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Beating of two FDML Lasers in Real Time

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ABSTRACT

Fourier domain mode locking (FDML) is a recently developed technique for lasers to generate ultra-rapid wavelength sweeps, equivalent to a train of extremely chirped pulses. FDML lasers are the light sources of choice for fastest megahertz optical coherence tomography (MHz-OCT). Measuring the coherence properties of FDML lasers is of particular importance for the image quality in OCT but it is also crucial to develop a better understanding of this unconventional mode locking mechanism. Usually, experiments to analyze the phase stability of FDML lasers use interferometers to generate interference of a single laser by delaying a part of the output to generate a beat signal. Here, for the first time, we present real time beat signal measurements between two independent FDML lasers over the entire sweep range of ~5 THz width for more than 80 roundtrips (~200 μs), evaluate their phase stability and explain the consequence for our understanding of the FDML mechanism. Beat signal measurements allow direct access to the phase difference between the FDML lasers and therefore the difference in timing of the circulating sweeps as well as their instantaneous frequency.

Keywords: FDML lasers, Fourier domain mode locking, fiber lasers, beat signal, OCT, optical coherence tomography

1. INTRODUCTION

Fourier Domain Mode Locking[1] is a laser technique, where the frequency of the laser light is modulated by a resonantly driven tunable optical bandpass filter. FDML lasers consist of a long fiber resonator, a broadband gain medium and a tunable Fabry-Pérot filter (see Figure 1). A semiconductor optical amplifier (SOA) generates broadband light, but only a small part is transmitted through the tunable filter. This light is amplified again in the SOA. If the roundtrip time of the light or an integer fraction of it matches the inverse sweep frequency for all wavelengths, the laser operates in a stationary regime called FDML “sweet spot“[2], which is an ultralow noise operating regime where all wavelengths are simultaneously “stored” in the cavity. The output of the FDML laser are extremely chirped pulses with tuning rates of $>10^{19}$ Hz/s and sweep ranges of up to 25 THz.

One application of FDML lasers is Optical Coherence Tomography (OCT), an imaging technology generating cross sectional images of biological tissue. Today it is a standard procedure in ophthalmology, but it also gains more and more importance in other fields. FDML lasers are the light sources of choice for fastest Megahertz Swept Source-OCT (MHz-OCT) and allow new applications like 3D video rate imaging and OCT assisted mixed reality systems for surgical guidance[3]. OCT image quality strongly depends on the coherence properties of the light source and therefore on its phase. Moreover, the coherence properties are also relevant for a better understanding of the Fourier domain mode locking mechanism itself. A standard method to get access to the optical phase are beat signal measurements. However, since the FDML laser sweeps span more than 5 THz, a simple superposition with a narrow band laser only yields a very short fringe signal for each sweep[4]. So, to access the differential phase between two FDML lasers for the entire sweep, it is necessary to very precisely match two independent FDML lasers in their timing, sweep range and repetition rate with an accuracy better than the electronic analogue detection bandwidth of the detector for the beat signal. In our case this is 35 GHz corresponding to ~0.2 nm at 1300 nm. The sweep filter in the FDML laser has a width of approximately ~0.16 nm which is effectively low pass filtering any phase and amplitude fluctuations of the light field, so the entire dynamics of the interference can be measured with our fast 63 GHz real time detection.

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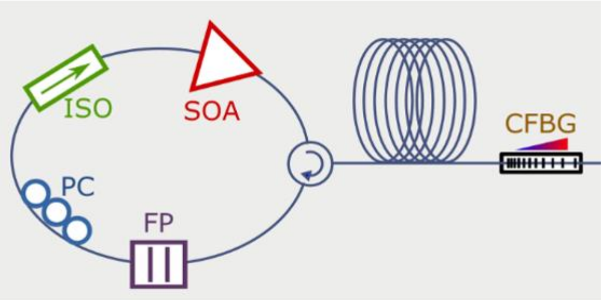

Figure 1: The FDML laser consists of a semiconductor optical amplifier (SOA) as light source and a tunable Fabry-Pérot filter (FP), which acts as the wavelength selecting element. The polarization is adjusted using a polarization controller (PC). A fiber isolator (ISO) ensures light propagation in only one direction. A chirped Fiber Bragg Grating (CFBG) is used to diminish the dispersion and to transmit a percentage of the light.

