HYPERSONTRAL LASERS FOR SPECTROSCOPIC MEASUREMENTS IN THE NEAR-INFRARED

by

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This project develops hyperspectral lasers that are built using fiber-optic cavities and broadband semiconductor gain media. These sources are custom designed for high-speed (typically 30 kHz) spectroscopic sensing applications, such as thermometry based on H₂O absorption spectroscopy in harsh, combusting environments that are generally not conducive to more conventional thermometry techniques.

Novel time- and frequency-division multiplexed lasers are introduced that either scan continuously over chosen wavelength ranges or switch among discrete wavelengths. One example is a laser that scans through a 0.1-4 nm range centered near 1350 nm every 10 µs; it is an advanced Fourier domain mode locked (FDML) laser that offers ultra low intensity noise and a significantly narrowed spectral linewidth compared to typical FDML performance. Another example is a discrete time-division multiplexed laser that cycles through 19 spectrally narrow wavelengths in a 44-nm-wide spectral band (1333–1377 nm) every 15 µs, where each wavelength can be aligned to a specific absorption feature.

Such engineered lasers are changing the way one looks at solving spectroscopic sensing problems as these sources can be custom designed to address a particular problem instead of making decisions based on the availability of light sources in the marketplace.
ACKNOWLEDGMENTS

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Outside of the research group, I would like to thank my parents, family, and friends for their support and encouragement. Especially, I would like to thank my two grandmas for “pushing their thumbs” (German equivalent to “keeping their fingers crossed”) for every single exam I took throughout college career. Without all that luck, I might not have made it this far, which is why it is to them that I dedicate this work.
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CHAPTER 1. INTRODUCTION

Hyperspectral lasers are versatile light sources for sensors appropriate for a wide range of spectroscopic applications. The term hyperspectral denotes a sensor system rapidly monitoring a target in different spectral bands [2]. Hyperspectral sensing provides a record of spectral responses of materials over the wavelengths considered. Such information can then be matched with spectral signatures of individual materials from either field measurements or data bases to obtain information about the target. Of particular relevance to this work, laser absorption spectroscopy is a very useful and well-established optical measurement technique in combustion applications, where gas properties such as temperature, pressure and composition can be inferred by probing the specimen with a hyperspectral laser and recording the transmission and reference signals.

1.1 MOTIVATION

Traditionally, high-speed multispectral absorption spectroscopy has been performed using tunable diode lasers, for example two scanning diode lasers [3,4] or five tunable diode lasers operated at fixed wavelength [5] for measuring parameters such as temperature and species concentration. It can be summarized that in the past, sensor development process depended on the availability of laser sources and decisions were made based not on what one needs to measure but what one can measure with the available wavelengths. This approach severely limited the overall sensor performance, motivating the development of custom sources.
Hyperspectral laser sources can be characterized according to:

- **Spectral encoding**
  
  - **Frequency-division multiplexed** (FDM) hyperspectral lasers encode the spectral information in frequency, meaning that each spectral band is modulated a unique frequency. Hence, the spectral information can be decoded e.g. via a Fourier transformation of the recorded time domain signal.

  - **Time-division multiplexed** (TDM) hyperspectral light sources provide spectral encoding in time, that is to say, the bands are emitted successively in time.

- **Spectral coverage**
  
  - **Continuous** hyperspectral light sources emit spectral bands in a way that two adjacent spectral bands are separated by not significantly more than the spectral resolution of the laser.

  - **Discrete** hyperspectral lasers emit spectral bands that are separated by significantly more than the spectral resolution of the light source.

The main specifications of hyperspectral light sources are

- **Output power**: The output power of a hyperspectral source is an important metric when it comes to the signal-to-noise ratio of the sensor system. For absorption spectroscopy based sensors, laser output power may be traded off with sensitivity if the experiment is limited by the intensity noise of the laser [6]. Also, high laser output...
power is sometimes necessary in absorption spectroscopy measurements in combustion to overcome a corruption of the transmitted signal by thermal emission. For multi-beam absorption tomography applications, a high output power of the hyperspectral source is required to allow for high beam counts.

- **Spectral coverage**: The spectral span, spectral breadth, or spectral range accessed by a hyperspectral light source. Broad spectral coverage is necessary to detect multiple species with a single source. Also, broad coverage allows monitoring of broad spectral features (heavy or high-pressure gases, supercritical fluids, liquids, solids, etc.).

- **Resolving power**: The resolving power of a hyperspectral source is the ability to resolve features in the spectrum. It can be defined by \( R = \frac{\Delta \lambda}{\lambda} \), where \( \Delta \lambda \) is the smallest difference in wavelengths that can be distinguished at a wavelength \( \lambda \). The discrimination of multiple species by absorption spectroscopy highly depends on resolving power. In a separate application, optical coherence tomography (OCT), a higher resolving power enables a larger ranging depth: 1 cm\(^{-1}\) resolution enables 3.7 mm-deep images, 20 cm\(^{-1}\) resolution only allows 185 \( \mu \)m-deep images.

- **Repetition rate**: The time it takes to make one measurement of a spectrum. A high measurement speed, and thus a high information rate, provides immunity to low-frequency noise sources, e.g. vibrations, beamsteering, etc. High repetition rates are necessary to monitor transient systems (explosions, shock tubes, pulsed magnetic fields, video-rate OCT, etc.)
1.2 OBJECTIVE

The principle objective of this work is to develop new hyperspectral laser sources for fluorescence and absorption spectroscopy based sensor systems in the near infrared. In addition to meeting the overall demands (such as output power or spectral resolution) the hyperspectral laser designs should be simple, rugged and cost-effective.

To give a better picture of the demands for a specific sensor system, Table 1.1 displays some typical target specifications for a hyperspectral laser as part of a sensor system for gas thermometry in combustion applications with water vapor as the target species.

<table>
<thead>
<tr>
<th></th>
<th>Target value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power</td>
<td>&gt; 10 mW</td>
<td>× m for m-beam tomography</td>
</tr>
<tr>
<td>Spectral coverage</td>
<td>1330 – 1380 nm</td>
<td>R-Branch of H₂O</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>~ 1 GHz</td>
<td>for atmospheric-pressure measurements: &lt;150 MHz; for high-pressure (e.g., internal combustion engine) measurements: &lt; 2 GHz</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>~ 30 kHz</td>
<td>to monitor dynamic events and to minimize issues arising from harsh environments, mainly beam steering [7,8]</td>
</tr>
</tbody>
</table>

Table 1.1 Typical target specifications for a hyperspectral light source

Given all the above definitions, hyperspectral sources can now be organized into 4 different categories [see Table 1.2].

<table>
<thead>
<tr>
<th></th>
<th>Continuous spectral coverage</th>
<th>Discrete spectral coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDM</td>
<td>Chapter 2: CW c-FTS</td>
<td>Chapter 3: dispersion mode locking</td>
</tr>
<tr>
<td>TDM</td>
<td>Chapter 5: FDML</td>
<td>Chapter 4: N-wavelength</td>
</tr>
</tbody>
</table>

Table 1.2 Topology matrix of hyperspectral laser sources
To evaluate trade-offs between the different designs, hyperspectral light sources in all 4 fields of the topology matrix in Table 1.2 should be investigated.

1.3 THESIS OVERVIEW

The progression of this thesis is as follows:

Chapters 2-5 will introduce novel hyperspectral light sources optimized for spectroscopic measurements in the near infrared.

Chapter 2 presents a continuous-wave comb Fourier transform spectroscopy source (CW c-FTS) that offers a unique continuous interferogram and an automatic modulation of all spectral bands. The CW c-FTS source is the only hyperspectral laser presented in this thesis that uses free-space optical components; all other sources are entirely fiber coupled.

Chapter 3 combines the idea of dispersion mode locking with the technology of fiber Bragg gratings. This mode locking technique offers an intrinsic benefit that each wavelength is intensity modulated at a unique frequency, thus producing a frequency-division multiplexed output.

Chapter 4 presents two discrete TDM laser designs. The first one is based on a matched stretcher / compressor and has the potential to reach a high wavelengths count (10s – 100s) with only a single gain medium. The second TDM laser utilizes a cascaded spectral filtering approach to reach narrow spectral linewidths that are needed for atmospheric measurements.

Fourier domain mode locking (FDML) was recently developed by Huber et al. [9] as a new technique for a continuous TDM hyperspectral laser and has been very successfully adopted in our lab for thermometry measurements in combustion applications [10-12]. Chapter 5
introduces two advanced Fourier domain mode locked (FDML) lasers. An ultrastable FDML laser is presented that offers ultra low intensity noise and a significantly narrowed spectral linewidth compared to typical FDML performance. Also, a piecewise continuous FDML laser is shown that combines the advantages of discrete and continuous hyperspectral sources.

Finally, Chapter 6 will conclude this thesis with a summary of all hyperspectral sources presented in this thesis and recommendations for future work.
CHAPTER 2. CONTINUOUS-WAVE COMB FOURIER TRANSFORM SPECTROSCOPY

This chapter presents a new hyperspectral laser based on continuous-wave comb Fourier transform spectroscopy (CW c-FTS), where the beat signal of an unequally spaced frequency comb is used to generate a replica of the native optical spectrum in the radio-frequency range. Compared to conventional FTS this technique does not involve moving parts, offers high repetition rates and an enhanced signal-to-noise ratio (SNR) due to high spectral radiance sources [13-15].

2.1 INTRODUCTION

A new approach to high-throughput high-speed FTS was pursued by Van der Weide et al. [16-18] and later on adapted among others by Coddington et al. [19]. It is based on heterodyne frequency-comb spectroscopy and employs two frequency combs with slightly different mode spacing. This approach, termed frequency-comb Fourier-transform spectroscopy (c-FTS), relies on expensive femtosecond mode-locked lasers but enables high-throughput FTS with demonstrated repetition rates of ~ 1 kHz. However, mode locked c-FTS still relies on moving cavity mirrors to obtain interferograms at sufficiently high duty cycles.

