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Calibration of high-accuracy spectrometers using stabilized 11-GHz femtosecond semiconductor laser

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Abstract: We demonstrate for the first time the calibration of the wavelength scale of high-performance spectrometers using a fully stabilized optical frequency comb from an ultrafast optically pumped semiconductor disk laser (SDL) as a traceable reference. The SDL is a modelocked integrated external-cavity surface-emitting laser (MIXSEL) with the gain and saturable absorber layers fully integrated into one wafer chip, which forms one end mirror of the simple straight cavity with a pulse repetition rate of 11 GHz. This MIXSEL comb is actively stabilized and opens new possibilities for easier and more accurate frequency calibrations of standard laboratory instruments.

1. Introduction

The calibration of high performance instruments such as spectrometers [1,2] or wavemeters requires complex and bulky primary standards, which are not easily available for most of the users, especially at the factory level. We therefore have developed simpler and more compact solutions to perform the absolute calibration of these instruments.

We demonstrate here the application of a stabilized compact and simple ultrafast optically pumped Semiconductor Disk Laser (SDL) [3,4] as a traceable standard for the calibration of the wavelength scale of spectrometers. The SDL is an optically pumped Modelocked Integrated External-Cavity Surface-Emitting Laser (MIXSEL) [5] combining InGaAs quantum well gain region and saturable absorber in a single semiconductor layer stack operated at anti-resonance [6] to support stable generation of an ultrafast train of pulses in a simple straight cavity with extremely low noise performance [7]. The modelocked optical spectrum of this MIXSEL consists of a comb of equidistant spectral line of a frequency $f_{\mathrm{REF},n} = f_{\mathrm{CEO}} + nf_{\mathrm{rep}}$ where f_{CEO} is the carrier envelope offset frequency (i.e. the optical frequency comb offset) [8], n is the index of the comb and f_{rep} is the repetition rate of the laser (i.e. optical frequency comb spacing). The cavity length can be adjusted to support comb spacing between 5 and 100 GHz [9]. Here we have a cavity length of 13.2 mm which results in a MIXSEL comb spacing of 11.3 GHz (Fig. 1(c)) The stabilization of f_{rep} is performed by comparison to a microwave standard [10], while the f_{CEO} is stabilized to an Extended Cavity Diode Laser (ECDL), which is locked to an absorption line of an acetylene gas cell. The calibration of a spectrometer is then performed by a direct comparison to this stabilized MIXSEL comb.

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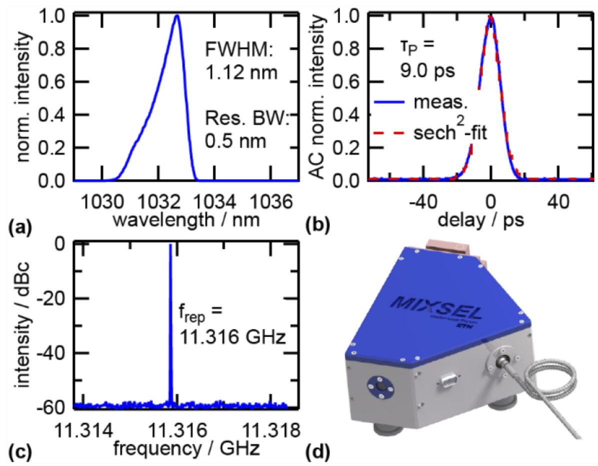

Fig. 1. 11-GHz MIXSEL comb: (a): Optical spectrum, (b): autocorrelation and pulse duration, (c): pulse repetition rate of the ultrafast SDL. With 2 nm spectral width centered around 1032 nm and a fundamental repetition rate of 11.316 GHz, more than 500 µW per comb line could be achieved directly from the oscillator. (d): The prototype housing of the MIXSEL comb is small $< (10 \times 20 \times 20)$ cm^3.