2. METHODS

Typically, phase stability in FDML lasers is analyzed through splitting, delaying and interfering the light of one single FDML laser in an interferometer. This only yields differential phase measurements and makes it very difficult to analyze long term drift effects over many roundtrips. Here, we superimpose two different lasers for beat signal measurements and examine coherence properties of these lasers. At first, the beat signal of a continuous wave (cw) ring laser and an FDML laser was measured. Afterwards, two FDML lasers were superimposed, whereat either both lasers had opposite sweep directions or the same.

2.1 Beating of continuous wave laser and FDML laser

The first beat signal measurements were performed with a cw ring laser and an FDML laser. The homebuilt FDML laser has a repetition rate of 411 kHz and a bandwidth of 40 nm around 1290 nm for this experiment. The wavelength of the ring laser is 1305 nm. The superimposition generates a short oscillatory interference signal on the FDML sweep as seen in Figure 2. The FDML laser's sweep is a backward sweep, meaning the wavelength changes from 1310 nm to 1270 nm. Hence, the visible beat signal is on the left side of the sweep around 1305 nm. The analog detection bandwidth of photodiode and oscilloscope limit the visible beat signal and only a small part of the sweep can be investigated. 83 consecutive beat signals were acquired with the real time oscilloscope (DSOZ634A Infiniium, 63 GHz, Keysight).

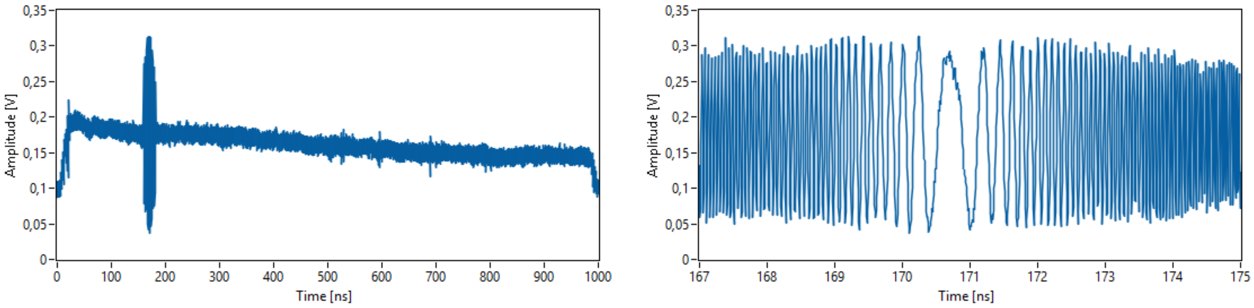

Figure 2: Left: Beat signal on FDML sweep. Right: Zoom into the beat signal. The frequency of FDML laser and ring laser are exactly the same in the middle at approximately 170.7 ns. The beat frequency increases in both directions until only the averaged signal is visible because of the limited analog detection bandwidth.

2.2 Beating of forward and backward sweep of two FDML lasers

Here, we present, for the first time, beat signal measurements between two independent FDML lasers. We built two temperature stabilized FDML lasers. The temperature was the same in both lasers. The lasers have a central wavelength of 1300 nm and a sweep range of up to 100 nm. We set their sweep range to 30 nm and exactly matched their sweep repetition rates at 417285 Hz through adding or removing optical fiber from the cavities. Simultaneously, the dispersion in both cavities is changed through applying a dispersion-balanced mix of different optical fibers (smf28, LEAF, HI1060). One of these lasers includes an adjustable free space beam path in its fiber cavity to exactly adapt its cavity length to the second one. The setup for beat signal measurements is seen in Figure 3. A 1 GHz auxiliary oscilloscope (DPO5104, Tektronix) was used to ensure that both FDML lasers were operating in the so-called “sweet spot mode”, the ultra-stable regime observed for almost perfect synchronization[2]. We showed that by a specific interferometer design[5], monitoring and regulating on sweet spot operation is possible even with a “slow” 1 GHz oscilloscope. The light of both FDML lasers was superimposed on a fast photodiode (DSC20H, 35 GHz, Discovery Semiconductors) and the beat signals were recorded with a 63 GHz real time oscilloscope (DSOZ634A Infiniium, 63 GHz, Keysight). This allowed us to observe a beat signal, when the instantaneous frequency difference of both FDML lasers is smaller than ~35 GHz corresponding to ~0.2 nm at 1300 nm. The 35 GHz limit is no strict threshold. The roll-off of the photodiode allows the visualization of even higher frequencies, but with reduced amplitude. The 63 GHz bandwidth of the oscilloscope is on the contrary a strict limitation.