Two different approaches to c-FTS were investigated that both employed relatively cheap CW light sources:

- A variant to mode-locked c-FTS that employed two inexpensive and technically simple all-fiber continuous-wave (CW) frequency comb generators [20]. The feasibility of CW c-FTS was shown but the spectral resolution and the measurement
repetition frequency that were achieved were both not sufficiently high to meet the 
demands of a hyperspectral light source set in Table 1.1. In particular the finesse and 
the stability of the cavity modes have to be improved to enhance the frequency 
resolution of the CW c-FTS signal.

- A CW c-FTS source based on a high-dispersion cavity that is presented in the 
  following sections of this chapter [14].

2.2 METHOD

The salient idea of this CW c-FTS method is to generate one optical frequency comb, in 
which nearby mode pairs beat at unique frequencies. This beating causes a frequency 
downshift of the infrared spectrum from native frequencies in the PHz domain into the radio-
frequency (RF) range, where the beat spectrum resides [for mathematical derivation, see 
Appendix I]. The RF spectrum is a replica of the actual spectrum and can be obtained by a 
fast Fourier transformation (FFT) of the time domain signal.

An unequally spaced frequency comb can be generated by including a highly dispersive 
element in a fiber ring laser. A simplified output comb of a ring cavity consisting of \( m \) 
fringes is outlined in Figure 2.1(a). The resonance frequencies are not equally spaced, as in 
the case of an etalon, but due to the aforementioned dispersion, the spacing of the cavity 
modes changes as a function of wavelength. Therefore, as required for this approach, the 
interference of adjacent fringes exhibits unique beating frequencies \( A_i \) and thus produces a 
first order replica of the original comb in the RF range (see Figure 2.1(b)). Furthermore, high
order replicas emerge from interference of nearby (but not adjacent) fringes, e.g. second order beating frequencies $B_i$.

Figure 2.1 Beating of the frequency comb. (a) Sketch of the output comb consisting of $m$ fringes. The fringes are not equally spaced, because of the high dispersion in the cavity; thus, adjacent fringes interfere at unique frequencies $A_i$. Beating also occurs in higher orders, e.g. the second order beating frequencies $B_i$. (b) First and second order replicas of the optical frequency comb in the radio frequency range.

Using high orders entails a coarser discretization but because of the diverging structure of the output comb of the cavity, the footprint in the Fourier space becomes larger in higher orders. Also, because the full width half max (FWHM) of each mode does not change when the mode is used in higher order, the effective finesse scales approximately with the order number.
An additional advantage of high orders is the possibility of averaging multiple orders. The maximum order number is set when the information in two consecutive orders starts to overlap.

2.3 SINGLE COMB CW C-FTS IMPLEMENTATION

This section presents the setup and experimental results of a single comb CW c-FTS hyperspectral light source.

2.3.1 Setup

The design, which is shown in Figure 2.2(a), relies on a ring cavity that is formed by a semiconductor-based linear optical amplifier (LOA, Finisar/Genoa G111 [21]), a polarization controller (PC, Fiber Control FPC), a self-built grating compressor (GC), and an isolator (ISO, AOC tap-WDM-isolator hybrid) that guarantees unidirectional lasing operation. Due to the grating dispersion, the length of the cavity is wavelength-dependent, since different colors have different path lengths through the GC as can be seen in Figure 2.2(b). The (equivalent free space) length of the cavity varied from 5.10 m at 1530 nm to 5.28 m at 1570 nm.

The efficiency of the gratings used in the grating compressor (1200 g/mm; blaze wavelength: 750 nm) is strongly polarization dependent. The layout of the grating compressor was designed for an operating wavelength range from 1530–1570 nm. In this spectral range, the reflectance efficiency for the S and P polarization plane is ~95% and ~5% respectively. Therefore, the grating compressor that employed four diffraction gratings as shown in Figure 2.2(b) acted as a polarizer with an extinction of ~ $1.3 \cdot 10^5$:1. The polarization controller in
the ring cavity was tuned to optimize the polarization state with respect to the gain of the LOA.

Figure 2.2 Experimental setup. (a) Sketch of the ring cavity that generates an unequally spaced frequency comb. The beating of this comb is then used to measure the absorption spectrum of hydrogen cyanide H\textsuperscript{13}C\textsuperscript{14}N via a fast Fourier transformation of the time domain signals: reference $I_o$ and transmitted $I$ recorded with two photo-receivers and an oscilloscope (OSC). Absorption is also spectrally analyzed with an optical spectrum analyzer (OSA). (b) Layout of the grating compressor following [1].

To show the feasibility of CW c-FTS, transmitted $I$ and reference $I_o$ of hydrogen cyanide H\textsuperscript{13}C\textsuperscript{14}N (Thorlabs, CQ09075-HCN13) were monitored with a data acquisition system consisting of two photo-receivers (New Focus 1592; 3.5 GHz bandwidth and New Focus 1544; 12 GHz bandwidth) and a real-time sampling oscilloscope (Tektronix TDS7404; 4
GHz bandwidth, 10 GSamples / s on each of 2 channels). The captured time traces were then Fourier transformed. $I$ and $I_0$ were also recorded with an optical spectrum analyzer (OSA; Agilent 86142B, ~ 8 GHz spectral resolution).

A picture of the experimental setup of the ring cavity with the grating compressor is shown in Figure 2.3.

![Figure 2.3 Picture of experimental setup. (1) Linear optical amplifier and driver board; (2) Polarization controller; (3) Grating compressor; (4) Optical isolator; (5) 50:50 output splitter; (6) H$_{13}$C$_{14}$N gas cell]
2.3.2 Results

The first 100 ns of the recorded 1 ms time trace of the transmitted \(I\) and reference \(I_o\) signals are shown in Figure 2.4. Note that compared to a more traditional FTS interferogram, there is no center burst in CW c-FTS.

![Figure 2.4 Transmitted signal \(I\) and reference signal \(I_o\) in the time domain.](image)

The spectral results of this experiment are shown in Figure 2.5. Lasing operation was achieved over about 0.4 THz as it can be seen in transmitted \(I\) and reference \(I_o\) spectra monitored with the OSA (750 ms measurement time) in Figure 2.5(a).

The injection current of the LOA was 200 mA, the insertion loss of the grating compressor 7 dB and the total output power of the cavity ~ 3 mW. The Fourier transformation of the CW c-FTS time signals (1ms measurement time) showed a first order replica of the optical frequency comb at 57.5–58.1 MHz, which results in an average FSR of the optical frequency comb of 57.8 MHz. This number in combination with the 0.4 THz spectral coverage gives an estimate of ~ 6920 total fringes composing the optical frequency comb. The beating of each fringe of the optical frequency comb with itself was observed at DC–500 kHz with a FWHM...
of 380 kHz. This gives a measure for the linewidth of individual cavity modes. From this observation, the effective finesse of the ring cavity can be estimated to be 152 under lasing conditions.

Figure 2.5 Transmitted $I$, reference $I_o$, and transmittance spectra of hydrogen cyanide. (a) $I$ and $I_o$ recorded with an optical spectrum analyzer in 750 ms. (b) $I$ and $I_o$ of 97th order via Fourier transformations of CW c–FTS signals measured with photo-detectors in 1 ms. (c) Comparison of OSA and CW c–FTS transmittance spectra $I/I_o$.

The replica of the native $I$ and $I_o$ presented in Figure 2.5(b) is the 97th order at 5.582–5.597 GHz but was aliased back to 4.403–4.418 GHz because of the 5 GHz Nyquist frequency of the oscilloscope. The replica was mirrored to compensate for the folding about the Nyquist
frequency and a moving average filter was applied to smooth out the comb structure. Simulations showed that for the presented 97th order, the mode spacing at both extremes of the replica is 2.325 kHz at 5.582 GHz and 2.327 kHz at 5.597 GHz, thus the spectral distribution is almost perfectly uniform in frequency. The footprint in the Fourier domain of the 97th order was significantly enhanced compared to the first order, which shows an improved effective finesse for high order replicas. Compared to the SNR of the time domain signals of $I$ and $I_o$ (18.75 dB), the SNR of this order was improved by a factor of 4.2 to 25 dB because the inherent noise in the data acquisition system was lower at high frequencies. The SNR was obtained by comparing the average signal power of the 97th order to the noise floor in the FFT. The comparison of OSA and CW c-FTS transmittance spectra ($I/I_o$) in Figure 2.5(c) shows absorption dips in both spectra that have about the same width.

2.4 ENHANCING THE SPECTRAL COVERAGE OF A FREQUENCY COMB

The span of the CW frequency comb presented in the previous section was relatively narrow (~ 3.2 nm). Broader coverage is often desired in sensing applications. For example, in optical coherence tomography (OCT), ~ 100 nm coverage gives ~ 9 um axial resolution in biological tissue [9], and in absorption thermometry, ~ 50 nm coverage allows absolute accuracies better than 2% in combustion environments [11]. The spectral coverage can be broadened by controlling the spectral attenuation in the ring cavity with a programmable spectral filter. An enhanced CW frequency comb span allows CW c-FTS lasers to be applicable to more sensing situations.
2.4.1 Method

Strong optical feedback in the ring cavity decreases the carrier density in the amplifier, which results in a red shift of the material gain spectrum [22]. Likewise, as the signal in the ring cavity is attenuated, the carrier density increases causing a blue shift of the spectrum. Qureshi et al. have reported a tuning range of 22 nm (1548-1570 nm) by attenuating the optical feedback in the cavity with a variable optical attenuator (VOA) [23].

Instead of a VOA that provides a variable but spectrally fixed loss profile, the method presented in this work uses a programmable optical spectral profiler (OSP-9500, Newport Cooperation). The OSP can apply a wide variety of dynamically configurable spectral profiles over a 100 nm range. Including an OSP in a ring cavity allows for a closed loop gain-flattening approach that enhances the spectral coverage of the laser output.

2.4.2 Setup

The experimental setup is shown in Figure 2.6. The cavity was composed of a semiconductor optical amplifier (LOA, Finisar/Genoa G111), a polarization controller (PC), an optical isolator (ISO), an output coupler and an optical spectral profiler (OSP-9500, Newport Cooperation). The spectral operating range of the OSP was 1520–1620 nm with an instrument resolution of 0.42 nm. To close a control loop, the spectrum of the ring laser was measured with an optical spectrum analyzer (OSA; Agilent 86142B, 0.06 nm spectral resolution) and uploaded to a computer that executed the control law and updated the OSP.
Because of the high non-linearity and sensitivity of the system, an adaptive, low gain integral control law was implemented. This type of controller has attracted considerable interest for such sensitive but stable systems over the last twenty years [24].