2. Setup and stabilization

The MIXSEL comb generates more than 200 mW of average output power at a center wavelength of 1032.3 nm, and is spanning over 2 nm (FWHM = 1.12 nm). With a nominal repetition rate of 11.316 GHz and a pulse duration of 9 ps, the power per comb line exceeds 500 µW across the FHMW. Figure 1 shows the optical spectrum, autocorrelation, microwave spectrum and the prototype housing of the 11–GHz MIXSEL comb.

Due to the non-octave-spanning spectrum of the MIXSEL comb, which only counts around 50 spectral lines, the offset frequency f_{CEO} cannot be stabilized using a classical f-to-2f self-referencing method [6]. Instead, the MIXSEL comb is locked to a stabilized ECDL, which consists of a commercial ECDL (Thorlabs, TLKL1050M) generating a narrow line of cw radiation tunable from 990 nm to 1110 nm. The frequency of the laser is locked to a Doppler broadened absorption line of acetylene at ν = 290 267 138 MHz (λ = 1032.79 nm) using a Pound Driver Hall method [11]. The wavelength of the stabilized laser is continuously monitored by a traceable referenced wavemeter. The PID feedback loop generates an error signal which is sent to the piezoelectric actuator controller of the ECDL . With this simple method a frequency accuracy better than 30 MHz can be achieved over several days.

The MIXSEL comb is then offset frequency locked to the stabilized laser by generating a beat note frequency f_{beat} between the stabilized ECDL and the closest comb line and by using a phase comparator-based feedback loop to control the SDL pump current. This technique enables an indirect stabilization of the OFC. This way, a beat frequency f_{beat} = 120 MHz was set, with a maximum deviation of 40 MHz observed over one day (Fig. 2).

The repetition rate f_{rep} is locked by comparison to a traceable reference microwave signal and by acting on the piezo element to control the MIXSEL cavity length, as described in [12]. With this method f_{rep} is stabilized to 11. 361 910 GHz, with an accuracy better than 1 Hz observed over several days (Fig. 3).

The frequency of each individual comb line f_{REF_n} can be calculated using the formula:

$$f_{\mathrm{REF}_n} = f_{\mathrm{ECDL}} \pm f_{\mathrm{beat}} \pm n \times f_{\mathrm{rep}} \tag{1}$$

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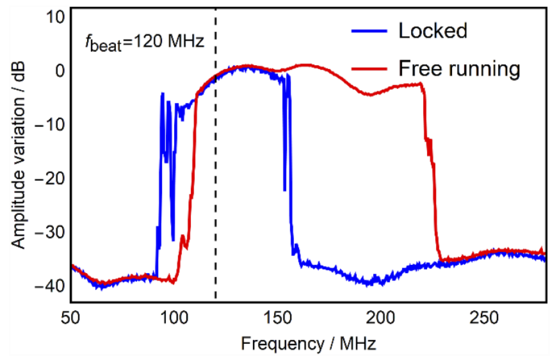

Fig. 2. Behavior of f_{beat} the beat-note frequency between the MIXSEL comb and the stabilized ECDL. When free-running, the frequency is drifting over more than 200 MHz over 15 min. When locked, the maximum frequency drift is maintained in a range of about 40 MHz.

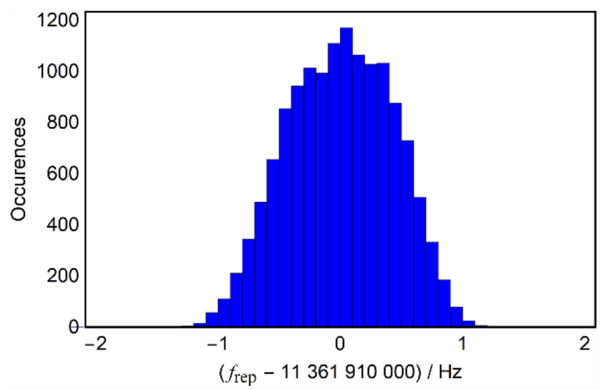

Fig. 3. MIXSEL comb histogram of the measured f_{rep}. One measurement being performed every second. We estimate the worst case uncertainty to be equal to 1 Hz after 2 days of measurement.

where f_{beat} is the beat note frequency between f_{ECDL} and the selected comb line used to stabilize the optical frequency comb, n is the position of the line ($n = 0$ being the position of f_{ECDL}).