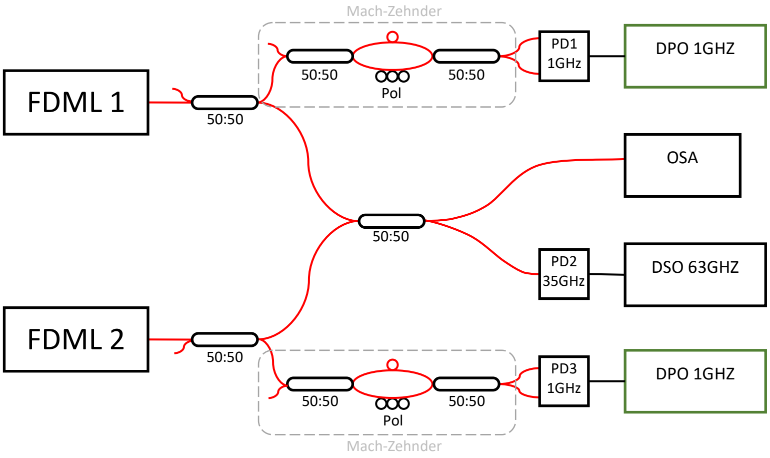

Figure 3: Setup for beat signal measurements between two FDML lasers. The laser light of each FDML laser is guided through a Mach-Zehnder interferometer and a photodiode (PD). The signal on an auxiliary 1 GHz oscilloscope (DPO) is used to regulate both lasers into sweet spot mode or check sweet spot operation. The light of both FDML lasers is superimposed in a 50:50 coupler for beat signal measurements. It is then guided to an optical spectrum analyzer (OSA) and to a 35 GHz photodiode where the signal is recorded with a fast 63 GHz oscilloscope (DSO).

First, one forward and one backward sweep were superimposed. This ensures that both lasers have the same wavelength at some moment during the sweep, but very rapidly thereafter, their frequency difference increases so that the beat signal goes beyond our 35 GHz detection bandwidth. The superposition of both lasers is seen in Figure 4. Both lasers have a central wavelength of 1300 nm and a sweep range of 30 nm.

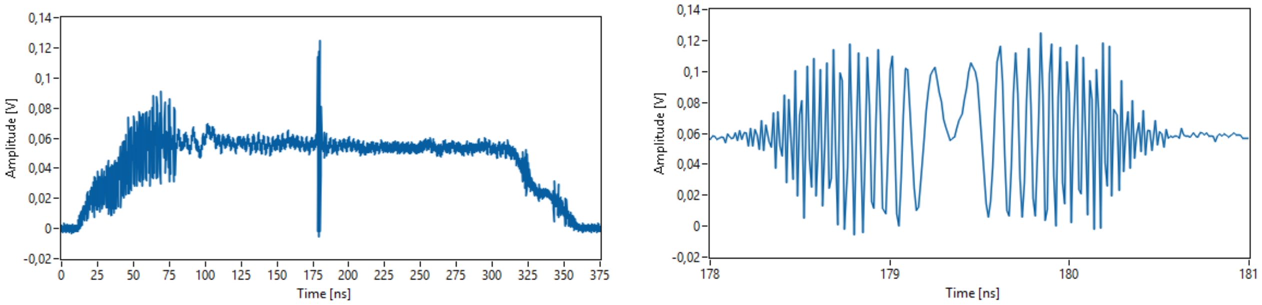

Figure 4: Left: Superposition of two FDML lasers with opposing sweep directions (forward sweep and backward sweep). At approximately 179.3 ns both lasers have the same frequency and generate a beat signal within the detection bandwidth. It is noticeable that at least one laser signal is noisy at the left edge and the lasers have a time mismatch, which generates the steps on both sides of the overlaid sweeps but does not affect the beat signal. Right: Zoom into the beat signal.

The data was recorded with a 35 GHz photodiode and an oscilloscope with 80 GSa/s. If all parameters are the same as in the previous experiment, the beat signal is even shorter, because both lasers change their wavelengths in opposing directions, which generates even higher beat frequencies.