2.4.3 Results

The recorded data for 127 closed loop iterations is presented in Figure 2.7. The top graph shows the spectral coverage of the CW frequency comb for different iterations. The comb span was enhanced from originally 18 nm to 61 nm [also see inlet in Figure 2.7(a)]. The spectrum was broadened asymmetrically. The enhancement was bigger in the direction to shorter wavelengths due to the blue shift of the material gain spectrum. The blue shift was caused by the lower optical feedback to the LOA, which increased the carrier density in the amplifier. The broadened spectra were stable but showed a relatively high ripple compared to
the original spectrum, which was caused by the limited spectral resolution of the OSP (0.42 nm) and probably by non-negligible inter-channel cross talk in the LOA, as indicated in [25].

Figure 2.7 Experimental results. Initial data with zero filter attenuation and final data after 127 iterations in black; data of intermediate steps in gray. (a) Spectra measured with the OSA. Original and final spectrum overlaid in inlet. (b) Filter attenuation levels.

The OSP attenuation profiles resulting from executing the control law are displayed in Figure 2.7(b). A relatively small ripple can be seen on the filter profiles, which turned out to be essential for lasing operation of the ring cavity. After applying a filter profile in which the ripple was filtered out, the ring cavity stopped lasing entirely.
2.5 CONCLUSIONS

In conclusion, the feasibility of CW c-FTS was demonstrated by measuring absorbance of hydrogen cyanide. Compared to the spectrum recorded with an OSA, the CW c-FTS measurement speed was significantly faster (OSA: 750 ms; CW c-FTS: 1 ms) with a similar spectral resolution. Transmittance spectra were also recorded with CW c-FTS in 10 µs but the quality was poor due to a reduced frequency resolution in the FFT. It was also shown that in principle, the spectral coverage of a CW comb can be substantially broadened through closed loop gain flattening.
CHAPTER 3. DISPERSION MODE LOCKED FREQUENCY-DIVISION MULTIPLEXING

Two dispersion mode locked laser experiments, each using a single, actively modulated linear optical amplifier and one or more fiber Bragg gratings, are presented in this chapter. The first experiment demonstrates multiwavelength lasing based on dispersion mode locking. This mode locking technique offers an intrinsic benefit that each wavelength is intensity modulated at a unique frequency, thus producing a frequency-division multiplexed output. The second experiment shows fine-tuning of the dispersion mode locked lasing wavelength. Tunability from ~ 1546.5–1547 nm with a linewidth of ~ 0.06 nm was achieved. A combination of the two experiments produces an excellent multiwavelength light source for sensing applications: for example, each of multiple wavelengths can be tuned and locked to a gas absorption feature. The transmission at each wavelength can then be monitored using a single photoreceiver and a multi-channel lock-in amplifier [26,27].

3.1 INTRODUCTION

Frequency-division multiplexing (FDM) can offer advantages over other spectroscopic techniques in terms of signal-to-noise ratio [28-30]. The dispersion mode locked FDM design shown in this section is an all-fiber light source with a simple and rugged cavity arrangement that includes no moving parts. Multiple output wavelengths can easily be tuned and locked to fixed values. In spectroscopic sensing applications, this gives the opportunity to align each channel to a specific absorption feature, which, in combination with the benefits of FDM, gives this novel FDM approach a significant practical potential. Although many applications
such as spectroscopic sensing require only steady operation (fixed wavelengths), the design can include fast arbitrary wavelength switching or sweeping if needed.

3.2 METHOD

Because it is very difficult to achieve multiwavelength lasing operation based on Erbium-doped fiber amplifiers, various realizations using the inhomogeneous gain medium of semiconductor optical amplifiers have recently been demonstrated [31-33]. For the multiwavelength laser experiments presented in this work, a linear optical amplifier (LOA) was employed in the cavity. The LOA is a semiconductor optical amplifier that offers an additional integrated vertical-cavity surface emitting laser (VCSEL) to provide a constant local gain. Therefore, the stability of the multiwavelength light source is improved by reducing crosstalk in the amplifier.

Dispersion mode locking relies on a high-dispersive cavity. The intensity of each selected wavelength is modulated at the fundamental or at a higher harmonic of its cavity frequency. Due to the high dispersion in the cavity, the modulation frequency for each selected wavelength is unique. In this way, each output wavelength of the dispersion mode locked laser is automatically tagged to a modulation frequency. Thus, the amplitude of each wavelength component can be simply retrieved by lock-in amplifying the recorded time domain signal at each modulation frequency. For retrieving multiwavelength signals, this is a significant advantage over non-dispersion mode locked sources [34,35] and order-degenerate multiwavelength dispersion-mode locked sources [36] where the mode locking frequency is identical for all channels. Dispersion compensating fiber (DCF) is commonly used to provide the necessary intra-cavity dispersion [36-38]. Instead of a relatively long
DCF, fiber Bragg gratings (FBGs) were used in this work to obtain maximum dispersion in a short length. As a result, fast cavity response times can be accomplished. For multiplexed fiber lasers, FBGs are ideal wavelength-selective components because of their large availability and selection. Various techniques have been proposed to realize tunable multiwavelength sources with FBGs [34,35,39,40]. In most of the proposed designs, tunability is obtained by compressing or stretching the incorporated FBGs for which high precision force actuators are needed. Using dispersion mode locking, wavelength tuning or switching can be achieved by simply varying the modulation frequency.

### 3.3 LASER BASED ON FBG ARRAY

The dispersion mode locked fiber source discussed in this section uses cascaded FBGs to generate a frequency-division multiplexed multiwavelength signal.

#### 3.3.1 Setup

The schematic of the laser is shown in Figure 3.1. The ring cavity consisted of a LOA (Finisar/Genoa G111 [21]), a circulator, two uniform FBGs (center wavelengths: $\lambda_1 = 1533.86$ nm and $\lambda_2 = 1536.53$ nm; spectral FWHMs: 0.41 nm and 0.45 nm), a polarization controller, an output coupler, and an optical isolator (AOC Tap-WDM-Isolator Hybrid). The fiber cavity lengths for $\lambda_1$ and $\lambda_2$ were 29.0 m and 34.6 m, respectively. All fibers in the cavity were standard single-mode fibers. The combination of a DC bias and sinusoidal modulation signals from two function generators (Stanford Research System, DS345; Agilent, 33250) was used to drive the LOA.
Figure 3.1 Schematic of the ring cavity, which was composed of a linear optical amplifier (LOA), two Fiber Bragg gratings (FBG), a polarization controller (PC), an output coupler, and a tap-isolator. The injection current of the LOA was a combined signal of a DC bias and two frequency generators (FG).

To achieve dispersion mode locking, \( f_1 \) was selected to match the 4\(^{th} \) harmonic and \( f_2 \) was selected to match the 5\(^{th} \) harmonic of the corresponding roundtrip frequency (\( f_1 = 28.14 \text{ MHz} \) and \( f_2 = 29.48 \text{ MHz} \)). The optical spectrum was recorded with an optical spectrum analyzer (Agilent, 86142B) and the time domain signal was measured with a photoreceiver and a high resolution digitizer (NI 5122, 100 MS/s, 40 MHz bandwidth).

3.3.2 Results

The optical output spectrum is shown in Figure 3.2(a). The measured spectral full width at half maximum (FWHM) of each channel was \( \sim 0.20 \text{ nm} \), or about twice as narrow as the passive FWHM of the FBGs. The corresponding temporal waveform is shown in Figure 3.2(b); the beat frequency \( \Delta f = f_1 - f_2 = 1.34 \text{ MHz} \) is clearly visible.
To evaluate stability of the multilambda source, a digital lock-in amplifier (time constant: 265 ns) was used to measure the signal strength at the two modulation frequencies $f_1$ and $f_2$; see Figure 3.2(c). The two signals have a slight anticorrelation of -0.23, attributed to cross talk in the LOA. The standard deviation of the two 10-ms-duration lock-in signals were 0.23 mV and 0.18 mV, respectively. To further investigate cross talk, one of the two wavelengths was suppressed with a filter outside the cavity. Although the filter suppressed one wavelength by 26 dB, the corresponding modulation in the time trace was only
suppressed by 13 dB. This result again indicates cross-talk: the unsuppressed wavelength is weakly modulated at the frequency of the suppressed wavelength.

3.4 LASER BASED ON CHIRPED FBG

In this section, a modified version of Figure 3.1 with a linear cavity is investigated. For a spectroscopic sensor, the use of multiple chirped FBGs rather than the uniform FBGs allows for a reliable, independent tunability of each output wavelength by slight changes in amplifier drive frequencies.

3.4.1 Setup

An initial experiment based on a single chirped FBG within a linear cavity is shown in Figure 3.3.

![Figure 3.3 Experimental setup involving a chirped FBG in a linear cavity. Dispersion mode locking in combination with the chirped FBG allows for adjusting the output wavelength by changing the frequency of the LOA injection current with the frequency generator (FG).](image)

The chirped FBG had a center wavelength of 1546.66 nm, a bandwidth of 0.71 nm, and a dispersion of 1000 ps/nm. The LOA was driven by a synthesized sweeper (Hewlett Packard, HP83620A). The injection current to the LOA was again a combination of a DC bias and a sinusoidal modulation current.
3.4.2 Results

The laser was mode locked at the 27th harmonic of the roundtrip frequency. Optical output spectra for various mode locking frequencies are presented in Figure 3.4(a). The fiber length of the cavity varied from 9.40 m at $f = 293.18$ MHz to 9.43 m at $f = 292.21$ MHz.

