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# Development and test of a broadband absolute frequency reference with sub-MHz precision based on a GHz mode locked laser source

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## ABSTRACT

Space lidar instruments for missions like AEOLUS or MERLIN require advanced high-power laser systems with according technical and financial effort. In order to increase the impact of such missions, it is advantageous to expand the versatility of their instruments. In the case of trace gas sensing, the ability to detect multiple trace gas species with the same instrument greatly enhances their value.

Multi-species trace gas differential absorption lidar (DIAL) systems require absolute frequency referencing across large spectral bandwidths. While absorption cell based references need individual lasers at online and offline wavelengths for each species, a broadband mode locked laser – offering a frequency comb – can provide the required frequency accuracy over the complete spectral range of the lidar instrument.

In the frame of the LEMON project, we developed a combined design for an absolute frequency reference based on a wavemeter for coarse frequency determination (<500 MHz accuracy) and a broadband mode locked laser for precise frequency detection by means of heterodyne beat generation. It features a large spacing of 1 GHz and is optimized for spectroscopic lidar applications covering the spectral range from 980 nm to 1100 nm and 1500 nm to 2300 nm. The achieved accuracy of <100 kHz of the optical frequency, satisfies the requirements needed to atmospheric gas analysis from space. The broadband approach offers a cost-effective solution to address multiple gas species simultaneously. The system can also be adapted to different spectral ranges of interest for gas spectroscopy and other applications.

**Keywords:** lidar, multi-species, frequency comb, frequency reference, spectroscopy, optical reference, wavelength stabilization, differential absorption

## 1. INTRODUCTION

Frequency referencing in the frame of laser gas spectroscopy is key in order to build sensitive instruments with a high signal to noise ratio (SNR). Especially for space based lidar instruments in atmospheric gas spectroscopy, where a power attenuation of typically  $10^{-13}$  between emitter and receiver occurs, any further source of noise has to be ruled out. For methane (CH<sub>4</sub>) an optical absolute frequency knowledge of better than 10 MHz, i.e. a fractional knowledge of better than  $5 \times 10^{-8}$  at 1645 nm, is sufficient. But carbon dioxide (CO<sub>2</sub>) demands for a knowledge below 1 MHz with a goal better than 100 kHz to achieve a sensitivity of better than 1 ppm CO<sub>2</sub> in the atmosphere.<sup>1</sup> At the spectroscopic wavelength around 2 μm this requires a fractional frequency knowledge below  $5 \times 10^{-10}$ . The relevant time averaging windows are typically about several seconds to several tens of seconds.

While single frequency referencing can be established with reasonable effort on a wavemeter in combination with a reference laser, for accuracies beyond 1 MHz, its practical resolution limit is hit. An alternative approach to detect the frequency of the light is heterodyne beating against a reference laser. This technique can detect frequencies with theoretically arbitrary resolution, which is on the order of the inverse integration time of the beat signal detection for continuous wave (cw) beating. In case of a DIAL where pulses are used, the useful integration time is not arbitrary and puts again limitations to the maximum accuracy. Finally, the different noise contributions will determine the achievable frequency knowledge. For a 12.5 ns laser pulses as foreseen for the LEMON instrument, a 100 kHz resolution is still

feasible. Figure 1 depicts the simulation of the heterodyne beating between a 12.5 ns laser pulse and a cw reference laser. The simulation took into account different noise levels and phases between OPO pulse and reference laser. The upper left panel of the figure shows the envelope of the OPO pulse and the amplitude noise that has been added to the signal. The lower left panel shows two examples of beat note signals with different phases and noise levels. The panel on the right hand side provides the results of the simulation where for each data point an ensemble of phase and noise parameters have been accumulated. The graph shows the frequency resolution levels for different beat frequency offsets (x-axes) and for different signal to noise ratios as indicated by the color coded legend.

From these results, we expect that for a signal-to-noise ratio below 0.1 %, the 100 kHz resolution is achievable. Additionally, it becomes clear that the best resolution obtains a beat frequency at  $\frac{1}{4}$  or  $\frac{3}{4}$  of the assumed 1 GHz sampling frequency.