2.3 Beating of two forward or two backward sweeps

As seen in Figure 2 left and Figure 4 left the beat signals only take a small part of the whole sweeps due to limited measurement bandwidth. Therefore, these measurements only reveal the phase information on a small part, but not the whole sweep. A visible beat signal over the whole sweep could be generated by superimposing two sweeps with the same frequency chirp. To achieve this, the two FDML were set up to produce two sweeps in the same frequency chirp direction, i.e. two forward or two backward sweeps. To see a beat signal over the whole sweep the lasers must be precisely matched in time such that the difference of the instantaneous frequencies of both lasers is smaller than ~35 GHz corresponding to ~0.2 nm at 1300 nm.

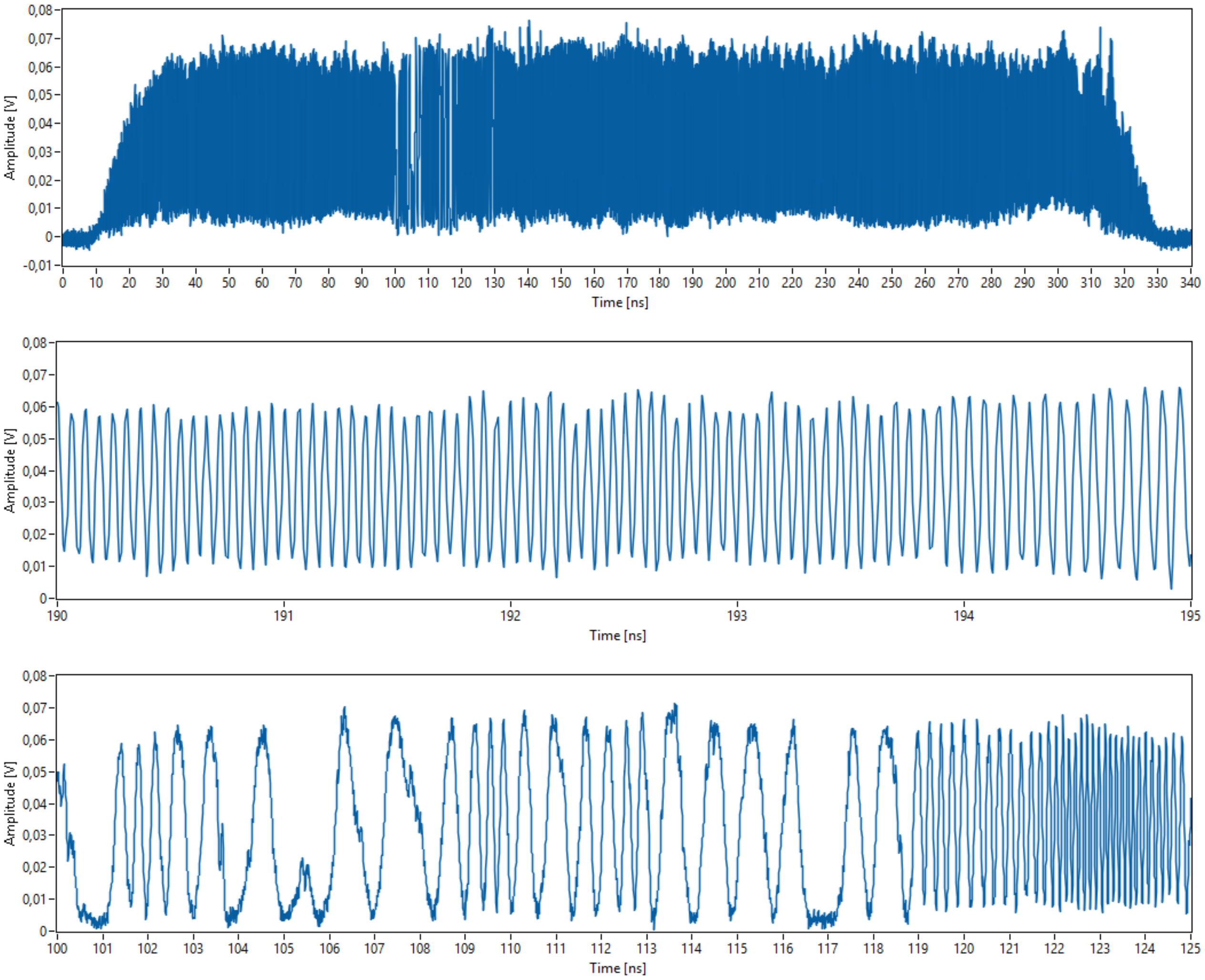

Figure 5: Top: Superimposition of two forward sweeps. When both lasers precisely match up, a beat signal can be seen over the whole sweep. The holes in the signal between 100 ns and 130 ns suggest that the frequency seems to not be the same over the whole length. Middle: Zoom into one part of the beat signal where the frequency difference between the two FDML lasers is alike. Bottom: Zoom into one part of the beat signal where the frequency difference between the two FDML lasers fluctuates.