![Figure 3.4 Experimental results.](image)

Tunability was achieved from ~ 1546.5–1547 nm, which is almost the full bandwidth of the chirped FBG. The linewidth of the laser output observed with the OSA varied from ~ 0.07–0.11 nm. Correcting for instrumental broadening of the OSA, we estimate an actual linewidth of ~ 0.04–0.09 nm or less. The output pulse waveform for an injection current frequency of $f = 292.21$ MHz is shown in Figure 3.4(b) recorded with the OSC (Tektronix, TDS7404).
3.5 CONCLUSIONS

Two experiments for dispersion mode locked multiwavelength sources based on FBGs have been demonstrated. The first unidirectional ring laser was based on a FBG array and generated a frequency-division multiplexed, quasi continuous-waveform multiwavelength output. In the second linear cavity design, tunability over almost the full bandwidth of a chirped FBG was achieved. The possibility to align each wavelength to an absorption feature in combination with the tagging of each wavelength to a unique modulation frequency makes the proposed dispersion mode locked laser an excellent source for spectroscopic sensing applications. For example, such a tunable FDM laser may be attractive for biomedical breath sensing of the isotropic ratio $^{13}\text{CO}_2/^{12}\text{CO}_2$. This key breath disease biomarker [41] could be monitored with a dispersion mode locked three-wavelength laser with one wavelength aligned to a $^{12}\text{CO}_2$ absorption maximum, another aligned to a $^{13}\text{CO}_2$ absorption maximum, and a third reference wavelength aligned to a minimum in the composite absorption spectrum of $^{13}\text{CO}_2$ and $^{12}\text{CO}_2$. 
CHAPTER 4. DISCRETE TIME-DIVISION MULTIPLEXING

This chapter introduces two multiwavelength, time-division multiplexed laser designs that continuously cycle through \( N \) spectrally narrow wavelengths, spending a specified, fixed time on each one. The first design is based on a single gain medium and a matched stretcher / compressor whereas the second design multiplexes single wavelength ring lasers, each featuring a very narrow spectral linewidth (< 80 MHz) due to cascaded spectral filtering.

4.1 TDM LASER BASED ON MATCHED COMPRESSOR / STRETCHER

This design is based on a matched compressor/stretcher and a custom waveform generator applying modulation preferably to the gain medium. The realization discussed here utilizes a pulsed semiconductor optical amplifier in an all-fiber cavity containing fiber Bragg gratings. The source contains no moving parts, offers high repetition rates, narrow spectral linewidths and custom spectral profiling of the output [42].

4.1.1 Introduction

A typical requirement in spectroscopic applications is a laser that continuously cycles through \( N \) stable, spectrally narrow wavelengths at high rates, and allows for the tuning of each wavelength to a spectroscopic feature. Recently, our research group applied a 19-wavelength TDM laser for engine gas absorption thermometry [43]; the initial results were promising, but did not match the \(~ 5 \) K precision achieved at 100 kHz using relatively mature swept-wavelength approaches [11,12]. Simulations show that discrete-wavelength TDM versions should have a better temperature precision because more measurement time is spent
on the key portions of the spectrum. The novel multiwavelength TDM laser design presented in this section may revolutionize multiwavelength sensing by providing high speeds and high wavelength counts at affordable prices. It offers a simple and rugged cavity that contains no moving parts.

4.1.2 Method

The laser design is the time-domain version of a recent multiwavelength laser [26] based on dispersion mode locking [37]. Like the Fourier domain mode locking design [9], this laser is based on storage of information and energy within the laser cavity and is suitable only for high-speed sensing. The design is based primarily on three components: A gain medium, a custom waveform generator applying modulation, and a matched stretcher / compressor (MSC). Although there are various techniques to form a MSC, such as dispersion management in optical fibers or traditional grating based pulse compressors / stretchers, the use of fiber Bragg gratings (FBGs) is very convenient in this application because of their fiber integration, wide availability, and discrete narrowband nature. The MSC is formed by a FBG array receiving light from different directions. TDM sources based on FBGs have found widespread application in structural sensing systems to measure stress or temperature by interrogating the gratings [44-46] and also in TDM sources for acoustical sensing applications [47].

The main difference between sources that use intra-cavity FBG arrays as stretchers only and the proposed MSC design is that the latter provides the same cavity length for each resonating wavelength but introduces a fixed time shift in the arrival of each wavelength at the output coupler. This time shift enables multiwavelength TDM lasing operation with an
intra-cavity FBG array. Advantages of an intra-cavity FBG array over a system that uses merely the reflection of a FBG array outside the cavity as the output signal [43,48] are substantially increased output power and narrower spectral linewidths due to gain narrowing inside the cavity. Also, the proposed design features a custom gain for each wavelength through which arbitrary output amplitudes can be obtained. For every-other amplification step, there is no amplifier cross talk, promoting stable, low-noise operation and thereby giving this novel multiwavelength TDM design significant practical potential in various optical sensing fields.

4.1.3 19-wavelength implementation

This laser cycles through 19 wavelengths in a 44-nm-wide spectral band (1333–1377 nm) every 15 µs [49]. The design shown in Figure 4.1 is composed of a semiconductor-based booster optical amplifier (Covega, BOA1036, ~ 1 ns minimum switching time), two polarization controllers (PC), an array of 19 fiber Bragg gratings (O/E Land, 0.1 nm reflection FWHM, spliceless) and an output coupler.

The ring-like linear cavity is produced by the FBG array at one end of the cavity that forms a discrete-wavelength stretcher, and the same FBG array at the other end of the cavity that exactly compensates the stretcher. Because the same FBG array is used at each end, the stretch-compress complements in the laser cavity are perfectly matched if dispersion in the fiber is ignored. Thus, the cavity length for all resonating wavelengths is the same, but in half of their cavity round-trip, they are shifted in phase. The BOA is controlled by an arbitrary waveform generator (AWG, Agilent 33250A) to amplify only the desired resonating
wavelengths and to suppress other optical signals (such as the simple ring mode) traveling through the cavity.

![Schematic of the N = 19 color TDM laser. The TDM output is monitored with an oscilloscope (OSC) and an optical spectrum analyzer (OSA).](image)

Each period of the BOA injection current pulse pattern is considered to start with a short pulse. For the first period, this pulse initializes the lasing operation of the source by sending out broadband amplified spontaneous emission (ASE) in both directions into the cavity. The x-t diagram shown in Figure 4.2 represents the travel of optical information in a cavity with 3 FBGs. The fiber lengths in the cavity are chosen so that when the ASE pulse that travels counter-clock-wise inside the cavity (right-to-left in the x-t diagram) and ultimately meets the FBG array, each wavelength selected by a FBG is returned to the BOA consecutively. Each wavelength of this chromatically stretched pulse can then be individually amplified in the BOA. This amplification step is not affected by cross talk (gain competition) because there is only one color present at a time. For all other times, the BOA is turned off so that only the colors selected by the FBGs are lasing, whereas ASE and other reflections from the FBGs are suppressed by the inactive BOA (which exhibits -7 dB gain at zero current). The stretched
pulse (burst of $N$ sequential wavelengths) then travels in the clock-wise direction inside the cavity and is transformed into a single compressed, multispectral pulse when each color is reflected by its corresponding FBG. The compressed pulse passes the BOA during the short on-phase of the BOA marking the beginning of each period. This amplification step involves an observable but tolerable level of gain competition. The TDM stretched pulse can be monitored with $out_1$ and the multispectral compressed pulse with $out_2$.

![Figure 4.2 Simplified optical x-t diagram and BOA injection current pattern for a 3-color TDM sensor.](image)

To ensure lasing operation at the desired wavelengths only, the duty cycle is limited to 25% and the initial pulse width $t_{PW}$ and the fiber lengths of the cavity are chosen as follows

$$t_{PW} = \frac{1}{4 f_{rep}} N \quad (4.1)$$

$$L_1 = \frac{1}{2} N v_g t_{PW} \quad (4.2)$$
\[ L_2 = \frac{1}{2} v_g t_{PW} \]  
\[ L_3 = \frac{1}{2} (2N + 1) v_g t_{PW} \]

where \( N \) is the number of wavelengths, \( v_g \) is the group velocity of light in fiber, and \( f_{\text{rep}} \) is the repetition frequency. In the experimental setup, the fiber lengths \( L_1, L_2 \) and \( L_3 \) were 383 m, 20 m and 786 m, respectively.

Two output spectra of the 19-wavelength light source are presented in Figure 4.3. In Figure 4.3 a), the gain of each wavelength was calibrated to obtain a flat output spectrum by appropriately adjusting the 19-levels in the BOA pulse pattern for the clockwise amplification phase. The maximum power deviation between the 19 wavelengths was 0.4 dB and the signal-to-ASE-floor was ~ 33 dB. The spectral full width at half maximum (FWHM) of each channel was narrower than the spectral resolution of our OSA (Agilent 86142B, ~ 8 GHz spectral resolution).

To measure the spectral linewidth and the gain narrowing factor of the cavity, we temperature-tuned one FBG over a 50-Torr H2O vapor absorption feature. The spectral linewidth was measured to be ~ 0.02 nm, from which we infer a gain narrowing factor of ~ 5. This spectral linewidth is sufficient for many atmospheric- and high-pressure gas spectroscopy applications, but even narrower spectral linewidths are often required and can be achieved using FBGs or other spectral filters with a narrower FWHM. In Figure 4.3 b) the BOA injection current pulse pattern was customized to form a ramped output spectrum.
A time trace of the 19-wavelength stretched pulse is shown in Figure 4.3 c). The cavity length was ~ 3080 m, which corresponds to a repetition rate of ~ 66.5 kHz. The temporal width of each of the 19 pulses was ~ 200 ns and the source cycled through all 19 wavelengths every 15 µs. The output power of the pulse train was ~ 10 mW, which offers ample power for most sensing applications. The noise on the pulse high levels is attributed to optical beating noise [50,51] associated with the multiple (~10^5) cavity modes that exist within the spectral FWHM of each of the 19 output pulses.
To prove that the 19 pulses carry only the information of the wavelength selected by the corresponding FBG, absorbance measurements of liquid phase methanol and isopropanol were performed. To cope with the optical beating noise, a split-pulse referencing detection strategy [12,52] was applied [see Figure 4.4]. The output of the TDM source was split into two parts with a 50:50 beam splitter and only one signal (I) was directed through the sample whereas the other signal (I\textsubscript{0}) was delayed in fiber spool. Both signals were then again combined with a beam splitter cube and detected with the same photoreceiver (Thorlabs PDA10CF) on the same oscilloscope channel (Tektronix TDS7404; 4 GHz bandwidth, 20 GSample/s; 8-bit resolution).

