Dispersion, coherence and noise of Fourier domain mode locked lasers

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Abstract: We report on the effect of chromatic dispersion on coherence length and noise of Fourier Domain Mode Locked (FDML) lasers. An FDML laser with a sweep range of 100nm around 1550nm has been investigated. Cavity configurations with and without dispersion compensation have been analyzed using different widths of the intra-cavity optical band-pass filter. The measurements are compared to non-FDML wavelength swept laser sources. Based on these observations, a simple model is developed providing a connection between timing, photon cavity lifetime and characteristic time constant of the filter. In an optimized configuration, an instantaneous laser linewidth of 20pm is observed, corresponding to a 10x narrowing compared to the intra-cavity optical band-pass filter. A relative intensity noise of -133dBc/Hz or 0.2% at 100MHz detection bandwidth during sweep operation is observed. For optimum operation, the filter drive frequency has to be set within 2ppm or 120mHz at 51kHz.

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References and links

1. Introduction

Recently, the introduction of Fourier Domain Mode Locking (FDML) [1] has helped to overcome physical limitations of the sweep repetition rate of rapidly wavelength swept laser sources [2]. Such sources can be employed for optical coherence tomography (OCT) [3] using frequency domain detection [4]. This technique is called swept source OCT (ss-OCT) or optical frequency domain imaging (OFDI). Especially for wavelengths longer than 1050nm, where standard silicon based line array detectors cannot be used, ss-OCT appears attractive in order to achieve fastest imaging rates. Standard swept lasers for OCT [2, 5, 6] essentially consist of a laser gain medium for light amplification, an output coupler for energy extraction and a periodically driven optical band-pass filter for active wavelength selection. FDML lasers have an additional optical delay line with a length of several kilometers, so that the optical roundtrip frequency in the cavity is shifted down to several tens of kHz and can be synchronized to the sweep frequency of the optical band-pass filter [1, 7-10]. In this operation mode, every sweep is seeded by the previous one, leading to a much more stable laser operation with respect to intensity and optical phase noise [11]. In addition, the laser has better coherence properties by a reduction of the instantaneous linewidth, making it suitable for OCT applications that need large imaging ranges [12, 13]. FDML lasers have already proven superior performance in a number of sensing and ranging applications [11, 14-24].

In this paper we present a detailed analysis of coherence and noise of FDML lasers, depending on filter drive frequency detuning and amount of cavity dispersion. The results provide insight into phase and amplitude noise of the laser light itself.

Because the optical delay line is implemented as additional km-long single mode fiber, the laser cavity can exhibit a significant amount of chromatic dispersion, resulting in different roundtrip times for different wavelength components. It has been demonstrated that a limited amount of dispersion can be tolerated at 1050nm and 1310nm and the output power and the maximum sweep bandwidth can be optimized by an appropriate choice of filter bandwidth and sweep rate even in a dispersive regime [17]. However, the influence of chromatic dispersion on laser intensity noise and instantaneous coherence properties has not been investigated in detail yet.

In this paper we address the questions: (1) How much dispersion compensation is necessary for optimum laser performance? (2) What is the connection between sweep filter bandwidth and amount of dispersion compensation? (3) How does chromatic dispersion affect the effective cavity photon life time, i.e. how many roundtrips can a photon make in the laser despite misalignment due to dispersion? (4) How do timing mismatch effects caused by detuning the drive frequency of the sweep filter affect coherence and noise and how does this interact with time mismatch effects caused by dispersion? (5) How much improvement in coherence length and reduction in noise can be achieved by a dispersion compensated setup?

To investigate these questions, we implemented an FDML laser at 1550nm center wavelength, because dispersion compensation fiber (DCF) to cancel chromatic dispersion in standard single mode fiber (SMF) is readily available at this wavelength. The dispersion compensated setup can be converted to a setup with higher dispersion by exchanging the spool of DCF with one of SMF. In addition, we have used two different fiber Fabry-Perot tunable filters (FFP-TF) as optical band-pass filter, one with a 0.28nm bandwidth and one with a 0.02nm bandwidth.
2. Experimental setup

2.1. Setup of the laser and the detection scheme for noise and coherence length

Figure 1 shows the FDML laser, which consists of a semiconductor optical amplifier (SOA, Covega Corp. - type BOA1004) as polarization dependent broadband gain medium centered at 1550nm. Two optical isolators (ISO), before and after the amplifier ensure unidirectional lasing. 30% of the intensity is coupled out of the resonator by a 70/30 coupler.