Two superimposed forward sweeps are seen in Figure 5. The FDML frequency is 417285 Hz. The central wavelengths of both lasers are 1300 nm and the sweep ranges are 30 nm.

3. RESULTS

Consecutive beat signals were recorded to investigate the phase evolution over time. Measurements last 0.2 ms generating a trace of 83 successive beat signals.

3.1 Beating of continuous wave laser and FDML laser

When one beat signal data point in the first of consecutive sweeps is selected and plotted with the data points at the same time in the following sweeps, the generated graph shows a sinusoidal evolution (Figure 6 left). Since every sweep contributes one data point to the graph, the sampling rate corresponds here to the repetition rate of the FDML laser. A Fourier transform of this graph shows one peak at a distinct frequency as seen in Figure 6 right.

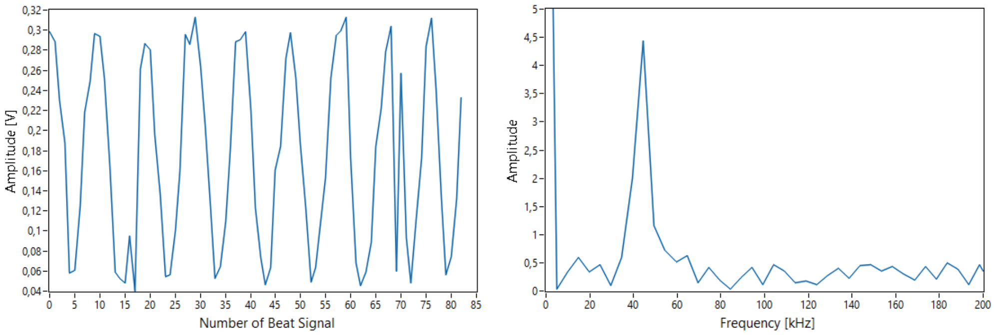

Figure 6: Left: Values at one moment of consecutive beat signals (one data point per beat signal) of a cw laser and an FDML laser. Right: Fourier transformation of these data.

3.2 Beating of forward and backward sweep of two FDML lasers

The same analysis was performed with the beat signals of the backward and forward sweep. Again, the generated graph is rather sinusoidal than a random noise (Figure 7 left). An applied Fourier transformation shows no sharp peak, but distinct frequencies and not only noise.

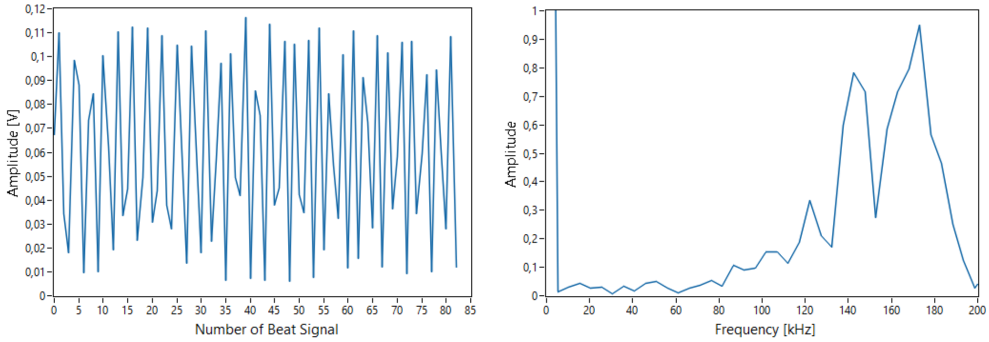

Figure 7: Left: Values at one moment of consecutive beat signals (one data point per beat signal) of two FDML lasers, respectively a forward and a backward sweep. Right: Fourier transformation of these data.

3.3 Beating of two forward or two backward sweeps

In the third experiment we overlaid two forward sweeps and can observe a fringe signal covering the entire 30 nm or 5 THz sweep range. This measurement yields information about the entire differential wavelength and phase evolution as well as the mode structure of the FDML laser. Again, a sinusoidal signal is found over consecutive sweeps and a Fourier transformation gives a distinct frequency for the phase evolution (Figure 8).