![Figure 4.4 Schematic of the split-pulse referencing strategy.](image)

This approach is directly useful for spectroscopic measurements because irregularities in the detection and data acquisition system that would cause a residual of the optical beating noise on the ratio of I and I\textsubscript{0} are eliminated.

The single-shot results in Figure 4.5 show very good agreement with reference measurements [53].
The standard deviation of 100 consecutive absorbance measurements was only 0.0013 and could be further improved using a higher bit-resolution oscilloscope.

### 4.1.4 10-wavelength H$_2$O and 4-wavelength CH$_4$ implementation

In this section, two discrete TDM sources are presented that were designed to allow for a combined H$_2$O and CH$_4$ sensor. Both lasers were tested in a high-pressure gas turbine combustor test article operating at the Wright-Patterson Air Force base in Dayton, OH.

The first laser was specifically designed for thermometry based on H$_2$O absorption spectroscopy by carefully choosing the Bragg wavelengths of the 10 FBGs to optimize temperature sensitivity [see Figure 4.6].
The passive spectral bandwidth of the FBGs varied from 0.13–0.17 nm. Correcting for instrumental broadening of the OSA, we estimate an actual linewidth during lasing operation of ~ 0.03–0.04 nm or less, which results in a gain narrowing factor of ~ 4. The FBGs were temperature controlled to align and lock the reflection wavelengths to H$_2$O absorption features.

The second discrete TDM source was engineered to measure the mole fraction and temperature of CH$_4$. This time, four wavelengths were chosen in the 1662.9–1666.7 nm region to monitor CH$_4$ absorption features. A simulated CH$_4$ spectrum at a temperature of 600 K, a pressure of 10 bar and a mole fraction of 0.1 can be seen in Figure 4.7.
Figure 4.7 Simulated CH\textsubscript{4} spectrum at 600 K, 10 bar and 0.1 mole fraction. The TDM wavelength selection is shown in red.

The repetition rate of both lasers was kept the same at 28.5 kHz, or one measurement every 35 µs, to allow for the opportunity to multiplex both signals and thus achieve a combined H\textsubscript{2}O and CH\textsubscript{4} sensor.

A schematic diagram of the test is shown in Figure 4.8. The 4-wavelength discrete TDM laser was used to monitor the temperature and mole fraction of CH\textsubscript{4} at an ‘upstream’ station, and the 10-wavelength discrete TDM laser operating in the 1328–1374 nm range was used to monitor the temperature and mole fraction of H\textsubscript{2}O at a ‘downstream’ station.

As in the 19-wavelength TDM experimental setup, a pulse delay referencing detection strategy [12,52] was applied to cope with optical beating noise [50,51]. Both the reference signal (\(I_0\)) and the signal that was directed through the test section were detected with the same photoreceiver (Thorlabs PDA10CF) on the same oscilloscope channel (National Instruments, PCI-5122).
Figure 4.8 Schematic of test article showing location of fuel and water vapor measurements performed by the discrete TDM source.

Single-cycle traces of the reference ($I_0$) and the transmission ($I$) signals can be seen in Figure 4.9.

![Figure 4.9 Sample single-cycle time traces of the reference ($I_0$) and transmission signal ($I$) of the 10-color H$_2$O TDM laser.](image-url)
In the plot, the two traces are overlaid to show the relative absorbance of each wavelength bin. The ratio \( \frac{I}{I_0} \) was averaged during each wavelength bin leading to the final value of relative absorbance for that particular wavelength. Repeating this process for \( N \) continuous cycles of the TDM laser, results in a time trace of relative absorbance at each wavelength.

In order to determine gas properties, the absolute absorbance is needed, which can be obtained by applying a baseline correction to the relative absorbance. In the case of the CH\(_4\) TDM sensor, this baselining was straightforward because some data was acquired before the main fuel valve was triggered to open, thus giving a period of time where no CH\(_4\) was present in the optical path. During this null time, the average value of the absorbance of each color is calculated and then subtracted from the entire time history giving rise to absolute absorption values which can then be compared with simulations based on the HITRAN2004 database [54] to infer the CH\(_4\) gas properties. The resulting time traces of CH\(_4\) temperature and mole fraction are shown in Figure 4.10.

![Figure 4.10 Results from CH\(_4\) discrete TDM sensor showing the possibility of simultaneously measuring temperature and CH\(_4\) mole fraction.](image)

Figure 4.10 Results from CH\(_4\) discrete TDM sensor showing the possibility of simultaneously measuring temperature and CH\(_4\) mole fraction.
Temperature was not a direct design objective for this particular sensor but reasonable estimates were also able to be inferred from the data and corroborated by means of a thermocouple in the fuel stream.

Throughout the entire time history of acquired optical data in the TDM H$_2$O measurement, H$_2$O was present in the optical path. Thus the baselining correction that was applied relied on data provided by a fast response thermocouple located near the H$_2$O TDM optical path. Least square fits of the corrected measured spectra to simulated spectra were carried out resulting in a time history array of inferred H$_2$O temperatures and mole fractions. The final results are shown in Figure 4.11 with the TDM H$_2$O temperature plotted in the top panel and the optical H$_2$O mole fraction shown in the bottom panel.

Figure 4.11 Results from H$_2$O discrete TDM sensor.
4.1.5 Conclusions

In the presented discrete TDM design, it is straightforward to reach a high wavelength count ($N$: 100s to 1000 if losses are carefully managed) with only a single gain medium and no need for external couplers / multiplexers while still maintaining the possibility to tune and stabilize each wavelength individually by controlling the temperature of the corresponding FBG. Thus, for high speed, multi-spectral sensing applications, the novel multiwavelength TDM laser presented in this section opens up an attractive alternative to conventional tunable diode laser approaches [3,5]. Relative to swept-wavelength approaches [11,12] the TDM source generally offers a reduced data acquisition burden, and therefore is especially attractive in applications such as multi-beam absorption tomography.

4.2 TDM LASER BASED ON CASCADED SPECTRAL FILTERING

In this section, a discrete TDM laser design is introduced that multiplexes single wavelength ring cavities. Spectral linewidths of less than 80 MHz were achieved.

4.2.1 Introduction

In the discrete TDM design presented in the first part of this chapter, spectral linewidths < 1 GHz could not be realized because the reflection full width at half maximum (FWHM) of available fiber Bragg gratings was not narrow enough. The narrowest spectral linewidth achieved under lasing conditions was ~ 5 GHz, which is too broad to resolve H$_2$O features at atmospheric pressure. To improve the spectral linewidth of the light source, narrow-band filters other than FBGs were considered.
Fiber Fabry-Perot interferometers (FFP-I) are a very attractive choice for narrow-band filters as they can achieve very spectrally narrow transmission bands. The FFP-I consists of a lensless plane Fabry-Perot interferometer with a single-mode optical fiber waveguide between two highly reflective mirrors. The FFP-I are manufactured with fiber pigtails so no alignment or mode-matching is required. The ratio of the free spectral range (FSR) and the spectral full-width-at-half-maximum (FWHM) of the FFP-I is defined as the finesse $F$ of the filter [55].

\[
F = \frac{FSR}{FWHM}
\]  

The finesse $F$ is also directly linked to the reflectivity $R$ of the FFP-I mirrors

\[
F = \pi \frac{\sqrt{R}}{1-R}
\]  

With a higher finesse, the reflectivity of the mirrors increases, which causes a higher intensity field in the FFP-I cavity. To prevent the mirrors from damage, the finesse and input power to the FFP-I have to be limited. With (4.5) and assuming a fixed finesse, the narrower the spectral bandwidth of the filter, the closer the transmission peaks. The resulting narrowly spaced transmission comb of the FFP-I in combination with the broad-band gain spectrum of a semiconductor optical amplifier causes a problem if single wavelength lasing operation is desired. One solution to this problem is to apply a cascaded spectral filtering approach combining the spectral filtering characteristics of FBGs and narrow-band filters, such as fiber Fabry-Perot interferometers (see Figure 4.12).
One possible hyperspectral laser design that applies the cascaded filtering idea to achieve spectral linewidths < 1 GHz is shown in Figure 4.13. This design was termed “add-drop TDM” because it incorporates the add-drop technique used in wavelength-division multiplexed (WDM) optical fiber communication systems.
Although some advantages of the original discrete TDM approach are conserved (e.g. only one gain medium for all wavelengths) the straightforwardness in reaching high wavelengths counts is no longer given due to higher losses in the cavity. For example, the total roundtrip loss for a 5-wavelength add-drop TDM laser with a 10% output coupling ratio is ~ 18 dB. Because of the high roundtrip losses of the add-drop TDM laser, a design was implemented that multiplexes single-wavelength ring cavities but still relies on cascaded spectral filtering.

4.2.2 Design

The schematic of the narrow spectral linewidth TDM light source is shown in Figure 4.14. One of the single-wavelength ring cavities is composed of a semiconductor optical amplifier, a three port circulator, a fiber Bragg grating, a polarization controller, two optical isolators, a fiber Fabry-Perot interferometer and an output coupler.
The SOAs are modulated by a pulse generator so that the output signals of all ring cavities can be multiplexed into a multiwavelength TDM signal.

**4.2.3 10-wavelength H$_2$O implementation**

A 10-wavelength discrete TDM laser according to the schematic shown in Figure 4.14 was built for H$_2$O thermometry. The wavelength selection was the same as for the 10-wavelength H$_2$O TDM laser that was based on a matched stretcher and compressor (see Figure 4.6). The spectral bandwidth of the 10 fiber Bragg gratings (O/E Land) varied from 0.07–0.10 nm. The FSR of the fiber Fabry-Perot interferometers (Micron Optics) was ~ 44 GHz and the Finesse was ~ 550. Both the FBGs and the FFP-Is had to be temperature controlled to tune and lock to the desired lasing wavelengths. First, the temperature of each FBG controlled such that the Bragg wavelength of the grating matched the target wavelength. Then, the corresponding FFP-I was tuned (Thorlabs, PRO8000 with TED8020 modules) such that one fringe of the transmission comb was in the center of the spectrally broader FBG line. For fine-tuning the FFP-Is and hence the lasing wavelengths, the ring cavities were operated one at a time in a CW condition and the output was monitored with a high resolution wavemeter (Bristol, 621A-IR, 44 MHz absolute accuracy). With this cascaded filtering approach, a linewidth of ~ 80 MHz was realized.