Shifting from a wavemeter based frequency detection approach to heterodyne beating opens up further options for the reference laser system. To drive the wavemeter accuracy to the limit, it is necessary to have a reference laser in the vicinity of the spectroscopy laser, i.e. both being in the same free spectral range (FSR) of the wavemeter, where the FSR is in the low GHz range. This is solved, by stabilizing the reference laser to an absorption in a local gas cell that contains the species of spectroscopic interest, e.g. CH<sub>4</sub> in the case of the MERLIN frequency reference unit.<sup>2,3</sup> In case of a multi species instrument this approach means that for every gas species, a laser source has to be carried along in order to allow for the calibration of the wavemeter. A frequency comb approach will not work with a wavemeter as due to the FSR ambiguity of the wavemeter single mode laser light of high spectral purity is necessary of the maximum possible accuracy of the wavemeter shall be achieved.

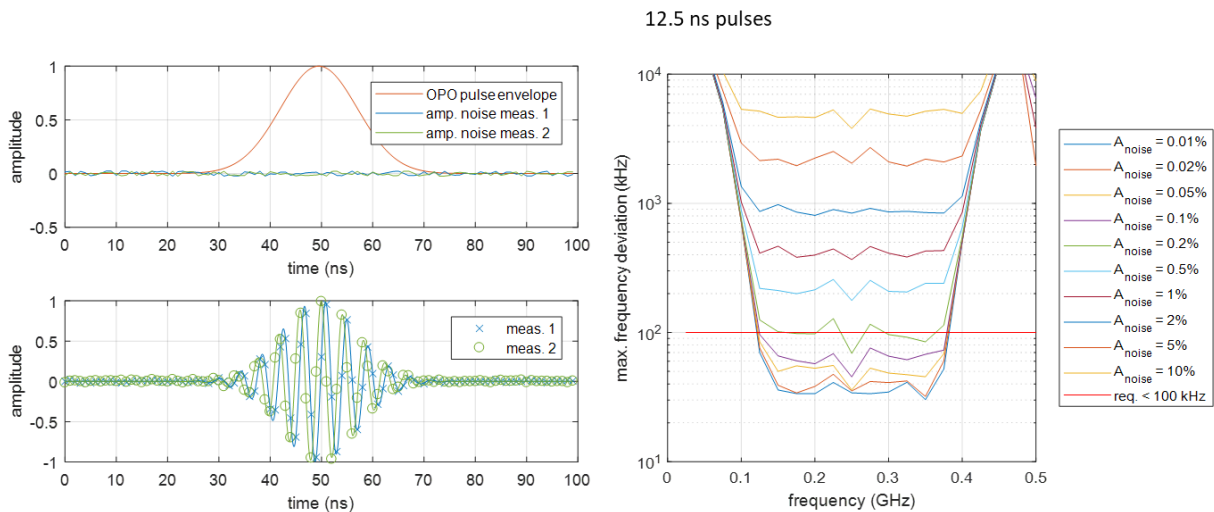


Figure 1. Simulation of resolution limits for heterodyne beat note detection: The upper left panel shows the envelope of the OPO-pulse and the noise contribution. The lower left panel gives two examples of simulated beat signals. The right panel provides the results. The detailed explanation can be found in the text.

This is completely different when heterodyne beating is done: Residual comb modes will not contribute to the beating signal as long as analog signal filtering and ADC-sampling respect the Nyquist frequency and avoid aliasing. For that purpose, a comb with high frequency spacing is favorable. At least it has to be well above the width of the laser pulse to ensure that higher order signals are well separated. Assuming a minimum pulse length of 7 ns, leading to a spectral width of 63 MHz, a comb with a mode spacing of 1000 MHz can solve this issue.