The remaining light in the cavity passes through a polarization controller (PC), a spool of 335m of either standard single mode fiber (SMF, OFS - type Allwave ZWP) or dispersion compensation fiber (DCF, OFS - type LLWBDK-C) and a spool of 3650m SMF. After passing through a FFP-TF of either 0.28nm (Lambda Quest, LLC - finesse 600, free spectral range (FSR) ~168nm) or 0.02nm (Micron Optics, Inc. - finesse 4800, FSR 100nm) full width at half maximum (FWHM) transmission window, the light is coupled back to the SOA. 90% of the light intensity from the laser is attenuated to ~1mW and detected with a 100MHz bandwidth photo receiver (Thorlabs - type PDB150C and 100MHz low-pass filter, Mini-Circuits). The signal is sampled by an analog-to-digital converter (ADC) at a rate of 200MS/s and a resolution of 12bits (GaGe Applied Technologies - model CS12400).

The remaining 10% of the light pass through a Mach Zehnder interferometer (MZI) consisting of two 50/50 couplers and a variable delay line. The delay line is actuated by a step motor and can be controlled by a personal computer. The interference signal is detected with a 1GHz bandwidth photo diode (Menlo Systems - model FPD310) and sampled with a digital oscilloscope (Tektronix, Inc. - model DPO7104) at 2.5GS/s with 8 bit resolution. The tuning frequency of the FFP-TF is given by the total optical path length of the cavity and is ~51kHz. The average output power of the laser was around 3.5mW.

By removing the delay fibers, a non-FDML laser could be configured for comparison. The cavity length was 18m and this laser was used as a fixed wavelength source and as swept source at lower repetition rates.

3. Chromatic dispersion

In our FDML laser cavity, chromatic dispersion is the main cause for synchronization errors, polarization mode dispersion (PMD) is neglected in our analysis. It is <400fs, according to the specifications of <0.2ps/(km^{0.5}) and therefore much smaller than chromatic dispersion.

The main part of chromatic dispersion is caused by the long spool of single mode fiber of the delay line, which essentially consists of fused silica. For fibers, the chromatic dispersion is
usually given by the parameter $D(\lambda)$ in units of ps/(nm·km). In our case, to quantify the synchronization mismatch after one roundtrip for the different wavelength components caused by dispersion in a cavity of length $l$, it is more practical to use the relative roundtrip time difference $\tau(\lambda)$ with respect to a center wavelength $\lambda_c$, which is given by the integral

$$\tau(\lambda) = \int_{\lambda_c}^{\lambda} D(\lambda')d\lambda'. $$

If we assume perfect synchronization in the center of the sweep at 1550nm, the dispersion of the FDML laser can be expressed as roundtrip time mismatch for a certain wavelength relative to the center wavelength. For highly accurate compensation, the total dispersion of the cavity was measured with a home built dispersion analyzer. We used 335m of dispersion compensation fiber and adjusted the length of the standard single mode fiber such that the dispersion was minimal in a 100nm window from 1500nm to 1600nm where the laser is operated. As can be seen from Figs. 2(a) and 2(b), the relative roundtrip time mismatch has been reduced by nearly two orders of magnitude by the use of DCF and is on the order of several tens of picoseconds with the DCF. For a narrower range of ~40nm around 1550nm it is only a few ps. To understand the influence of dispersion on FDML operation in a simple model, we estimate the maximum possible photon cavity lifetime, which is a measure for how many roundtrips a photon can make until it is absorbed. This value can be used to compare FDML with continuous wave (cw) operation in lasers [12].

In this simple model, the number of possible roundtrips gives the maximum number of repetitive filtering events in the laser limited by missynchronization caused by dispersion. The transmission through a Fabry-Pérot cavity around the transmission wavelength $\lambda_0$ is given by the Airy formula

$$T(\lambda) = \frac{1}{1 + \left(\frac{2F}{\pi}\right)^2 \sin^2 \left(\frac{\pi}{\Delta\lambda_{fsr}}(\lambda - \lambda_0)\right)},$$

where $F$ denotes the finesse of the filter and $\Delta\lambda_{fsr}$ the free spectral range. When the filter is sinusoidally tuned over a range of $\Delta\lambda = \alpha \Delta\lambda_{fsr}$ with a frequency $f$, the maximum sweep speed is given by $v_{\text{max}} = \pi f \alpha \Delta\lambda_{fsr}$. The maximum number of roundtrips $n$ in a cavity with chromatic dispersion is reached, when the additional loss $q$ caused by the $n$th filtering event exceeds the effective gain of the cavity, which is around 10dB for our laser. A lower limit for the number of roundtrips can then be estimated to be

$$n = \frac{\arcsin \left(\frac{\pi}{2F} \sqrt{10^{10} - 1}\right)}{\alpha \pi^2 f \tau}.$$
roundtrips \( n \) is plotted for the two fiber Fabry-Pérot filters with different transmission bandwidths used in this experiment. For the 0.28nm and the 0.02nm FWHM filter, the number of roundtrips rises from below 10 and below 1 in the case without to around 1000 and 100 in the case with dispersion compensation, respectively. This consideration does not account for amplitude- and phase-noise effects caused by the amplification in the SOA that is required to balance the losses. However, an effect of the increased number of filtering events should be seen in the instantaneous coherence length and linewidth as well as in the noise performance.