The pulsed injection current to the SOAs was supplied by an amplifier circuit, which was gated by three synchronized pulse generators (Berkeley Nucleonics Corporation, BNC555). The 10 single-wavelength cavity outputs were multiplexed with a 16x16 coupler (AC Photonics) giving this sensor system 16 practically identical outputs. Having multiple outputs
makes this sensor system and excellent light source for multi-beam tomographic imaging applications. Pictures of the narrow-linewidth discrete TDM source are shown in Figure 4.15.

![Figure 4.15 Pictures of the 10-wavelength TDM sensor. Sensor system shown in a 19” rack (left). Temperature control setup of the 10 FBGs (right): Intermediate installation step (top) and completed unit in the rack (bottom).](image)

### 4.2.4 Experimental results

It was originally hoped that because of the spectrally narrow FFP-Is (80 MHz bandwidth) in combination with a rather short cavity length (17 m fiber length, ~ 12 MHz cavity mode spacing) the laser output might be single mode. Although single mode lasing operation was achieved, it couldn’t be stabilized over a long period of time. Four different laser output cases are presented in Figure 4.15. For ~ 5% of the pulses, the output was single mode as
shown in the first plot. However, most of the time, the pulses were either transitional (second and third plot) or multimode (fourth plot).

Figure 4.16 Measured time traces of a pulsed single-wavelength ring cavity. Only ~ 5 % of the pulses were single mode (first plot), the others were either transitional (second and third plot) or multimode (fourth plot).

One way to cope with optical beating noise in spectroscopic sensing application is to apply the delayed-pulse referencing detection strategy [12,52].

The sensor system was tested in a 2-dimensional tomographic imaging experiment at the Wright-Patterson Air Force base in Dayton, OH. Six beams were used to monitor temperature and H$_2$O mole fraction of a H$_2$-air flame. The Hencken burner was well
stabilized and as a result, beam steering was minimal, which made it possible to couple the six beams back into single mode fiber. Hence, multi mode fiber noise was not present in this measurement. Pictures of the setup are shown in Figure 4.17.

Figure 4.17 Pictures of the 6-beam tomographic imaging setup. Beam arrangement (left) and night-vision picture of Hencken flame (right).

With one FBG damaged, the TDM laser output was cycling through 9 wavelengths every 30 µs. The signals of the reference beam \( I_0 \) and the six beams that were directed through the flame were detected with fast photoreceivers (Thorlabs, PDA-10CF) and sampled with a 12 bit digitizer card (National Instruments, PXI-5105, 60 MS/s, 8 channels). Different detection strategies were carried out and the best noise performance was achieved by reducing the pulse width and low pass filtering the electrical detector signal (Minicircuits, BLP-2.5+, 2.5
GHz bandwidth). A single-shot time trace of reference beam $I_0$ and beam 1 is presented in Figure 4.18.

![Figure 4.18 Single-shot time traces of reference signal $I_0$ and transmitted signal $I$ of beam 1.](image)

Although the evaluation of the recorded time traces is still ongoing, temperature and H$_2$O mole fraction distributions reconstructed from data recorded with a relatively slow scanning laser (100 Hz) that was also implemented in the sensor system showed good agreement with those obtained via independent computations [56].

### 4.2.5 Conclusions

Combining the spectral filtering characteristics of fiber Bragg gratings and fiber Fabry-Perot interferometers allowed the discrete TDM laser design presented in this section to achieve very narrow spectral linewidths. With the 80 MHz that were realized gas properties at atmospheric conditions can be monitored. However, compared to the discrete TDM laser that
was based on a matched stretcher / compressor (~ 5 GHz spectral linewidth), the laser system is more complex and more expensive.
CHAPTER 5. ENHANCED FOURIER DOMAIN MODE LOCKED LASER DESIGNS

The discrete hyperspectral light sources that were introduced in the last two chapters are best suited to dynamic sensing applications where interfering wavelength dependent effects (etalons, interfering absorbers, …) are well known or reliably estimated. However, if these interference effects are unknown or if they change during the experiment, sensor systems that incorporate continuous hyperspectral lasers are preferred.

In this chapter, two advanced Fourier domain mode locked (FDML) lasers are presented. An ultrastable FDML laser is introduced that offers ultra low intensity noise and a significantly narrowed spectral linewidth compared to typical FDML performance. Also, a highly adaptable, piecewise continuous FDML based laser system is shown that combines the advantages of discrete and continuous spectral coverage.

5.1 ULTRASTABLE FDML LASER

A FDML laser sweep was performed in our research lab in 2007 scanning the 1335-1373 nm region roughly every 5 ms. As the laser output was monitored vs. the FFP tunable filter drive frequency, a region was spotted were the intensity noise was significantly reduced. It was observed that the low noise region was highly sensitive to the polarization state inside the cavity and that the spectral location of the low noise region was a function of the filter drive frequency [see Figure 5.1].
5.1.1 Introduction

Since its introduction [57,58], the Fourier-Domain Mode Locked (FDML) laser has been widely and successfully applied for optical coherence tomography (OCT) [9,59-61] as well as other applications including high-speed molecular spectroscopy [11,12] and fiber Bragg grating interrogation [62,63]. To the best of our knowledge, the FDML lasers used in these applications have in all cases been approximately mode locked, but not perfectly mode locked. Here, near-perfect mode-locking of a FDML laser sweeping over a 3.5 nm range is demonstrated. This truly mode-locked condition is characterized by ultra low intensity noise (when viewed with a 4 GHz oscilloscope) and narrow instantaneous spectral linewidth. Although the 3.5 nm range is too small to be of direct applicability in most OCT settings, it is of interest because it offers insight into the potential for perfect mode locking over broader...
wavelength ranges and because it is directly useful for some applications, including high-speed molecular spectroscopy.

5.1.2 Design

A schematic of the laser design is shown in Figure 5.2. The cavity is composed of a semiconductor optical amplifier (SOA, Covega Corp., BOA 1036-0-0-T-S-S-A-A), a polarization controller (PC), two optical isolators (ISO), a dispersion compensated fiber (DCF) delay, a fiber Fabry-Perot tunable filter (FFP-TF, Micron Optics, spectral bandwidth: 3.24 GHz, Finesse = 5590) and an output coupler. Fourier domain mode locked lasing operation is achieved by driving the FFP-TF with a function generator (FG, Agilent 33220A) at the fundamental or a harmonic of the cavity roundtrip time.

![Figure 5.2 Schematic of the ultrastable FDML laser cavity.](image)

In addition to a very precise polarization control and a high, passive cavity finesse, it was found that the FFP-TF drive frequency must match the cavity roundtrip time very accurately.
in order to achieve the ultrastable FDML performance. A frequency resolution of 1 mHz was needed to mode lock the laser at 49.892207 kHz. Because of the high timing requirements, the long-term stability of the laser is limited without a precise temperature control of the entire cavity. The spectral scanning width is limited by fiber dispersion.

5.1.3 Results

For the laser presented here, the scanning width was 3.5 nm centered at the zero-dispersion wavelength of the DCF spools (1365.5 nm). The signal to ASE floor separation was 40 dB [see Figure 5.3].

![Image](image-url)

**Figure 5.3** FDML scanning spectrum recorded with an optical spectrum analyzer (OSA, spectral resolution: 0.06 nm).

The top plot in Figure 5.4 shows an extremely low noise intensity trace of the ultrastable mode locked laser recorded at 4 GHz analog bandwidth and 10 GS/s. The noise band visible
in the plot is entirely data acquisition noise; it is present even with the laser off. In contrast, a typical FDML intensity trace is presented in the bottom plot in Figure 5.4. All operating parameters were kept the same as in the ultrastable mode locked case, only the polarization state was slightly misaligned from the optimal state. The large noise complicates sensing strategies by demanding advanced referencing strategies as described in the literature [12,51,52].

![Intensity trace of FDML: ultrastable (top) and typical (bottom) mode locked laser operation.](image)

**Figure 5.4** Intensity trace of FDML: ultrastable (top) and typical (bottom) mode locked laser operation.

In addition to the low intensity noise of the ultrastable FDML, the spectral linewidth is narrowed significantly compared to the typical FDML: 7-times narrower (251 MHz compared to 1.76 GHz) or about 13-times narrower than the bandwidth of the intra-cavity FFP-TF. To measure the linewidth, the output of the FDML was directed through a fiber
Fabry Perot interferometer (FFP-I Micron Optics, spectral bandwidth: 84 MHz) [see Figure 5.5].

![Graph](image)

**Figure 5.5** Spectral linewidth measurement with an 84 MHz bandwidth post-cavity FFP-I.

The linewidth of the near-perfect case may be limited by saturation-induced self-phase modulation in the SOA [64].

### 5.1.4 Conclusions and outlook

Although the improvements in intensity noise and spectral linewidth of this ultrastable FDML laser compared to typical FDML performance are very promising, the major limitation of the source is the long term stability and the rather narrow spectral scanning width. The presented 3.5 nm scanning width is wide enough for some molecular
spectroscopy measurements but has to be significantly enhanced for practical OCT applications.

To realize broader scanning ranges, the second generation ultrastable FDML source, which is currently being implemented in our lab, was designed in the C-band, where dispersion compensation technology is far advanced due to the fiber optic communications market. The cavity roundtrip dispersion that can be achieved with off-the-shelf dispersion slope compensating modules (e.g. OFS, LLMicroDK) is low enough to allow for broad ultrastable scanning widths (10s of nm).

The second generation design that is shown in Figure 5.6 is based on a sigma cavity [65,66] that eliminates the high polarization sensitivity that was observed in the first generation design [see Figure 5.2]. To cope with the polarization sensitivity, ideally, the cavity would be composed entirely of polarization maintaining (PM) fiber. However, because of the long cavity length of a FDML laser (typically 1-10 km), the cost and the losses inside the PM fiber would be too high. In the proposed sigma cavity design, the PM fiber part could be as short as ~ 1 m. Almost the entire cavity is still single-mode (SM) fiber but any changes in the polarization state that might occur from the polarization beam splitter (PBS) to the Faraday rotator mirror (FRM) are being reversed on the return way.
Figure 5.6 Schematic of the proposed FDML sigma cavity. Any changes in the polarization state in the SM fiber part of the cavity are reversed on the way back from the Faraday rotator mirror (FRM) to the polarization beam splitter (PBS).