Changes in the pump intensity of the MIXSEL cause a shift in f_{CEO} and thus a shift of the comb lines. The value of the sign is experimentally determined by varying the current of the pump laser while observing the variation of f_{beat} [13]. Figure 4 shows the experimental setup which can be divided into three main parts, each of which stabilizes one of the three fundamental frequencies mentioned above.

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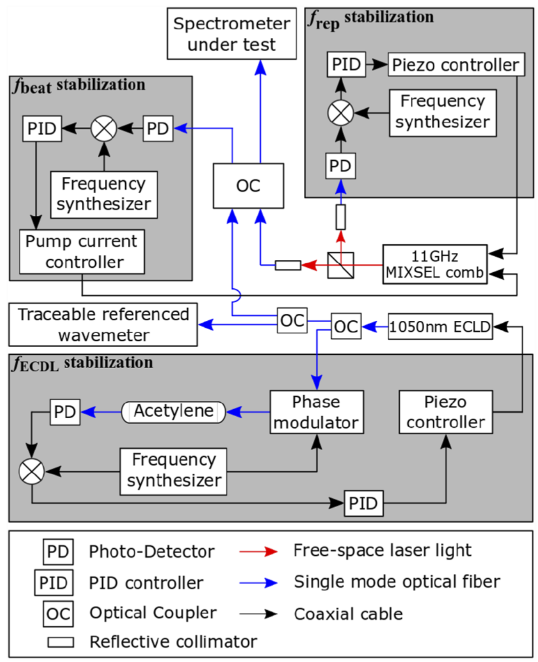

Fig. 4. Simplified schematic of the experimental setup showing the three main stabilization parts, namely the stabilization of f_{rep}, the stabilization of f_{ECDL} on the acetylene reference and the stabilization of f_{beat}, corresponding to an indirect stabilization of the carrier-envelope offset frequency of the laser. All the frequency synthesizers use a 10 MHz external reference which is generated by an atomic clock traceable to the International Time Scale (TAI). Proportional-Integral-Derivative controllers (PID) are used to lock the 3 different frequencies.

3. Frequency uncertainty

With the optical frequency comb being fully stabilized and traceable, it is now possible to calculate the frequency of each line of the MIXSEL comb by using the formula (1) with an uncertainty given by the following equation:

$$u(f_{REF_n}) = \sqrt{u^2(f_{ECDL}) + u^2(f_{beat}) + n^2 \times u^2(f_{rep})} \tag{2}$$

Due to the low value of n (<100) and the size of $u(f_{rep})$ compared to $u(f_{ECDL})$ and $u(f_{beat})$, the term $n^2 \times u^2(f_{rep})$ can be neglected, which leads to:

$$u(f_{REF_n}) \approx u(f_{REF}) = \sqrt{u^2(f_{ECDL}) + u^2(f_{beat})} = 50 \text{ MHz} \tag{3}$$

This uncertainty, which corresponds to a wavelength uncertainty of 0.17 pm at 1032 nm, is low enough to enable the calibration of a grating-based Optical Spectrum Analyzer (OSA) and a Fourier Transform Infrared (FTIR) spectrometer.

4. Results

4.1. Calibration of an optical spectrum analyzer

The spectrum of the stabilized MIXSEL comb measured with an OSA (ANDO AQ6319) is shown Fig. 5(a), while its wavelength scale deviation $\Delta\lambda = \lambda_{OSA}$- λ_{REF} is shown in Fig. 5(b). We are able to determine the wavelength deviation for each line of the MIXSEL comb between