4. Instantaneous coherence length and linewidth

4.1 Measuring the linewidth of rapidly swept lasers

The instantaneous linewidth or coherence length of a laser is of high interest for a comprehensive understanding of the laser operation, because it is linked to its phase noise properties. Characterizing the instantaneous linewidth of rapidly swept lasers is not straightforward, because the laser sweeps or switches wavelength on a time scale of nanoseconds, far beyond the typical acquisition time of spectrometers. Furthermore, for many applications, not only the instantaneous linewidth, but also the jitter or uncertainty of the center wavelength is important, because in most cases rapidly swept lasers are used to encode optical wavelength in time. As a consequence, a highly accurate time–wavelength relation between successive sweeps is required, not only a narrow linewidth. Furthermore, it is often important to correlate the time-wavelength jitter to the jitter of neighboring wavelengths to distinguish between a “shift” of the whole spectrum from a “breathing” in between wavelength regions within the sweep. Therefore, sampling techniques using fast shutters are also not the ideal solution. In some cases, for special spectral positions, narrow gas absorption features can be used to get access to the laser linewidth [18, 19], but they also only represent a spectral gate and do not directly measure the laser linewidth.

For these reasons, rapidly swept lasers are often characterized using a Michelson interferometer or a MZI. The laser is wavelength swept and the fringe signal is observed while the arm length imbalance of the interferometer is increased. The decay or roll-off in fringe amplitude, i.e. fringe visibility over arm length difference is then often used to quantify the instantaneous coherence length [2, 25, 26]. However, this approach does not account for phase fluctuations in the sweep. An alternative is to resample the signal to an equidistant raster in optical frequency and perform a Fourier transform for each arm length mismatch. When the resulting peaks are plotted versus arm length difference, the roll-off of peak amplitudes can be considered as a measure for the “average” instantaneous coherence length of the source over the sweep. This method to measure swept laser sources is most often used in OCT applications, because it also provides the point spread functions (PSF), the axial resolution in OCT applications [2, 27] and information about the accuracy of the time-frequency resampling step [28]. We will apply this method here and derive the parameter \( R \) - a single number to characterize the roll-off.

4.2 Interferometric roll-off measurements of FDML laser

In an FDML laser, it is expected that the instantaneous linewidth depends on the bandwidth of the FFP-TF and on the number of successive spectral filtering events, narrowing the spectrum. In FDML operation for a constant FWHM filter bandwidth (FBW), the cavity photon lifetime or the number of possible roundtrips should increase with smaller relative roundtrip time difference \( \tau \) caused by dispersion and lower tuning range of the filter \( \alpha \) (see section 3).

Figure 3 shows the Fourier transforms for different arm length imbalances in a Michelson interferometer corresponding to the measured PSFs in OCT application. As described, the envelope of the roll-off is the Fourier transform of the “averaged” instantaneous spectrum, the shape of each peak corresponds to the envelope spectrum of the whole sweep. The scale is adjusted such that it corresponds to the offset in a Michelson interferometer that is half the
difference in optical path length. The tuning range of the laser was 100nm. The displayed data was recorded from the sweep which runs from long to short wavelengths. As previously reported [29], a significant difference for the other sweep direction could not be observed. It can be seen that in the case of the FFP-TF with a FBW=0.28nm there is a substantial increase in coherence length by dispersion compensation (Figs. 3(a) and 3(b)). For the FFP with FBW=0.02nm, there is only a very minor increase in coherence length (Figs. 3(c) and (d)), but the coherence is already very good in the non-compensated setup and comparable to the dispersion compensated setup with the FBW=0.28nm filter. For a more quantitative discussion, we will introduce the R-number for swept laser sources.

4.3 The R-number: A measure for coherence

For further discussion of the coherence properties, we want to derive a single number to characterize the roll-off properties of wavelength swept lasers. This parameter R should have the following 3 properties: (1) It should be numerically stable and robust against systematic errors. This means, in contrast to the often cited 6dB roll-off point [30], it ideally takes all measured PSFs into account using the maximum available amount of information. (2) R should be proportional to the coherence length rather than any inverse quantity, like spectral width. Thus, a better source has a higher R number. (3) R should have a descriptive unit that makes it easy to judge the sources practical use, especially in OCT and ranging applications. Such a R-number with the described properties will be derived in the following.

