An Ultra-stable Generator of Absolute Length Based on Femtosecond Mode-lock Laser and Optical Resonator

Ondřej Číp, Radek Šmíd, Josef Lazar, František Petrů, Zdeněk Buchta and Martin Čížek
Department of Coherence Optics
Institute of Scientific Instruments, Academy of Sciences of the Czech Republic
Brno, Czech Republic
e-mail: ocip@isibrno.cz

***Abstract*— In the work we present a proposal of a system converting excellent frequency stability of components generated by the mode-locked laser into a set of discrete values of length represented by a spacing of mirrors of an optical resonator.**

I. Introduction

Metrology of optical frequencies in these days often deals with frequency synthesis through pulsed femtosecond mode-locked lasers [1]. Value of repetition rate of generated pulses determines (in the frequency domain) spacing of discrete coherent components of the whole supercontinuum. The spectrum of the supercontinuum has profile like a comb. The device that generates the stable comb spectrum is called an optical synthesizer [2]. It can convert stability of rf (radio frequency) repetition frequency into light spectral domain and vice versa. Therefore the synthesizer is considered as a very modern metrology tool because it bridges large gap between optical and radio frequency bands. The main application of the synthesizer is a comparison of stabilities between ultra-stable rf generators based on microwave atomic clocks (i.e. Rb, Cs) [3] with optical frequency standards like lasers stabilized by molecular, atomic, or ions transitions (i.e. I_2, Yb^+) [4].

Because the beam of stabilized mode-lock laser can be imagined as a train of pulses with very stable spacing a new application in the field of generation of standardized lengths deals. In the work we propose and experimentally verify a method, which converts excellent frequency stability of the mode-lock laser into a set of discrete values of length represented by a distance between mirrors of the optical resonator [5].

II. Methodology

Optical cavity with the length L_{cav} has a periodic frequency transmission spectrum where frequency of m-th component can be expressed:

$$f_m = m\, c / (2\, L_{cav}),$$

where c is speed of the light in the air.

Similarly the frequency of n-th component of the optical synthesizer is written as:

$$f_n = f_{ceo} + n\, f_{rep}$$

where f_{ceo} is the comb offset frequency and f_{rep} is the repetition rate. For the simplicity we presume the offset frequency f_{ceo} equals to zero.

The mode-lock laser has the comb frequency spectrum like the optical synthesizer; therefore frequencies f_{ceo} and f_{rep} are the same for mode-lock laser and synthesizer. Now we presume the beam of the mode-lock laser illuminates the plan-parallel resonator with the cavity length L_{cav}, which is set in accordance with the condition:

$$L_x = c / (2\, x\, f_{rep}).$$

where, x is an integer value. In this case the group of laser discrete spectral components coincide with those of the cavity. It is based on condition that frequency of certain spectral components of the resonator (m-th) and the comb (n-th) periodically are equal (see Fig. 1). It produces resonance intensity maximum at the output of the cavity, which can be detected by a photodetector.

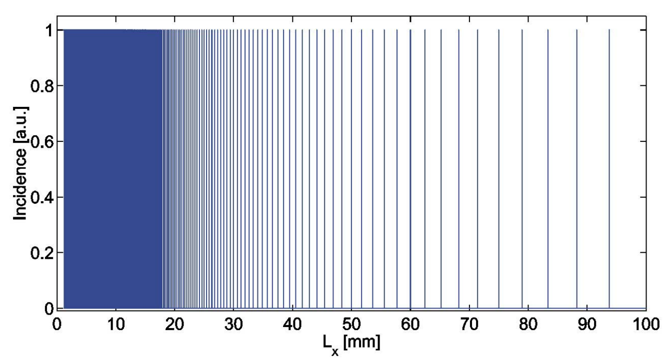

Figure 1. Places of incidence between spectral components of the optical resonator and mode-lock laser vs. resonator length L_x. The calculation is done for the mode-lock laser with the repetition frequency f_{rep}=100 MHz. The refractive index in the cavity is not considered.

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On basis of the theory we propose a setup shown in Fig. 2. The output of the mode-lock laser is steered into the optical resonator with a plan-parallel configuration. The resonator has fine control of the cavity L_x driven by a piezo-electric transducer.