## 2. AIRBORNE DESIGN AND IMPLEMENTATION

Within the present LEMON project the design and implementation of an airborne demonstrator of a multi species lidar is foreseen.<sup>4</sup> From the environmental view, this differs in some points from the requirements of a space instrument. On the

one hand, the lower height and shorter detection range reduce not only the laser light attenuation but also relax the requirement to the frequency knowledge of the laser by one order of magnitude. On the other hand, the required performance has to be provided in the environment of the airplane, where temperature and pressure are not stable and vibrations are disturbing the laser systems. This is in contrast to the rather quiet and stable space environment.

## 2.1 Design

For this development step, it has been decided to do the laser pulse characterization in the frequency doubled spectral range of the OPO around 1  $\mu\text{m}$ , which is a straightforward task thanks to the high peak power available from the laser emitter source. This enables to benefit from the superior availability and lower cost of 1  $\mu\text{m}$  electro-optical and fiber-optical components. Still, the same concept is applicable directly in the 2  $\mu\text{m}$  region, too.

The outline of the LEMON frequency reference unit is shown in the next figure and described in detail in a reference.<sup>5</sup>

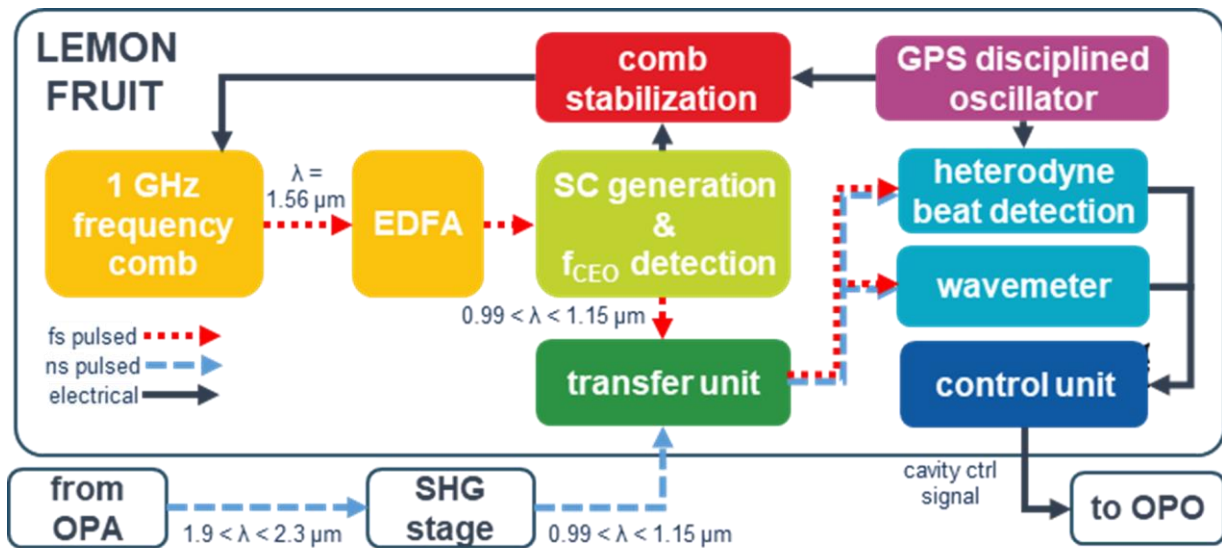


Figure 2. Overall outline of the LEMON frequency reference unit (FRUIT) with the main interfaces to the other instrument subunits. EDFA: erbium doped fiber amplifier, SC: super continuum, OPA: optical parametric amplifier, being the last amplification stage of the main laser, SHG: second harmonic generation, OPO: optical parametric oscillator, being the first element of the main laser that generates the spectroscopic laser pulses.

In the following, we will focus on the comb generation and beat note detection being the essential developments of the new frequency reference design. The master oscillator is a diode pumped femtosecond laser at 1560 nm wavelength, providing at least a 10 nm broad spectrum and several tens of milliwatt output power at 1 GHz repetition rate. The repetition rate is stabilize to a GPS (global positioning system) disciplined oscillator with a long term fractional stability of better than  $10^{-10}$  on the relevant time scale of several tens of seconds and longer. This transfers to a frequency stability of 30 kHz for the optical laser modes at 1  $\mu\text{m}$  wavelength, which is sufficient to support the 100 kHz requirement for  $\text{CO}_2$ .