Figure 3 shows that the roll-offs exhibit a predominantly single exponential decay characteristic, which would correspond to a Lorentzian shaped instantaneous spectrum. Such an exponential decay, i.e. a linear roll-off on a logarithmic scale has been observed for most rapidly swept laser sources over a major part [1, 14, 30] or almost the entire range [21, 25, 27, 29, 31, 32] of measured delay settings in the interferometer. In the cases where the roll-off does not exhibit a highly linear roll-off on a logarithmic scale, often the measured range was too small, only up to a roll-off of 5-10dB. If the measurement extends to a range of 20dB or more, roll-offs of most sources appear to exhibit the exponential coherence decay characteristic.

Now, to quantify the coherence roll-off properties of the laser with a single number, an exponential decay curve is fitted to the signal maxima of the linear PSFs and the inverse decay constant in units of mm/10dB is used as a measure of coherence – we term this constant roll-off length R. At the center wavelength of the laser, an inverse Fourier transform of the transmission spectrum of the 20pm and 0.28nm FBW FFP-TFs lead to R-numbers of R=1.3mm/10dB and R=0.14mm/10dB, respectively (see Table 1 – column iFFT spectrum).

![Fig. 3. Roll-off of PSFs for different setups with 100nm tuning range. a) dispersion compensated, FBW=0.28nm; b) uncompensated, FBW=0.28nm; c) dispersion compensated, FBW=0.02nm; d) uncompensated, FBW=0.02nm.](image-url)
4.4 Coherence and drive frequency detuning

To investigate the dependence of the coherence properties on timing mismatch effects caused by chromatic dispersion and detuning of the filter drive frequency, we measured the R-number dependence on drive frequency for setups with different total dispersion. The laser has been detuned relative to the frequency with maximum R-number.

Depending on cavity losses, FBW of the FFP-TF and SOA gain, detuning of more than 10Hz suppresses lasing over the full 100nm tuning range and leads to an increased width of the PSF. However, in the frequency range of Fig. 4 of only ±8Hz, no variation in the width of the PSF could be observed. In the dispersion compensated setup with FBW=0.28nm (Fig. 4(a)), we observe a sharp feature within a very small frequency range of ~0.12Hz FWHM, where the R-number is improved up to 1.4mm/dB. Without dispersion compensation (Fig. 4(b)), there is no such feature and the curve appears flatter with a FWHM of ~10Hz. This effect can be explained by the increased number of spectral filtering events through dispersion compensation. In the compensated setup it is possible to achieve good synchronization of all wavelengths simultaneously. Therefore, the maximum achievable R-number is higher, but only for a very narrow range of filter drive frequencies. The non-compensated setup is more forgiving and less critical, because due to dispersion, there is always good synchronization in some parts of the spectrum, but never over the full sweep range. So the curve in Fig. 4(b) has a lower maximum and is broader. Compared to the width of the filter of FBW=0.28nm, which corresponds to an R-number of 0.14mm/dB, the dispersion compensated setup achieves a 2-10x line narrowing, the non-compensated setup a 2-4x improvement by FDML operation.

Surprisingly, with the FBW=0.02nm filter and with dispersion compensation (Fig. 4(c)), there is no sharp resonance peak as in Fig. 4(a), only a flat feature with a width of ~1.5Hz is observed. In the non-compensated setup, the R-number is almost constant for all measured values of detuning. This observation may be explained by the optical filter response times and will be discussed in the next sub-section.

The maximum achievable R-numbers are summarized in Table 1. It also shows the R-numbers for FDML lasers with reduced sweep range as well as for a non-FDML laser with a FBW=0.28nm at 2kHz and 20kHz sweep rate. The reduction in sweep range from 100nm to 40nm reduces the effective sweep speed and enables more effective roundtrips. This leads to an increase in the R-number.

4.5 Resonance time constant of the FFP-TF

Most of the observed features in Fig. 4 can be explained by the typical resonance time of the FFP-TF. For a FBW=0.28nm and a FBW=0.02nm at 1550nm, corresponding to optical frequency bandwidths of BW=35GHz and BW=2.5GHz, the characteristic time constants τ=1/BW are 29ps and 400ps, respectively. We only consider “typical timescales” for a rough
estimate and neglect effects of the actual envelope of the E-field. This means that in a simple model, any optical field passing through the filter is “washed out” over ~30ps or ~400ps.

Table 1. R-numbers for different FBWs for dispersion uncompensated (DNC) and dispersion compensated (DC) FDML lasers as well as for a standard swept laser. iFFT gives the R-number corresponding to the different widths of the FFP-TF calculated by inverse Fourier transformation of the FFP transmission spectrum.