Temperature control of the entire cavity will ensure long term stability of the ultrastable FDML laser.

5.2 PIECEWISE CONTINUOUS FDML LASER SYSTEM

In this section, hyperspectral sensor systems are presented that multiplex two or more FDML lasers. The first implementation is a 2-FDML laser system. The FDML lasers were synchronized and operated at a repetition rate of ~ 40 kHz. The 2-FDML system is a special case where an automatic power modulation can be achieved by operating the two FDML lasers in a quasi-periodic pulsed mode. This mode, which is effectively blinking the laser output at a 50 % duty cycle, is obtained by detuning the FFP-TF drive frequency away from the cavity roundtrip frequency. The second implementation multiplexes 3 FDML lasers at an overall repetition rate of 67 kHz using active modulation.
5.2.1 Introduction

The spectrum and time trace of an example output of a piecewise continuous source that multiplexes 3 FDML lasers are shown in Figure 5.7 and Figure 5.8. In this case, the laser output continuously scans over three spectral regions, which are all well separated from each other [see Figure 5.7].

![Figure 5.7 Spectra of a 3-FDML laser system shown for 0.6 and 2 nm wide scans.](image)

The time trace of a multiplexed FDML laser source is a pulse train, where each pulse contains the information of one scan [see Figure 5.8].

![Figure 5.8 Time trace of a 3-FDML laser system.](image)
A piecewise continuous source combines some of the major advantages of discrete and continuous hyperspectral sources:

- Compared to continuous hyperspectral sources, in piecewise continuous lasers, more time is spent on monitoring the most important wavelengths, as is the case in discrete hyperspectral lasers. This improves the signal-to-noise ratio of a spectroscopic measurement and also lessens the burden on the data acquisition system (DAQ), as fewer points have to be sampled.

- Compared to discrete hyperspectral sources, where baseline correction can be a problem, in piecewise continuous or continuous systems, a baseline correction can be performed for each scan.

5.2.2 2-FDML laser implementation

By detuning the fiber Fabry-Perot tunable filter drive frequency away from the cavity round trip frequency, the FDML laser can be operated in a quasi-periodic pulsed mode rather than the traditional CW mode. However, if the frequency shift is positive \((f - f_{\text{roundtrip}} > 0)\) this pulsed mode can only be achieved during the backward scan of the filter (from longer to shorter wavelengths) and vice versa. There is no lasing operation during the other scan direction. This quasi-periodic pulsed mode is presumably due to the balance between frequency shifting and spectral broadening through SOA nonlinearities [67].

A time trace of a FDML laser running in the quasi-periodic pulsed mode is presented in Figure 5.9. The FDML laser was scanning from 1348-1373 nm with a detuned frequency of 49.0257 kHz (cavity roundtrip frequency: 49.9002 kHz). The FDML output was directed
through a 1 m room air path, collected back into single-mode fiber and detected with a fast photoreceiver (New Focus 1592; 3.5 GHz bandwidth) and digitized with a 4 GHz oscilloscope (Tektronix TDS7404).

Figure 5.9 Pulsed FDML output that was directed through 1 m of room air. FFP-TF frequency was detuned from 49.9002 kHz (cavity roundtrip frequency) to 49.0257 kHz.

If only two FDML lasers are multiplexed to form a piecewise continuous source, this quasi-periodic pulsed FDML mode allows for multiplexing the two FDML outputs without actively modulating the signals, as schematically shown in Figure 5.10.
A piecewise continuous TDM 2-FDML laser source was implemented and tested at the Wright-Patterson Air Force base in Dayton, OH. Each FDML cavity was composed of a semiconductor optical amplifier (SOA, Covega Corp., BOA 1036-0-0-T-S-S-A-A), a polarization controller (PC), two optical isolators (ISO), a fiber delay, a fiber Fabry Perot tunable filter (FFP-TF, Micron Optics, spectral bandwidth: 3.24 GHz) and an output coupler. The two FDML lasers were operated in the quasi-periodic pulsed mode so that the two output signals could be multiplexed without the need of an external modulator [see Figure 5.10]. To synchronize the two FDML lasers, the cavity lengths were matched within 1 inch. Also, the function generators (FG, Agilent 33220A) that provided the drive signal for the FFP-TFs were locked to a synthesized clock generator (Stanford Research Systems, SRS CG635). The FDML lasers were both operated at 40.2903 kHz but 180 degrees out of phase.

During the igniter test at the Wright-Patterson Air Force base one FDML laser was scanning 1349.75–1350.85 nm and the other one was scanning 1364.05–1365.15 nm. The wavelength ranges were selected in order to optimize temperature sensitivity of the measurement. Also, the spectral scanning widths can be adjusted to the experimental conditions, e.g., the scan amplitude can be increased for high-pressure gas and lowered for low-pressure gas.
The signals of a reference beam $I_0$ and 4 beams that were directed through an igniter test section were detected with fast photoreceivers (Thorlabs, PDA-10CF) and sampled with a 12 bit digitizer card (National Instruments, PXI-5105, 60 MS/s, 8 channels). Single shot time traces from the 2-FDML laser system are shown in Figure 5.11.

![Figure 5.11](image)

Figure 5.11 Single-cycle time traces of the reference ($I_0$), the transmission ($I$) signal and inferred absorbance.

The left features are ‘hot’ features: features which become stronger as temperature increases, and the right features are ‘cold’ features: features which become weaker as temperature increases. Laser cycles as shown in Figure 5.11 were repeated every 25 µs.

### 5.2.3 3-FDML laser implementation

The TDM 2-FDML laser design introduced in the previous section is a special case, where the two FDML output signals can be multiplexed without the need for external modulators if the FDML lasers are operated in the quasi-periodic pulsed mode. For piecewise continuous
hyperspectral sources that multiplex more than two FDML lasers either the intra-cavity SOAs have to be pulsed or the output signals have to be modulated. The 3-FDML laser implementation presented in this section was designed for multi-beam H₂O absorption spectroscopy. Due to high number of output beams, each of the 3 FDML output signals was modulated and boosted with an external cavity SOA to compensate for the multiplexing loss (-16 dB for 32 fiber coupled outputs). The overall system design is shown in Figure 5.12.

As in the TDM 2-FDML source presented in the previous section, the three FDML cavity lengths were matched within 1 inch (cavity lengths: ~ 3020 m) so that it was possible to run all three FDML lasers at the same frequency: 67.743 kHz. The injection current to the external cavity SOAs was controlled by fast diode laser controllers (Wavelength Electronics,
LDTC 2/2 E, 2 MHz modulation bandwidth. The gate signals to the diode laser controllers were provided by a pulse generator (Berkeley Nucleonics Corporation, BNC555) that was locked with the three FFP-TF drive signal generators (FG, Agilent 33220A) to a synthesized clock generator (Stanford Research Systems, SRS CG635).

Pictures of the TDM 3-FDML sensor system are shown in Figure 5.13. The signal generation stage (top left) and the boosting, modulating and multiplexing stage (bottom left) were built on 19” rack mountable panels so that the entire system including the data acquisition and photoreceivers could be installed in one 19” rack (left).
Water absorption features were measured in an 18 inch long cell that was heated up to 1000 C (pressure: 0.958 bar, H$_2$O concentration: 9.052 mol/m$^3$). One of the single-mode fiber coupled output beams of the 3-FDML source was directed through the cell and then collected into multi-mode fiber (length: 30 m, NA: 0.22). This transmitted beam $I$ and a reference beam $I_0$ were then each detected with a photoreceiver (Thorlabs, PDA10-CF) and sampled with a 12 bit digitizer (National Instruments, PXI-5105, 60 MS/s, 8 channels). Single cycle time traces of $I$ and $I_0$ are shown in the top plot of Figure 5.14.

![Figure 5.14 Single shot 3-FDML laser output. Top plot: Reference beam $I_0$ (blue) and transmitted beam $I$ (red) that was directed through an 18 inch long cell containing water (temperature: 1000 C, pressure: 0.958 bar, H$_2$O concentration: 9.052 mol/m$^3$). Bottom plot: Inferred absorbance signal.](image-url)
The inferred absorbance signal \([-\ln(I/I_0)]\) is presented in the bottom plot of Figure 5.14. The minimal detectable absorbance (MDA) of this measurement was \(2.1 \cdot 10^{-3}\). The MDA was limited by the modal dispersion inside the multi-mode fiber.

### 5.2.4 Conclusions

Time-division multiplexed, piecewise continuous hyperspectral lasers offer some unique features that give these light sources a very high potential for spectroscopic sensing applications. The piecewise continuous approach has the advantage of discrete sources, namely, that more time is spent monitoring the most important wavelengths rather than scanning the entire spectral range. But piecewise continuous sources also offer the ‘reality check’ that is inherent for continuous hyperspectral sources: “Am I really measuring what I think I’m measuring?” Additionally, piecewise continuous sources that are based on multiplexing multiple FDML lasers are highly adaptable to various measurement conditions. Both scan locations and scan widths can be simply changed by adjusting the electrical drive signals to the FFP-TFs.

However, the complexity of these sources is no longer as simple as it was for most hyperspectral sources presented in previous chapters.
CHAPTER 6. CONCLUSIONS

The goal of this project has been to design and implement hyperspectral lasers with target specifications listed in Table 1.1. Various hyperspectral sources have been presented in this thesis: Time-division and frequency-division multiplexed sources as well as discrete, piecewise continuous and continuous designs. In this concluding chapter, all hyperspectral laser designs and techniques that were shown in this work will be evaluated and summarized.

6.1 FDM VS. TDM

The comparison of FDM vs. TDM depends strongly on the specific hyperspectral laser design. Dependent on the specific application, FDM or TDM might have the advantage in signal-to-noise ratio. However, TDM has an advantage over FDM in data acquisition (DAQ) cost and data evaluation.