After passing a dispersion compensation fiber for stretching and pre-compensation of the femtosecond pulses the average power is amplified by means of an erbium doped fiber amplifier to about 1.5 Watts.

This provides peak powers sufficient to drive non-linear optical processes in an optical fiber. On the one hand, this provides a spectrum that spans from the 2  $\mu\text{m}$  meter spectral region of the DIAL instrument down to its frequency doubled spectrum at 1  $\mu\text{m}$  and it enables the characterization of the laser pulses generated by the optical parametric oscillator (OPO) at both, the fundamental and the harmonic frequencies.

On the other hand, this allows offset locking of the comb with an f-2f-interferometer.<sup>6</sup> In combination with the stabilization of the repetition rate to the GPS disciplined oscillator, we achieve full stabilization of the comb. Relying on a global time reference (GPS, GALLILEO or similar) reference instead of a local gas cell reference has several

advantages. System complexity is outsourced from the instrument with the expectation to improve in the future to a fractional stability below  $10^{-15}$ .<sup>7</sup> While a 10 MHz optical accuracy is achieved with reasonable effort for a gas cell reference as in the case of the MERLIN instrument, a 100 kHz accuracy would require a substantial development effort in order to ensure the long term stability. Here, the frequency comb opens up a simple connection to external references in the radio frequency spectrum. Even more, the comb can easily access optically distributed time references that may become more important in the future, too.<sup>7</sup>

## 2.2 Airborne Implementation

Currently, the final assembly, testing and optimization of the airborne instrument is ongoing. Due to shorter distances compared to a space instrument, the stability requirements are one order of magnitude lower than for the space instrument. On the other hand, the performance has to be kept under airborne vibration levels. The results from the present testing activities are shown in figure 3 where the optical frequency stability of the comb modes is shown. Having the design goal of a 100 kHz stability in the final space implementation, the design and implementation of the comb stabilization electronics have been kept as simple as possible, too. This will reduce the effort for the final space design. In principle, the selected comb source allows for much higher stabilities.<sup>8</sup>

For the characterization of the comb stability on the relevant time scale of several seconds, it has been heterodyned against a non-planary ring oscillator at 1064 nm. As the shown graph illustrates, at the present implementation the threshold limit for the stability is respected for all vibration levels, while the goal stability needs some improvement of the stabilization. From further investigations it turned out, that the repetition rate stabilization loop is the limiting factor and needs to be improved. The offset frequency stabilization is yet stable below 100 kHz for all vibration levels and does not need further improvement.

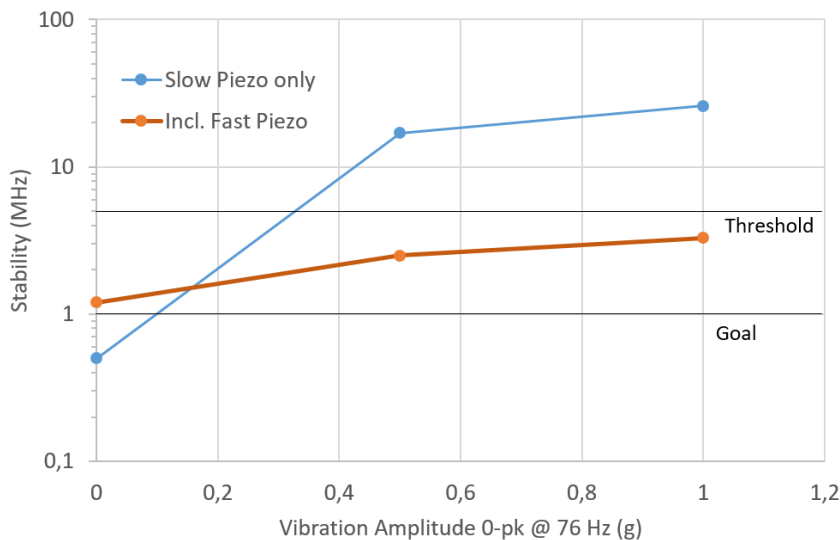


Figure 3. Stability of the comb modes at 1064 nm wavelength for different vibration levels and stabilization implementations. Threshold and goal stabilities for the airborne lidar are indicated by horizontal lines.