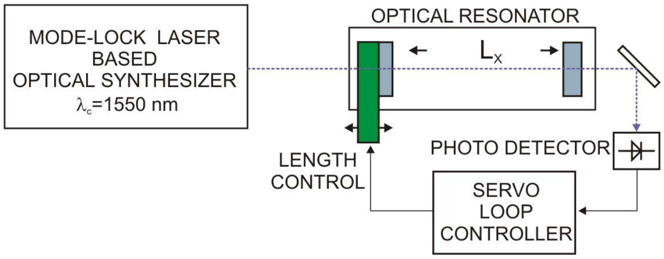

Figure 2. The proposal of the optical arrangement with the mode-lock laser and the optical resonator.

If the length L_x is adjusted approximately to any place of incidence with respect to graph in Fig. 1 the interference of femtosecond pulses at the output of the resonator is observed. Then a servo-loop controller tunes the length of the cavity towards the interference maximum. Thus the mode-lock laser controls the length of the cavity of the optical resonator. By another words, the distance between plan-parallel mirrors of the resonator represents geometrical length with the precision and stability, which the optical synthesizer has.

III. Proposal of Verification of the Method

For easier adjustment of the optical resonator and verification of the absolute length generator we proposed a comparison method. It is based on measurement of an inter-mode frequency ν_x of the optical resonator in the time when the cavity is locked to the mode-lock laser. Then the frequency ν_x equals:

$$\nu_x = c / 2\, L_x = k\ f_{rep}\,.$$

This equation determines the inter-mode frequency of the resonator and the repetition frequency of the laser are in an integer multiple (the symbol k). Therefore if we compare these both frequencies in the case when the optical resonator is locked to the interference maximum, values must be in this multiple k.

In our proposal, for measurement of the inter-mode frequency we introduced two tunable single-mode lasers working at a different wavelength than the mode-lock laser works. Each of these lasers is locked to one of neighboring longitudinal modes of the resonator. The frequency of beats between these two lasers determines the inter-mode frequency ν_x.

IV. Pilot Experiment and the First Results

The schematic diagram of the whole optical and electronic arrangement is in Fig. 3 and the photo of our pilot experiment is in Fig. 4. The pilot experiment we made with our femtosecond mode-lock laser based optical synthesizer working at the central wavelength $\lambda_c \approx 1550$ nm and with $f_{rep} \approx 100$ MHz. We designed the cavity of the optical resonator in a plan-parallel configuration. We collected two laser beams produced by He-Ne lasers *L1* and *L2* into the same axis of propagation. But we eliminated possible interference between them by different polarization. We used polarizing beam splitters *PBS* and set of half-wave plates *λ/2* for this purposes.

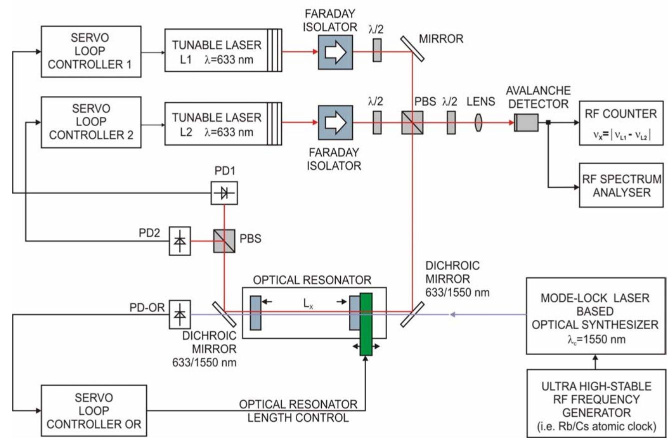

Figure 3. The schematic diagram of the optical and electronic arrangement of the method and its verification. The symbols *PD1*, *PD2*, *PD-OR* are photodetectors, *λ/2* are half-wave plate for 633 nm, *L1* and *L2* are He-Ne lasers used for measurement of inter-mode frequency ν_x, and *OR* is abreviation of the optical resonator.