<table>
<thead>
<tr>
<th></th>
<th>DNC 100nm</th>
<th>DC 100nm</th>
<th>DNC 40nm</th>
<th>DC 40nm</th>
<th>iFFT spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDML: FBW=0.28nm</td>
<td>0.6</td>
<td>1.4</td>
<td>0.9</td>
<td>1.7</td>
<td>0.14</td>
</tr>
<tr>
<td>FDML: FBW=0.02nm</td>
<td>0.9</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Non FDML: FBW=0.28nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.36 (2 kHz) / 0.14 (20 kHz)</td>
</tr>
</tbody>
</table>

The light intensity after the filter cannot change substantially on a time scale much faster than the ~30ps or ~400ps. Thus, timing errors, no matter if they are caused by dispersion or detuning of the sweep filter drive frequency, should only be critical if they are substantially larger than the 30ps or 400ps.

The observed peak feature in Fig. 4(a) has a width of ~120mHz. This corresponds to a timing error of $\Delta T = \Delta f/F_{\text{DRIVE}} = 0.12\text{Hz}/(51000\text{Hz})^2 = 46\text{ps}$. This value is on the order of the characteristic time constant of the FBW=0.28nm filter of 30ps. Accurate timing is needed due to the fast response of the wide filter. This means that an accurate setting of the sweep filter drive frequency and good dispersion compensation is required.

The observed, wider peak feature in Fig. 4(c) has a width of ~1.5Hz. This corresponds to a timing error of $\Delta T = \Delta f/F_{\text{DRIVE}} = 1.5\text{Hz}/(51000\text{Hz})^2 = 577\text{ps}$. This value is on the order of the characteristic time constant of the FBW=0.02nm filter of 400ps. The peak in Fig. 4(c) is wider; the coherence is good over a broad range. Even if it appears non-intuitive, timing is less critical with the narrower filter because the characteristic time constant is longer.

The observed, wider peak feature in Fig. 4(b), in the case of the non-dispersion-compensated setup, has a width of ~10Hz. This corresponds to 4ns timing error, which is roughly the timing error caused by dispersion: $\Delta T = 16\text{ps/nm/km} \times 3.5\text{km} \times 50\text{nm} = 2800\text{ps}$. In Fig. 1(d) no characteristic resonance or time constant is evident.

So, in a simple model, most of the observed features in Fig. 4 can be explained and we observe that as a rule of thumb, for FDML operation with maximal coherence length, the timing error caused by dispersion and sweep filter drive frequency error has to be on the order of the typical filter time constant $\tau = 1/BW$ or less.

5. Relative intensity noise (RIN)

5.1 Measuring the RIN of rapidly swept lasers

In the previous section the coherence properties and linewidth of FDML lasers have been discussed. They are related to the phase noise of the laser output. In this section we will investigate the amplitude noise of the FDML laser, which is linked to the intensity noise of the laser. We will investigate the relative intensity noise (RIN) performance depending on the amount of cavity dispersion and filter drive frequency detuning. For this quantitative analysis, a discussion of how to measure noise in a rapidly wavelength swept laser will be given first.

The power of a laser can be expressed as $P = P_0 + \Delta P(t)$ with an offset power $P_0$ and time dependent fluctuations $\Delta P(t)$. When the intensity noise of a fixed wavelength continuous wave (cw) laser is analyzed quantitatively, often the single-sided noise power spectral density $S_{\Delta P}(f)$ is used. It can be measured with a photodiode and a radio frequency (RF) spectrum analyzer or calculated by Fourier transformation of normalized power fluctuations recorded in the time domain [33]. Such measurements are shown in Fig. 5 for the ASE output from the
SOA (a-b) and the swept FDML laser (c-e). About 1mW of the output from the SOA or the FDML laser was recorded with a 100MHz bandwidth photo receiver and digitized at 200Msamples/s at 12bit resolution. A trace of 1 or 16 million points was Fourier transformed and the square of the amplitude is displayed as power spectrum. The equivalent RF-resolution bandwidths (RBW) are 200Hz and 15Hz, respectively. The spectrum is normalized to units of dBc/Hz by adding a constant on the logarithmic scale such that the DC component is $10 \cdot \log(1\text{Hz}/\text{RBW})$.

5.2 Disadvantage of RIN characterization of wavelength swept lasers by the noise RF-spectrum

It can be seen in Fig. 5(a) that the noise power spectral density (PSD) of the ASE for the SOA has an almost completely flat characteristic throughout the detection bandwidth at a mean value of -126dBc/Hz. At the very low frequency end <2kHz the PSD slightly increases (Fig. 5(b)). For a cw light source the RF spectra provide direct access to noise performance. However, in the case of wavelength swept lasers, the disadvantage of the noise PSD characterization can be seen in Figs. 5(c)-5(e).