To implement the heterodyne beat detection around  $1 \mu\text{m}$ , the light of the comb is filtered to a sufficient small fraction of the spectrum and overlapped with the second harmonic of the laser pulses. The signal is detected in a differential manner so that the pulse envelope is electronically subtracted before digitization and allows having the full vertical resolution (12 Bit) available for the beat note detection. (See figure 4.) The 1 GHz analogue-digital-converter (ADC) is working fully synchronized with the 1 GHz reference signal to which the laser oscillator pulse repetition rate is locked. This avoids aliasing effects that might disturb the precise frequency determination. Details about the electronic stabilization scheme are described in a reference.<sup>5</sup>

A pulsed ‘micro-laser’ with about 15 ns pulses and a 4 kHz repetition rate has been used for testing the beating implementation during integration of the frequency reference unit (FRUIT). One of the single shot beating traces is presented in figure 4. The left panel provides the time domain signal that has been sampled. The panel to the right provides fast Fourier transformation that is used to receive the centroid of the spectrum for monitoring and stabilization

purposes of the OPO and the whole laser emitter, respectively. The single scan still incorporates a relevant noise floor which originates from the reference signal: The 1 nm broad spectrum brings along unwanted sources of noise. Within the 1 nm spectrum about 300 comb modes are present whereof only one contributes to the relevant signal while the others can interact with the incoherent background light of the OPO signal.

Because of the stability being required on a longer time scale (100 s), averaging of the pulses – that are measured with a 70 Hz rate – will reduce the background noise by more than one order of magnitude. If this is still not sufficient to achieve the requirement for airborne implementation of 1 MHz, additional filtering can be implemented. This is part of the space design and described in more detail in the following section.

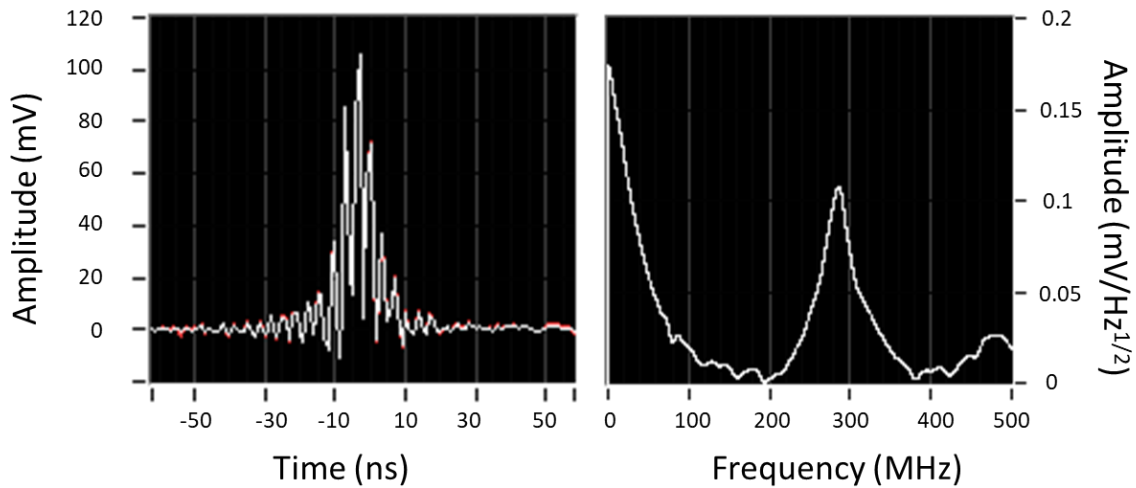


Figure 4. Beat Signal obtained between the FRUIT and pulsed laser @ 1064 nm. Left hand side: The transient beat signal as detected with the 1 GHz analogue-digital-converter (ADC) – 1 Sample = 1 ns. Right hand side: Fourier analysis of the same signal for retrieving the centroid of the offset frequency between the known comb mode and the laser pulse.