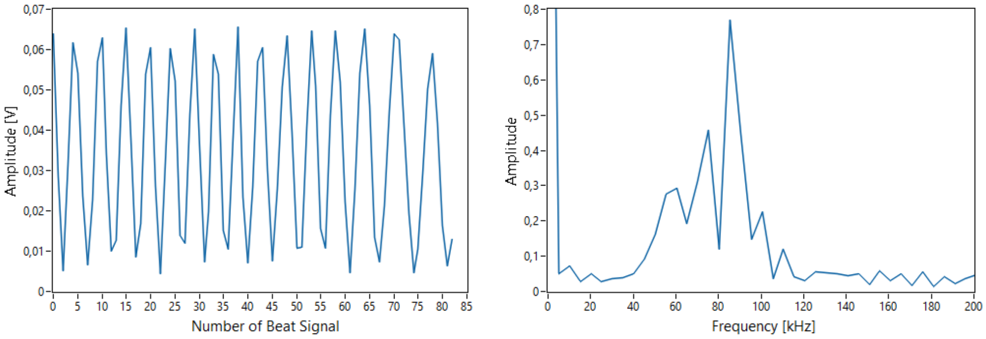

Figure 8: Values at one moment of consecutive beat signals (one data point per beat signal) of two FDML lasers, respectively two forward sweeps. Right: Fourier transformation of these data.

The fluctuating frequencies from Figure 5 could occur due to long term drifts in the FDML laser. Such a long term drift can also be observed in our not yet published FDML laser simulations, where it originates from the laser dynamics and the nonlinear nature of the FDML laser. Another reason for the differences in the middle and bottom graph from Figure 5 could be due to remaining differences in the two lasers, respectively different residual dispersions in the two lasers. So, some wavelengths are at different positions in the sweeps of the two different lasers.

3.4 Summary of the results

By analyzing the fringe phase at the exact same time in the sweep over 83 sweeps, we can get direct access to the mode profile of the FDML laser at this wavelength. A stable phase is evidence for a pronounced laser mode profile. Sometimes this phase evolution contains disturbances, but that does not interrupt the sinusoidal shape in the long term (see Figure 6 left). Moreover, this phase evolution is sometimes chirped or modulated, but we always observe a periodic evolution rather than a random fluctuation, which proves the existence of laser modes and gives access to their shape as a comb like structure. When the distinct frequency peak (the frequency with the highest amplitude in Figure 6 right, Figure 7 right or Figure 8 right) is plotted for thousands of data points over the beat signals, a flat graph is seen. This graph could be at different levels, but it never fluctuates over the whole possible range as seen in Figure 9.

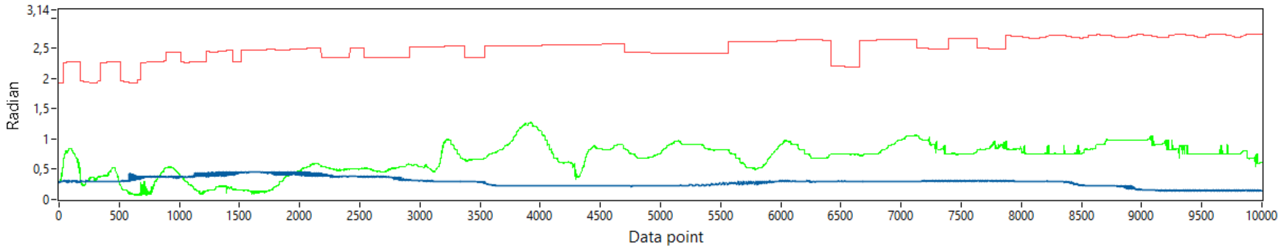

Figure 9: Phase evolution over different beat signals. Blue: cw laser and FDML laser. Red: Forward sweep and backward sweep of two different FDML lasers. Green: Two forward sweeps of two different FDML laser. Note: The number of data points does not correspond to a specific period of time. 10000 data points were evaluated for each beat signal, independent from its time duration. The 10000 data points correspond to approximately 20 ns (blue), 2 ns (red) or 300 ns (green).

4. CONCLUSION

We presented the first successful beat signal measurements of two independent FDML lasers over the entire sweep range. This provides valuable access to information about the phase stability and mode structure of FDML lasers. We provide evidence for a comb like spectrum of the FDML laser. Moreover, this beat signal over the whole sweep can make long range sensing possible in the future. This application will be further investigated.

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