In wavelength swept laser sources, the output power changes while the laser is tuned due to the spectral dependence of the gain profile. This results in a periodic power modulation with the filter drive frequency. This modulation does not represent noise, but actually in many OCT applications, a specially tailored power envelope rather than constant output level is desired [34]. This modulation leads to a superimposed signal in the noise power spectral density with equidistant frequencies corresponding to the laser cavity mode spacing. The feature appears as spikes with a 51kHz spacing in the RF spectrum (Fig. 5(e)) similar to RF spectra of pulsed lasers. Especially because of their narrow frequency spacing, the observed peaks obscure the noise. Furthermore, the disadvantage of RF spectral analysis is that it cannot measure the noise of the laser at different wavelengths.

Thus, it is better to use the root mean square value of relative intensity noise $\delta P/P$, which is defined as:

Fig. 5. Normalized RF power spectra of ASE from the SOA (a-b) and the swept FDML laser (c-e). The ASE emission shows a flat spectrum over almost the entire measurement bandwidth (a). A slight increased noise level is observed for frequencies <2kHz (b). The peak signals from laser emission obscure measurement of the noise level (c). The background is flat at least for a frequency range from 0.8MHz – 100MHz.
where $f_1$ and $f_2$ are the boundaries of the detection bandwidth interval $\Delta f = f_2 - f_1$ of the measurement system and $S_{\Delta P}$ is the mean noise PSD. A drawback of this single number $\delta P/P$ is that the information on the frequency dependence of the noise is lost. However, since the noise PSD $S_{\Delta P}$ is almost flat over our measurement bandwidth $\Delta f$ as shown in Figs. 5 (a)-5(e), the noise power for any bandwidth can easily be calculated from the single RIN value $\delta P/P$. The RIN $\delta P/P$ can be measured by recording the laser intensity with an ADC and calculating the standard deviation of the samples. This gives the mean noise PSD $\overline{S_{\Delta P}}$ over the measurement bandwidth. The advantage of taking only the RIN for characterizing swept source lasers is that this value can be measured for each wavelength of the laser independently. In our setup the mean noise PSD $\overline{S_{\Delta P}}$ was determined by first measuring the transient power of 100 unidirectional sweeps with a 150MHz photo diode and a 100MHz low-pass filter, sampling at 200MS/s with a 12bit resolution ADC. Each of the 100 records consisted of 2000 samples, corresponding to 10µs total duration for each record, which is half the cycle duration of the FDML laser.

5.3 Intra-sweep and inter-sweep noise (sliding RIN / ortho RIN)

In order to investigate the wavelength dependence of the RIN performance, the sampling points should be selected in a way such that all samples correspond to a particular wavelength. The symmetry of a repetitively wavelength swept laser source offers two distinct ways to allocate the samples for the calculation of the standard deviation $\delta P/P$.