### 3. SPACE DEVELOPMENT AND MINIATURIZATION

The space development of the LEMON DIAL system is already part of the running project. Focusing on the most critical issues with analysis and tests (radiation and vibration), the cornerstone for the space development of a multi species DIAL shall be set and lead to a defined roadmap. Apart from radiation testing of components,<sup>5</sup> the development of a space compatible design outline of the FRUIT is expected. The wavemeter, which is still part of the FRUIT as a coarse calibration tool to resolve the 1 GHz comb ambiguity, has a space compatible prototype that has been developed for the MERLIN FRU.<sup>3</sup> For to the larger frequency space of the multi species instrument, the wavemeter has been extended to have two Fizeau wedges inside to cover a larger spectral window. In order to stick closely to the design of MELRIN and keep the design compact, a two-dimensional approach was chosen, where the two Fizeaus deflect the laser in orthogonal directions.<sup>5</sup>

Currently, we focus on the space development of the frequency comb. Within the space development work package, the technology of photonic integrated circuits (PIC) has been evaluated. The chosen material platform was silicon nitride (SiN) due to its known radiation hardness and well established manufacturing processes. Founding on this technology, several components of the FRUIT have the perspective of a much more compact implementation: A 2.5 GHz repetition rate femtosecond oscillator<sup>9</sup> is chosen as a baseline for the comb generation in the space design. As an advantageous side effect, the resonator will shrink, too. Similar to the present design, an erbium doped fiber amplifier (EDFA) will increase the power. Due to the SiN platform an average power of 400 mW will be sufficient for super continuum generation even with the high repetition rate.

All components behind the EDFA have the chance to be condensed into a single SiN chip of about 15 by 10 mm size. The scheme is depicted in the following figure. Inset a) shows an outline of a design that supports the afore-mentioned replacement: In the upper branch the 1560 nm narrow band frequency comb is coupled in. A pick-off is taken to a photo



diode that measures the repetition rate and is used for closing the loop of the repetition rate lock. After that, a straight waveguide of several mm length broadens the spectrum to define an octave spanning spectrum that also spans over the desired spectroscopic wavelengths.

This super continuum is guided into two sub divisions: The straight elongation guides into an area of second harmonic generation with a subsequent photo detector for  $f-2f$  interferometry. This signal is used for offset detection and stabilization.

Next to the straight waveguide, a detuned double micro ring resonator is placed that allows to filter a comb mode with an effective finesse of  $300^2 = 90\,000$ . Assuming a filter width (full width half maximum) of  $1/3$  GHz and an FSR of 100 GHz, the effective stop band is 30 000 GHz or 100 nm at  $1\ \mu\text{m}$  central wavelength. That means, the ring resonator filter allows to select a single comb mode in a window of 100 nm which is well above the expected tuning range of the LEMON lidar instrument. This light is mixed for heterodyne beating with the light from lower branch that stems from the laser source that shall be measured or stabilized – e.g. in the case of LEMON the optical parametric oscillator/amplifier (OPO/OPA) output from the lidar emitter. At the beginning of the lower branch, a split off has been taken for reference that monitors the pulse shape and can be used for subtraction from the beat-note prior to digitization to improve the signal size.

A further perspective is given in case the micro ring resonator filter can be calibrated down to an *absolute* accuracy of 1.25 GHz. If this was the case, also the coarse wavemeter, that is presently the baseline for the comb mode index identification, can be ruled out of the design, which means an enormous impact to the design in terms of weight, space, power, computational effort and last but not least, radiation susceptibility.