- **Signal-to-Noise Ratio**: For spectral encoding in time measurements, each resolution element is scanned consecutively, so for a total scan time $T$, the time $t$ that it takes to record one resolution element is $T / n$ where $n$ is the number of resolution elements. For spectral encoding in frequency measurements, all spectral bands are recorded over the total scan time $T$.
  - Assuming that the SNR is proportional to the square root of the measurement time, the multiplex or Fellgett advantage [28] enhances the signal-to-noise by a factor of $\sqrt{n}$ for FDM systems compared to TDM systems.
  - Because all spectral bands are recorded over the total scan time, the noise of each spectral band is multiplexed on all other bands. This can be a critical
disadvantage for FDM systems if, for example, the noise level of one spectral band (intensity noise, shot noise, ...) is significantly higher than the noise level of another band.

- **DAQ cost:** In an ideal TDM system, each spectral band has to be sampled only once per measurement cycle resulting in \( N \) samples for \( N \) spectral bands. For an ideal FDM system, \( 2 \cdot N \) sample points are needed because of the Nyquist criterion. However, in practical applications, the number of sampling points of a TDM compared to a FDM system is lower by about one order of magnitude.

- **Data evaluation:** In sensing applications that are based on absorption spectroscopy, the transmitted intensity \( I \) and the initial intensity \( I_0 \) have to be measured to calculate the absorbance \( \alpha \) at a specific wavenumber \( \nu \): \( \alpha_\nu = -\ln \left( \frac{I}{I_0} \right)_\nu \). In TDM sensor systems, it is very straightforward to obtain the values for \( I \) and \( I_0 \) as they are directly related to the recorded time traces. In FDM systems, the intensity values are encoded in the frequency domain. The values of \( I \) and \( I_0 \) can either be decoded by a Fourier transformation of the recorded time domain signals or by lock-in amplifiers. Both options, however, add some complexity to the system.

Depending on the specific application, one of the advantages or disadvantages listed above might be the decisive factor when it comes to the question of whether to select a TDM or FDM hyperspectral source. For example, if a light source has to be designed for a multi-beam tomography application [56,68-70], which allows for spatially resolved information
from line-of-sight measurements, the lower DAQ burden of the TDM approach might be pivotal.

6.2 CONTINUOUS SPECTRAL COVERAGE VS. DISCRETE SPECTRAL COVERAGE

The output of a discrete hyperspectral sensor system consists of only a few specific wavelengths. For gas thermometry applications, wavelengths are chosen that allow the interrogation of absorption features that are highly sensitive to temperature changes. Thus, in discrete sensor systems, more time is spent monitoring these most important wavelengths than it is in the case of a continuous spectral coverage system. This yields an improved signal-to-noise ratio for the absorbance signal of the most sensitive features and hence a more sensitive measurement.

Wavelength-dependent effects including etalons, beamsteering, window fouling and interfering absorbers can have a big impact on the accuracy of a spectroscopic measurement if they are not corrected for. These interference effects however are very difficult to detect if only a few wavelengths are monitored, whereas a continuous spectral coverage reveals them more clearly.

The piecewise continuous spectral coverage approach (see Section 5.2) has the potential to combine the advantages of discrete and continuous sources: A more sensitive measurement (by spending more time monitoring the more important wavelengths) while still being immune to interference effects.
### 6.3 BRIEF INDIVIDUAL DESIGN EVALUATION

The pros and cons of the six hyperspectral laser designs presented in Chapter 2 through Chapter 5 are listed in Table 6.1.

<table>
<thead>
<tr>
<th></th>
<th>Positive</th>
<th>Negative</th>
</tr>
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<tbody>
<tr>
<td><strong>CW c-FTS</strong></td>
<td>- free modulation through cavity mode spacing</td>
<td>- narrow spectral width</td>
</tr>
<tr>
<td></td>
<td>- higher replica orders to improve finesse and FFT resolution</td>
<td>- difficult to get linewidths &lt; 1 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- high intensity noise</td>
</tr>
<tr>
<td><strong>DML FDM</strong></td>
<td>- simple setup</td>
<td>- cross talk in amplifier</td>
</tr>
<tr>
<td></td>
<td>- high output power</td>
<td>- one function generators per wavelength needed for modulation</td>
</tr>
<tr>
<td></td>
<td>- improved signal-to-noise ratio</td>
<td>- beating noise</td>
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<tr>
<td></td>
<td></td>
<td>- difficult to get linewidths &lt; 1 GHz</td>
</tr>
<tr>
<td><strong>N-color TDM</strong></td>
<td>- simple setup</td>
<td>- difficult to get linewidths &lt; 1 GHz</td>
</tr>
<tr>
<td></td>
<td>- straightforward to achieve high number of wavelengths</td>
<td>- beating noise</td>
</tr>
<tr>
<td><strong>Cascaded spectral filtering TDM</strong></td>
<td>- narrow spectral linewidth (&lt; 80 MHz)</td>
<td>- complex and expensive setup</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- beating noise</td>
</tr>
<tr>
<td><strong>Ultrastable FDML</strong></td>
<td>- ultralow intensity noise</td>
<td>- narrow spectral width</td>
</tr>
<tr>
<td></td>
<td>- narrow spectral linewidth (250 MHz)</td>
<td>- long-term stability</td>
</tr>
<tr>
<td><strong>Piecewise continuous FDML</strong></td>
<td>- highly adaptable (spectral scan center and width)</td>
<td>- complex and expensive setup</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- fiber lengths have to be matched to synchronize FMDL lasers</td>
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<tr>
<td></td>
<td></td>
<td>- beating noise</td>
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</table>

Table 6.1 Summary of presented hyperspectral light sources.
The selection of one of the hyperspectral light sources listed in Table 6.1 over the others may be application driven. However, in the theoretical case that nothing is known about a certain application but the target species, the piecewise continuous FDML laser presented in Section 5.2 would probably be the best choice, if it can be afforded, because of its high versatility.

6.4 RECOMMENDATIONS FOR FUTURE WORK

Because of the very low intensity noise and the narrow spectral linewidth, the ultrastable FDML laser presented in Section 5.1 would be a near perfect light source for optical coherence tomography as well as for general absorption and fluorescence spectroscopy applications, if the long-term stability and the spectral breadth were improved. An advanced design was proposed in Section 5.1.4 that has the potential to improve both stability and spectral coverage by at least an order of magnitude. In addition to implementing the sigma-cavity design [see Figure 5.6], a better understanding of Fourier-Domain mode locking might help to improve the performance of the ultrastable FDML even further.

The fiber Fabry-Perot tunable filter (FFP-TF) used in the laser designs presented in Chapter 5 is a limiting component because it is based on mechanical motion and is therefore somewhat unreliable and offers only a limited dynamic performance. For example, in the piecewise-continuous laser design, it might not be possible for one filter to scan the narrow target ranges while stepping or quickly sweeping the in-between wavelengths, which would simplify the sensor system. For future designs, other spectral filters could be considered. For example, while acousto-optical tunable filters (AOTFs) have broader spectral FWHMs, they offer faster dynamics and are more rugged due to an operation principle that is based less on moving parts.
REFERENCES


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APPENDIX I BEAT SIGNAL OF A SINGLE FREQUENCY COMB

The intensity \( I_{\text{total}} \) of all lasing modes in ring cavity can be found as:

\[
I_{\text{total}} \propto (E_{\text{total}})^2 = \left( \sum_{i=1}^{N} A_i \cos(\sigma_i t + \theta_i) \right)^2
\]

where \( E \) is the electrical field, \( N \) the number of modes, \( A_i \) the amplitude of mode \( i \), \( \omega_i \) the frequency of mode \( i \), and \( \theta_i \) the phase of mode \( i \).

\[
= \sum_{i=1}^{N} A_i^2 \cos^2(\sigma_i t + \theta_i) + 2 \sum_{i=2}^{N} \sum_{j=1}^{i-1} A_i A_j \cos(\sigma_i t + \theta_i) \cos(\sigma_j t + \theta_j)
\]

with:
\[
\cos^2 \alpha = \frac{1}{2}(1 + \cos 2\alpha)
\]
and:
\[
\cos \alpha \cos \beta = \frac{1}{2}(\cos(\alpha - \beta) + \cos(\alpha + \beta))
\]

\[
= \frac{1}{2} \sum_{i=1}^{N} A_i^2 \left(1 + \cos(2\sigma_i t + 2\theta_i)\right) + \sum_{i=2}^{N} \sum_{j=1}^{i-1} A_i A_j \left[ \cos\left((\sigma_i - \sigma_j) t + \theta_i - \theta_j\right) + \cos\left((\sigma_i + \sigma_j) t + \theta_i + \theta_j\right)\right]
\]

\[
= \frac{1}{2} \sum_{i=1}^{N} A_i^2 + \sum_{i=2}^{N} \sum_{j=1}^{i-1} A_i A_j \cos\left((\sigma_i - \sigma_j) t + \theta_i - \theta_j\right) + ... + \sum_{i=2}^{N} \sum_{j=1}^{i-1} A_i A_j \cos\left((\sigma_i + \sigma_j) t + \theta_i + \theta_j\right) + \frac{1}{2} \sum_{i=1}^{N} A_i^2 \left(2\sigma_i t + 2\theta_i\right)
\]

\[
= \frac{1}{2} \sum_{i=1}^{N} A_i^2 + \sum_{i=2}^{N} \sum_{j=1}^{i-1} A_i A_j \cos\left((\sigma_i - \sigma_j) t + \theta_i - \theta_j\right) + \frac{1}{2} \sum_{i=1}^{N} A_i^2 \left(2\sigma_i t + 2\theta_i\right)
\]

\[
\text{DC low frequency beat signal}
\]

\[
= \frac{1}{2} \sum_{i=1}^{N} A_i^2 + \sum_{i=2}^{N} \sum_{j=1}^{i-1} A_i A_j \cos\left((\sigma_i - \sigma_j) t + \theta_i - \theta_j\right)
\]

\[
\text{low frequency beat signal}
\]

\[
= \frac{1}{2} \sum_{i=1}^{N} A_i^2 + \sum_{i=2}^{N} \sum_{j=1}^{i-1} A_i A_j \cos\left((\sigma_i + \sigma_j) t + \theta_i + \theta_j\right)
\]

\[
\text{high frequency beat signal}
\]