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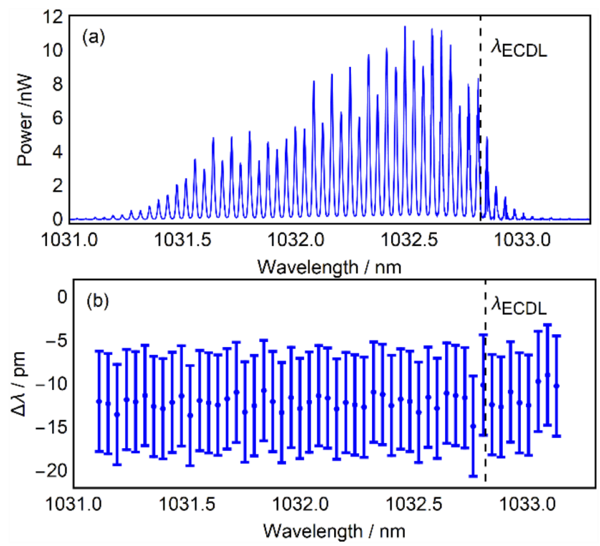

Fig. 5. (a) Spectrum of the stabilized MIXSEL comb measured with the OSA and (b) its wavelength scale deviation. The dashed black lines correspond to the position of the ECDL reference wavelength. The spectrum corresponds to a single shot measurement and was not averaging.

1031.13 nm and 1033.14 nm, where 51 combs lines can be resolved. The width of each measured comb line is limited by the resolution bandwidth of the OSA, which is of 10 pm and the sampling period is of 1 pm. The error bars are given by the quadratic sum of the uncertainty arising from the reference optical frequency comb $u(f_{\mathrm{REF}})$ and from the Device Under Test $u(f_{\mathrm{DUT}})$, whose

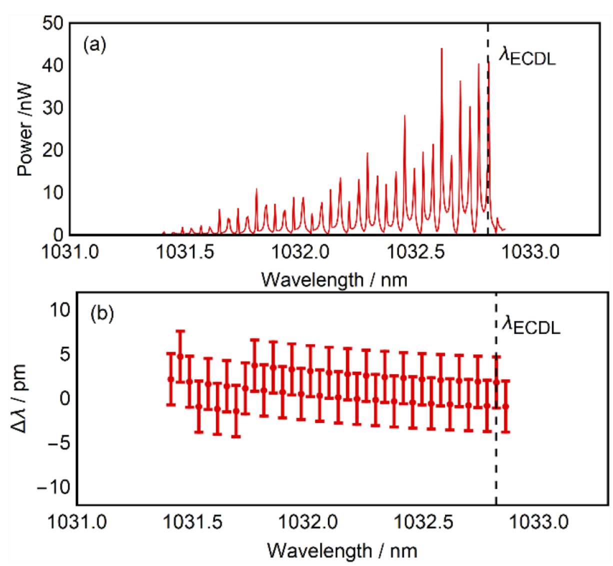

Fig. 6. (a) Spectrum of the stabilized MIXSEL comb measured with the FTIR spectrometer and (b) its wavelength scale deviation. The dashed black lines correspond to the position of the ECDL reference wavelength. The spectrum corresponds to a single shot measurement and was not averaging.

limited resolution bandwidth gives the major contribution to the uncertainty budget. This leads to a combined expanded uncertainty (coverage factor k = 2 [14]) of $U_{\Delta f} = 1623$ MHz, which corresponds to a $U_{\Delta\lambda}$ =5.78 pm.

4.2. Calibration of a FTIR spectrometer

This instrument consists of a classical wavemeter (Burleigh WA-1500), for which the interferogram is synchronously sampled and processed. The spectrum of the stabilized MIXSEL comb measured with the FTIR spectrometer is show Fig. 6(a), while the evaluation of its wavelength scale deviation is shown in Fig. 6(b). We are able to determine the wavelength deviation for each comb line between 1031.41 nm and 1032.86 nm, where 37 combs lines can be resolved. It has a resolution bandwidth of 5 pm which is also the value of the uncertainty attributable to each point. The uncertainty of the measured deviation is also limited by the resolution bandwidth of the FTIR, which leads to a combined expanded uncertainty (k = 2) of $U_{\Delta f} = 811.5$ MHz, corresponding to a $U_{\Delta\lambda}$ =2.89 pm.

