. Either a single-stage or double-stage pulse picking arrangement was implemented to improve the dynamic optical pulse extinction ratio, which was measured to be up to ~ 27 dB after the pulse picker. After the pulse picker, custom EDFAs were used to amplify the optical signal with minimal distortion. The autocorrelation width at the input of the HNLF is measured to be < 200 fs with low pedestal (Fig. 13a). The shorter pulse width was attributed to slight nonlinear compression inside the EDFAs. An octave was easily generated with ~ 1 nJ of

energy, and 45cm of HNLF (Fig. 13b). The f and $2f$ signals were obtained using a standard free-space f - $2f$ interferometer that utilized a Periodically Poled LiNbO₃ crystal (Fig. 13c). Unfortunately, the CEO beat notes could not be observed on the RF spectrum, but rather there was an increase in the overall noise floor when the interferometer delay was aligned correctly (Fig. 13d).

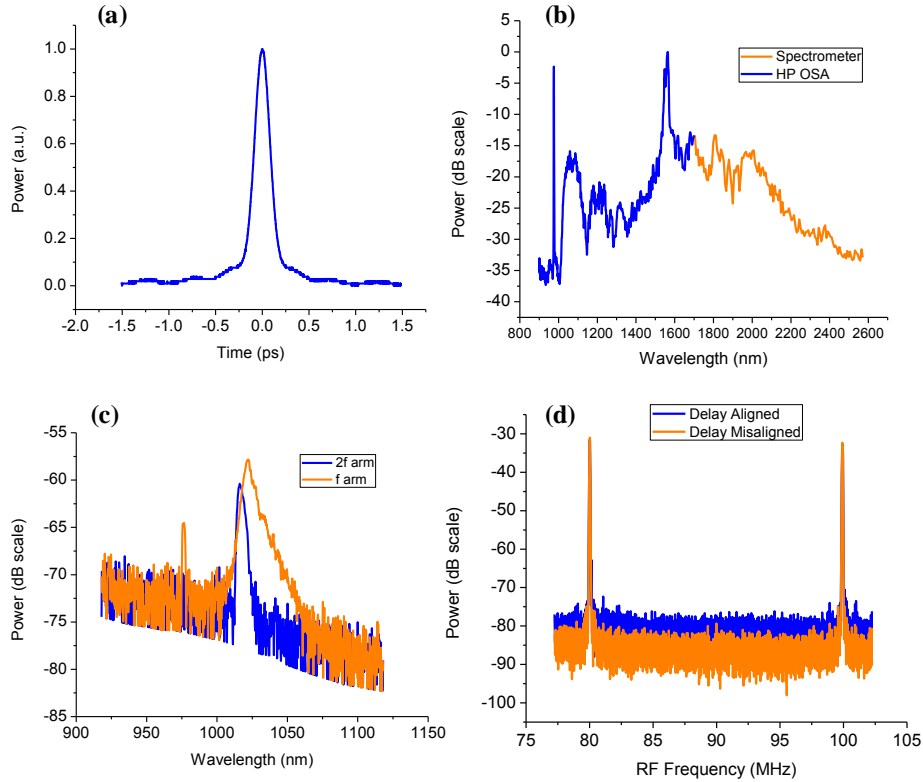


Fig. 13. (a) Pulse picked laser autocorrelation, (b) Sample octave, (c) f - $2f$ signals, (d) RF spectrum with and without correct delay alignment

The operation of the EDFA, HNLF and f - $2f$ interferometer was verified independently with a 20 MHz repetition rate, ~ 300 fs passively mode-locked Erbium-doped fiber laser. We did not try to optimize any of the supercontinuum or f - $2f$ mixing processes with the passively mode-locked laser. This was a quick sanity check to make sure our setup can generate CEO beat notes. It was also useful in observing the dynamics of the octave generation, and how it is different from the pulse-picked etalon based comb source. The passively mode-locked laser easily yielded an octave and CEO frequency beats (Fig. 14). In this case, the optical octave was generated with more flatness compared to the pulse picked laser, and the dominant effect of Self Phase Modulation (SPM) was clearly visible on the OSA during the evolution of the octave. This lead us to the conclusion that the coherency of the optical combs were degraded for the pulse-picked etalon-stabilized comb source, possibly due to the noise introduced by significant demultiplexing and amplification processes. In fact, a clear leakage peak at the center wavelength of the comb source is visible in the octave in Fig. 13b, indicating that the pulse picker extinction ratio is not sufficient. We believe that the unpicked pulses result in the peak power reduction at the output of the fiber amplifier, which reduces the effect of SPM. In order to compensate for this peak power loss, we have to increase amplification, which leads to more noise, and possibly undesired Four-wave mixing processes. Future plans include

improvement in the pulse picker extinction ratio, and better amplification prior to the pulse picker in order to reduce the noise and increase coherence.

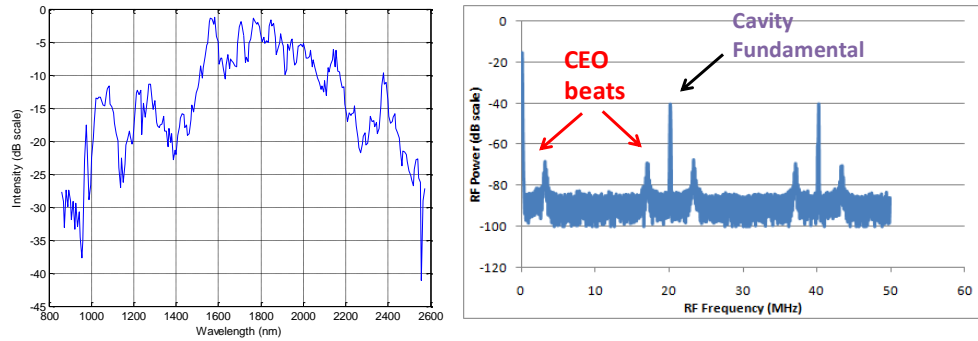


Fig. 14. Octave generation (left) and f-2f CEO frequency measurement (right) using a passively mode-locked fiber laser

5. Conclusion

In conclusion, we demonstrated the measurement of the CEO frequency for a ~10 GHz etalon-stabilized actively-harmonically mode-locked semiconductor optical comb source for the first time. The CEO frequency was measured as ~1.47 GHz (or ~8.77GHz). The technique for measurement was optical multi-heterodyne mixing with a reference CEO-stabilized optical comb source. CEO frequency drift of ~50MHz over 1.5 hours is observed and attributed to air temperature fluctuations inside the etalon. Preliminary results of an attempt to measure the CEO frequency through the f-2f self-referencing technique were also reported. Both direct and demultiplexed comb source outputs were used to generate an optical octave. However, the RF beat notes were not observed in the f-2f experiments due to excess noise in the setup.

Acknowledgments

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