(1) The first method to measure wavelength resolved noise in periodically swept lasers is to analyze the power fluctuations within one sweep over a short time span. The measured “intra-sweep noise” can be understood as short term time fluctuations while the source is sweeping. The concept is sketched in Fig. 6(a) in form of the magnified inset. The samples to calculate the RIN are taken with a very short time window, over which the laser does not significantly change its wavelength. This “sliding RIN” standard deviation (STD) is calculated by analyzing the deviation of several (~2-100) neighboring samples. To account for the power envelope of the laser, a fit curve has to be subtracted from each sample point first. Alternatively, the mean power value of each sample point, determined by averaging a sufficient number of sweeps, can be subtracted. The second method is valid, if the integrated noise power up to the repetition frequency is negligible compared to the power of the sliding RIN bandwidth (see below), i.e. the fluctuation from sweep to sweep is substantially smaller than fluctuations within one sweep. In our case, this ratio was ~1:200, so we used the second method, because it is less complex and more robust than section wise data fitting. The sliding RIN is very critical for OCT applications, because it directly affects the dynamic range. If the
source power fluctuates within one sweep, the fringe signal is modulated, generating a background. Dual balancing does not reduce this effect and weak reflections might be obscured by the noise background, generated from a strong reflection. We will refer to this type of noise as intra-sweep noise measured with a "sliding RIN analysis". In the frequency domain, the sliding RIN analysis measures the integrated noise from the maximum analog bandwidth $f_{\text{max}}$, in our case 100MHz, down to $2f_{\text{SR}}/n$ with $n$ being the number of neighboring samples and $f_{\text{SR}}$ the sample rate. The sketch in Fig. 7(b) visualizes the relevant RF bandwidth in the blue filled area, which is only a part of the OCT relevant RF bandwidth. For a unidirectional ss-OCT setup, the relevant RF-bandwidth stretches approximately from the inverse sweep duration up to the maximum analog detection bandwidth. For the bidirectional sweep operation in our case, this is from ~102kHz up to 100MHz (green filled area, Fig. 7(a). (2) The second method to measure spectrally resolved noise in periodically wavelength swept lasers is to select samples of different sweeps but at the same wavelength position. This measurement reflects the change of the intensity from one sweep to the next at a certain wavelength position. It would be directly relevant for spectroscopic measurements, where small changes in transmitted intensity are to be measured [18, 19]. The concept is sketched in Fig. 6(a) in form of the red marked dots, indicating the temporal positions of the samples to calculate the standard deviation for a certain wavelength. It could be expected, that this “inter-sweep noise” is suppressed in FDML lasers, since they have a feedback in between sweeps. We measured this type of noise by calculating the standard deviation for one sample out of each of the 100 acquired records at the same time position within each sweep. Figure 6(b) shows the concept and why we will refer to this type of noise as “inter-sweep noise” or “ortho-RIN”. In the frequency domain, this type of measurement covers a RF bandwidth from half the laser repetition rate $f$ down to the inverse sampling duration $1/T_{\text{acquisition}}$. The corresponding frequency span is indicated by the green filled area in Fig. 7(b). The temporal spacing of the 100 samples is 20µs, resulting in a RF bandwidth of 250Hz up to 25kHz.
However, it is important to emphasize that the noise, measured with this technique, covers the range from 250Hz up to 100MHz, because higher frequency components are aliased into the measured low frequency range (Fig. 7(b)), as the analog bandwidth of the detection system is 100MHz. The ortho-RIN measurement covers more than the OCT relevant RF-bandwidth and is therefore the most conservative value, which yields the worst case values for noise. The ortho-RIN values are always higher than the sliding RIN values. This can be seen in Fig. 7(c) where the ortho-RIN is plotted (black curve) as well as the sliding RIN for different numbers of neighboring points, 2 up to 100. As described, the ortho-noise covers a RF range of 250Hz up to 100MHz, the sliding RIN measurements cover 2MHz and 40MHz to 100MHz for 100 and 5 points, respectively. In the special case of n=2, both lower and upper cutoff frequencies are 100MHz. As the cutoff-edges of the frequency response are softened for smaller values of n, the response function still exhibits a significant effective area. For higher values of neighboring points, the calculated noise value does not really represent the noise for a “single wavelength” but rather for a range.

Therefore, we will use the ortho-noise (inter-sweep noise) values in the following. To measure the ortho-noise, 100 records, each of which contained 2000 samples of the intensity trace of one sweep, have been analyzed. Then, the standard deviation at fixed positions within the records was calculated, corresponding to certain wavelengths. This yields the wavelength dependence of the RIN $\delta P/P(\lambda)$. The calculated RIN values are then the integrated noise spectral density for a detection bandwidth of 250Hz to 100MHz.

The RIN of 1mW spectrally unfiltered ASE from the SOA has a value of 0.4% which translates to a mean power spectral density of -128dBc/Hz over the 100MHz detection bandwidth. The relative intensity noise of ASE in a 0.28nm band, i.e. the noise of ASE transmitted through the filter, is much higher and was measured to be -108dBc/Hz, which corresponds to a RIN of 4%. This high value would be the RIN per pixel in spectral OCT systems and may affect their dynamic range. The RIN of a non-swept, fixed wavelength short fiber-ring laser (same setup, no FDML fiber spool) with the same SOA and FFP-TF and a power of 1mW gives a RIN value of 0.15% translating to a noise PSD of -136dBc/Hz. This
was the lowest achievable with this setup. The shot noise limit for a 1550nm light source with 1mW power is \(-156\text{dBc/Hz}\) equivalent to a RIN of \(1.5 \times 10^{-4}\) at 100MHz detection bandwidth.

### 4.4 The spectral dependence of ortho-RIN in FDML lasers

The RIN performance of non-FDML lasers typically exhibits a strong dependence on sweep frequency especially for sweep rates near the single roundtrip limit [2]. We observed for the non-FDML laser an ortho-RIN value of 0.8\% at 2kHz sweep rate and 3.0\% for 25kHz sweep rate, measured at 100MHz analog detection bandwidth. It is expected that FDML lasers are less noisy than standard wavelength swept lasers, as every wavelength component is seeded by the light from the preceding roundtrips and therefore lasing does not have to be build up from amplified spontaneous emission (ASE) repetitively. Obviously, the seeding is only efficient for all wavelength components, if the laser is driven at its resonance frequency [1] and if the chromatic dispersion lies below a certain threshold [17].

As with the coherence length, a compensation of dispersion in the cavity should increase the number of effective roundtrips for a specific wavelength and decrease noise. Increasing the finesse of the FFP should impede seeding, therefore increased noise is expected. As the optimum laser frequency and each wavelength component are linked by the dispersion relation, we plot the relative intensity noise versus frequency and versus wavelength of the laser. The results are two dimensional plots, where the RIN value is color coded (Fig. 8).