5. Conclusion

We have demonstrated that optically pumped passively modelocked semiconductor disk lasers, more specifically a MIXSEL comb, can be stabilized to a level of accuracy which makes them suitable for the calibration of the frequency scale of high performance spectrometers. Thanks to the bandgap engineering capabilities of semiconductors, MIXSEL combs with gigahertz pulse repetition rates can be designed for almost any wavelength region of interest [10], opening the way to a new range of precise wavelength calibration tools for optical metrology.

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Disclosures

The authors declare no conflicts of interest.

References

1. P. Huke, M. Debus, M. Zechmeister, and A. Reiners, "Characterization and calibration of a Fourier-transform spectrometer using a laser frequency comb," J. Opt. Soc. Am. B **36**(7), 1899–1906 (2019).
2. P. Huke, M. Debus, and A. Reiners, "Phase-correction algorithm for Fourier transform spectroscopy of a laser frequency comb," J. Opt. Soc. Am. B **36**(5), 1260–1266 (2019).
3. B. W. Tilma, M. Mangold, C. A. Zaugg, S. M. Link, D. Waldburger, A. Klenner, A. S. Mayer, E. Gini, M. Golling, and U. Keller, "Recent advances in ultrafast semiconductor disk lasers," Light: Sci. Appl. **4**(7), e310 (2015).
4. U. Keller and A. C. Tropper, "Passively modelocked surface-emitting semiconductor lasers," Phys. Rep. **429**(2), 67–120 (2006).
5. D. J. H. C. Maas, A.-R. Bellancourt, B. Rudin, M. Golling, H. J. Unold, T. Südmeyer, and U. Keller, "Vertical integration of ultrafast semiconductor lasers," Appl. Phys. B **88**(4), 493–497 (2007).
6. B. Rudin, V. J. Wittwer, D. J. H. C. Maas, M. Hoffmann, O. D. Sieber, Y. Barbarin, M. Golling, T. Südmeyer, and U. Keller, "High-power MIXSEL: an integrated ultrafast semiconductor laser with 6.4 W average power," Opt. Express **18**(26), 27582–27588 (2010).
7. M. Mangold, S. M. Link, A. Klenner, C. A. Zaugg, M. Golling, B. W. Tilma, and U. Keller, "Amplitude noise and timing jitter characterization of a high-power mode-locked integrated external-cavity surface emitting laser," IEEE Photonics J. **6**(1), 1–9 (2014).

Optics EXPRESS

8. H. R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, and U. Keller, "Carrier-envelope offset phase control: A novel concept for absolute optical frequency measurement and ultrashort pulse generation," Appl. Phys. B **69**(4), 327–332 (1999).
9. M. Mangold, C. A. Zaugg, S. M. Link, M. Golling, B. W. Tilma, and U. Keller, "Pulse repetition rate scaling from 5 to 100 GHz with a high-power semiconductor disk laser," Opt. Express **22**(5), 6099–6107 (2014).
10. M. J. W. Rodwell, D. M. Bloom, and K. J. Weingarten, "Subpicosecond laser timing stabilization," IEEE J. Quantum Electron. **25**(4), 817–827 (1989).
11. F. Riehle, *Frequency Standards: Basics and Applications* (Wiley, 2006).
12. M. Guina, A. Rantamäki, and A. Härkönen, "Optically pumped VECSELs: review of technology and progress," J. Phys. D: Appl. Phys. **50**(38), 383001 (2017).
13. C. A. Zaugg, A. Klenner, M. Mangold, A. S. Mayer, S. M. Link, F. Emaury, M. Golling, E. Gini, C. J. Saraceno, B. W. Tilma, and U. Keller, "Gigahertz self-referenceable frequency comb from a semiconductor disk laser," Opt. Express **22**(13), 16445–16455 (2014).
14. JCGM 100:2008, Evaluation of measurement data – Guide to the expression of uncertainty in measurement (2008).