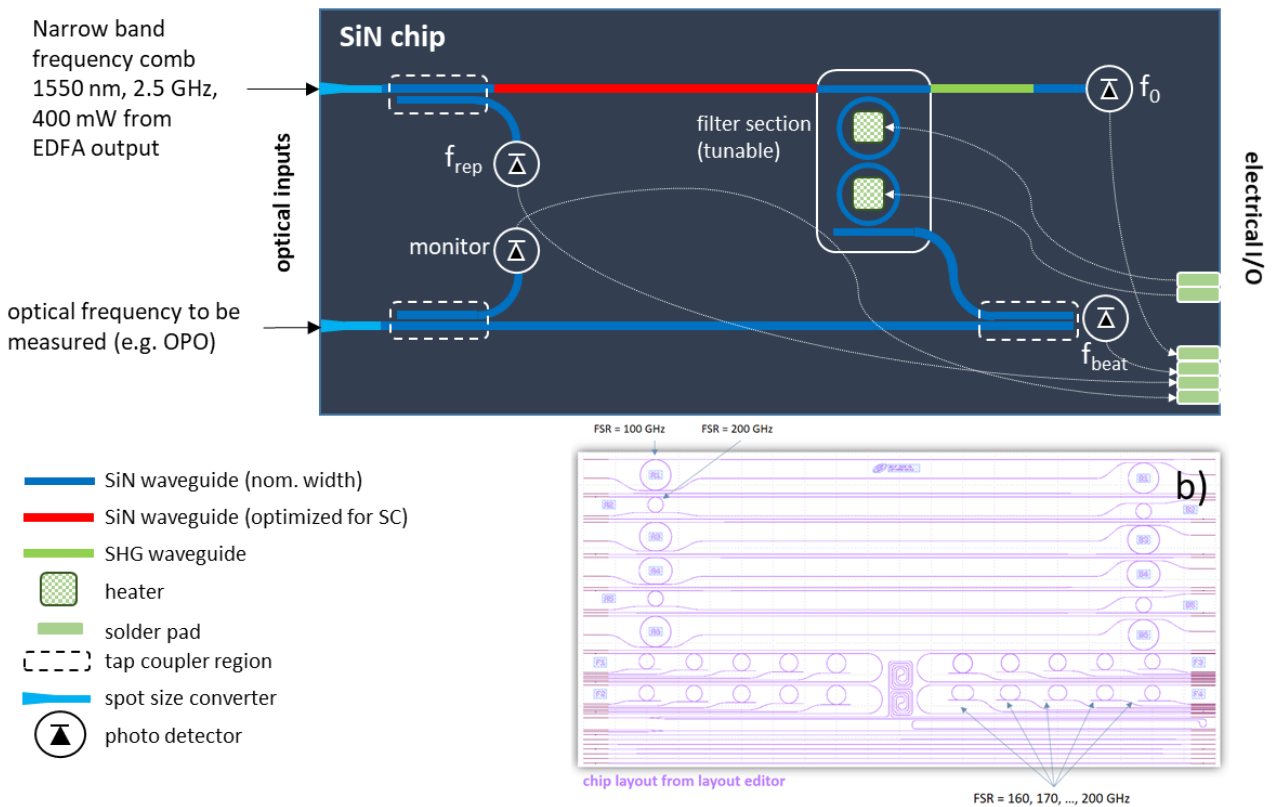


Figure 5. a) Schematics of a SiN based frequency detector:  $f_{\text{rep}}$  – pulse repetition rate / comb spacing,  $f_{\text{beat}}$  – heterodyne beat frequency between comb and instrument (e.g. OPO/OPA output),  $f_0$  – Offset frequency  
b) Design outline of the SiN test chip that has been manufactured for parameter optimization and radiation testing.

Inset b) of the above Figure presents the design of a SiN-chip that has been manufactured in the frame of the current LEMON project. It has been used for design verification, parameter optimization and radiation testing. Several tests have been performed and one result is shown in figure 6, where one of the filter rings has been used to filter the comb

spectrum: A single micro ring resonator has been used to select single comb modes (red curve) out from the comb spectrum (blue curve) with an FSR spacing of about 190 GHz. The FWHM of the filter is below 500 MHz leading to a Finesse of 380 being well above the expected design goal of 300. Modes next to the selected modes are suppressed by more than 6 dB. For some single parasitic modes in between the suppression is at least more than 10 dB and for all other modes more than 15 dB.