Figures 8(b) and 8(c) show the ortho-RIN for the non-dispersion compensated cavity and for a FBW=0.28nm for the two sweep directions of the laser. In both plots, there is a region of low noise which follows the dispersion relation shown in Fig. 2(a). While in non-FDML swept lasers the sweep from short to long wavelengths exhibits more power [2], we found for our FDML setup, that the other sweep direction performs better with respect to RIN. This is consistent with the observation that the dynamic range in OCT application of FDML lasers at 1310nm was observed to be better for backward-sweeps (long to short wavelength sweeping) [29]. Also, as previously reported, we did not observe a significant difference between in the roll-off length R for the two sweep directions [29]. In FDML operation near resonance the backward sweep does not exhibit reduced power compared to the forward sweep as in non-FDML sources, so it is unclear if there is a connection between the observation of reduced RIN in one sweep direction and the frequency downshift by non-linear effects in the SOA [35].

Surprisingly, in the dispersion compensated case shown in Fig. 8(a), both the absolute value of noise and the frequency span of low noise operation is not better or even worse than without the compensation fiber. The region of low noise operation is narrower. The behavior is equal for both sweep directions. As in the uncompensated case, a line of low noise follows qualitatively the dispersion relation given in Fig. 2(b), when the frequency differences are translated into relative roundtrip time differences. Why the noise level is not lower than in the uncompensated setup is currently unclear. It might be speculated that the increased number of effective roundtrips in the dispersion compensated setup makes the laser more sensitive to any noise or perturbation. Additionally, the reduced linewidth and increased coherence length might enhance parasitic non-linear effects due to the increased interaction length, like Brillouin scattering or four-wave mixing in the long fiber delay line. Nevertheless, in both, the dispersion compensated and the non-compensated setup with an FBW=0.28nm, there are frequency-wavelength combinations, where the noise approaches 0.15\% or \(-136\text{dBc/Hz}\). This value was the noise observed for the fixed wavelength non-FDML short ring laser and might be dominated by the gain element. However, in none of the FDML configurations, compensated or non-compensated, there is a filter drive frequency, where all wavelength components exhibit this low noise level of 0.15\%.

The FBW=0.02nm setup exhibits in general more noise than the setup with FBW=0.28nm. This may be explained by the inversely proportional increase of the noise of filtered ASE with filter bandwidth [36]. With high dispersion in the cavity, the RIN for both sweep directions is
shown in Figs. 8(e) and 8(f). As in the case with the large bandwidth filter, the noise performance of the setup with high dispersion is better than that of the dispersion compensated setup. In the case with low dispersion shown in Fig. 8(d), there is no decrease in noise level visible. The lack of sharp features in Figs. 8(d) and 4(c) may again be explained by the long filter response time.

5. Conclusion

We investigated the noise performance and the coherence properties of an FDML laser with different amounts of chromatic dispersion in the laser cavity. The laser covered a wavelength sweep range of 1500nm-1600nm at a sweep repetition rate of 2x51,000 sweeps per second. For a systematic investigation, the roll-off length R was introduced to specify the coherence. This value is numerically stable, robust against errors and the graphic unit mm/db is useful for OCT applications. We show that for FDML lasers it is sufficient to characterize the RIN by the standard deviation of the measured intensity at identical positions across successive sweeps. This ortho-noise value covers the full RF bandwidth relevant for optical sensing and it can be measured for each wavelength independently.

Compared to the used optical band-pass filter, we observe a linewidth reduction in FDML operation by a factor of 4 without dispersion compensation and more than a factor of 10 with dispersion compensation. The corresponding linewidth of the laser emission was around 20pm using an FBW=0.28nm filter. A drive frequency accuracy better than 120mHz at 51kHz was required. Using a more narrowband filter of FBW=20pm, the synchronization is much less critical and good coherence properties are observed over a larger range of drive frequencies. Sufficient coherence for depth ranging capabilities of several centimeters in OCT applications is demonstrated.

An analysis of the relative intensity noise shows that with the FDML laser -136dBc/Hz RIN can be achieved over an RF measurement bandwidth of 250Hz to 100MHz. This corresponds to 0.15% power fluctuations. At the laser power of 1mW, this value is 20dB higher than the shot noise limit.

The underlying mechanisms causing the observed properties of coherence and noise can be explained by the specific time constant of the intra-cavity filter. The inverse time constant corresponding to the optical filter bandwidth on a frequency scale corresponds well with the time mismatch introduced by slight detuning of the filter drive frequency.

The presented observations can serve as basis to estimate the performance achievable with FDML lasers, they can be used for the design and layout of FDML lasers tailored for specific applications and they can serve as basis for a comprehensive theoretical understanding of FDML in the future.

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