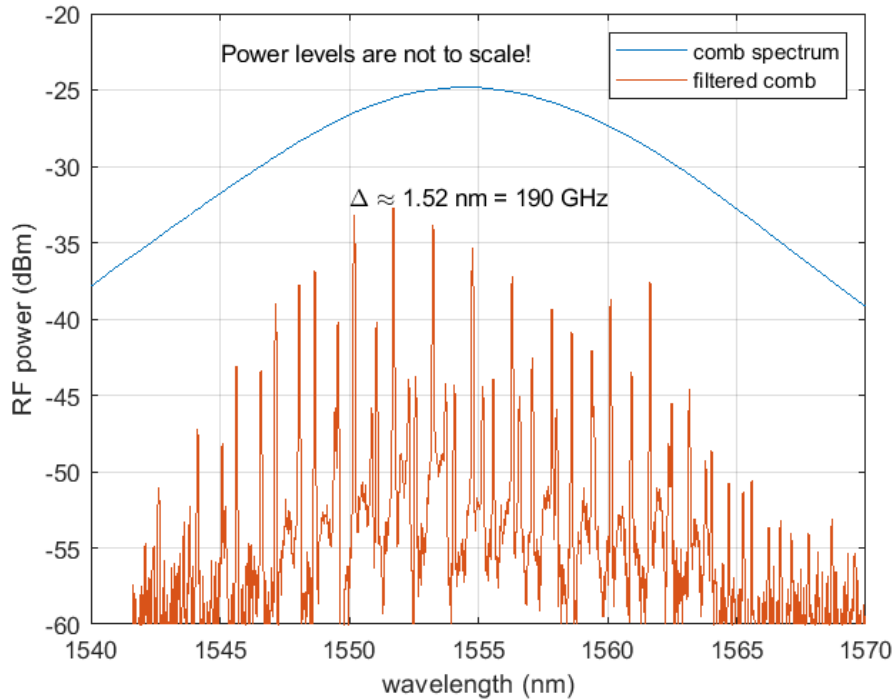


Figure. 6 a) Filtering of the comb. A single micro ring resonator is used to select single comb modes (red curve) out from the comb spectrum (blue curve). For more details see text.

With the change from 1 GHz repetition rate to 2.5, the suppression of adjacent modes will increase from 6 dB to 15 dB. Additionally, a two stage filter will be used to allow the selection of one comb mode within a 100 nm spectral area. Apart from increasing the effective FSR, a detuned double micro ring resonator filter will also improve the side mode suppression to 30 dB for the adjacent modes, 20 to 25 dB for single parasitic modes and 30 dB for all other modes, respectively. For a 2.5 GHz comb this leads to a spectrum, where about 2.5 % of the power is located in the selected mode within the 100 nm spectral area. Assuming a spectral power density of  $1 \mu\text{W}/\text{nm}$  in the relevant super continuum spectral area at the input of the double filter and 40 % transmission for the passband, this corresponds to a power level of  $1 \mu\text{W}$  in the relevant mode, which is typically sufficient for generating a good heterodyne beat signal.

#### 4. CONCLUSION

We have set up a frequency comb based spectroscopic absolute reference, which is stabilized to an RF signal provided by GPS to an accuracy below 1 MHz. A heterodyne beating setup allows to characterize spectroscopic laser sources with pulse lengths as short as 10 ns.

First developments have been started in the direction of a space compatible design which aims for higher performance and compactness compared to the airborne instrument.

The main requirement is to provide absolute optical frequency references at different wavelength. Apart from that, a path has been started that may allow to omit the wavemeter to further improve the overall design w.r.t. weight, size and radiation tolerance.



## ACKNOWLEDGEMENT

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