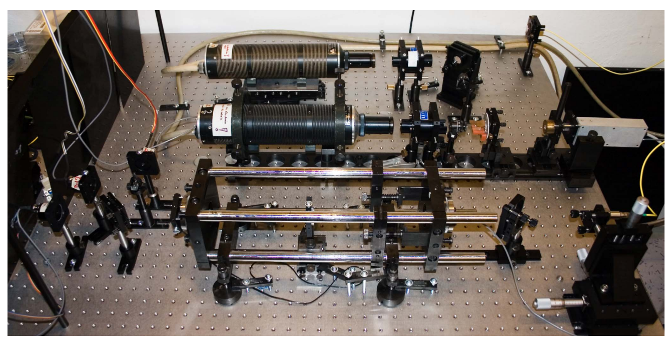

Figure 4. We put together the experimental arrangement of the method with respect to the proposal described in Fig. 3.

For locking of the optical frequency of each laser *L1* and *L2* to neighboring longitudinal modes of the optical resonator we used a harmonics detection technique known at the laser spectroscopy [6].

On basis of places of incidence shown in Fig. 1 we selected the length of the cavity of the optical resonator L_x to 375 mm approximately. After the locking of both lasers *L1* and *L2* to neighboring longitudinal modes we tuned the length of the cavity L_x precisely with respect to possible range of repetition frequency of the mode-lock laser $f_{rep} = 100.000$ MHz (+129kHz –257kHz). We reached the inter-mode frequency $\nu_x = 399.7500$ MHz by very precise tuning of the cavity length L_x.

The recordings of the spectral profile of the resonator are in Fig. 5 (detection chain with the laser *L1*) and Fig. 6 (detection chain with the laser *L2*).

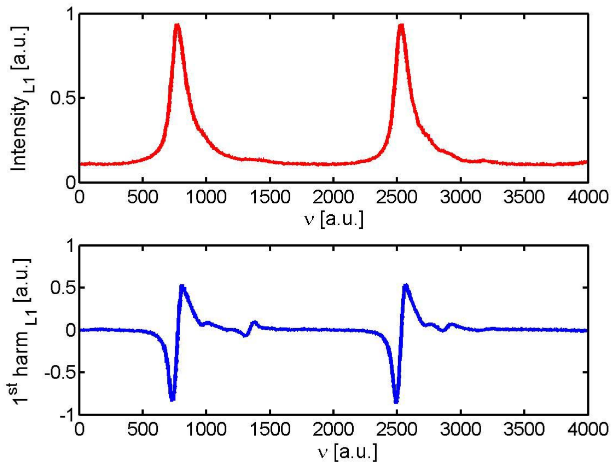

Figure 5. The spectral profile of the optical resonator measured by scanning of the laser *L1* along two neighboring longitudinal modes of the optical resonator.

There are intensity spectra and their first harmonics courses detected by our electronics. The resonance peaks in both cases have the distance ν_x = 399.7500 MHz.

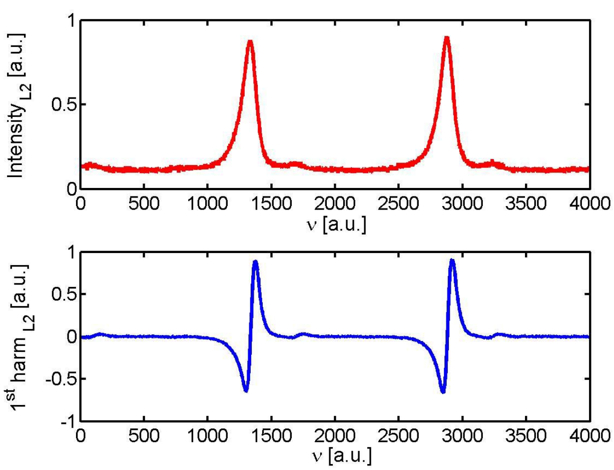

Figure 6. The spectral profile of the optical resonator measured by scanning of the laser *L2* along two neighboring longitudinal modes of the optical resonator.

On basis of the equation $\nu_x = k\, f_{rep}$ we tuned the repetition frequency of the mode-lock laser to f_{rep} = 99.9375 MHz with respect to selected $k = 4$. When we approached this theoretically calculated value we observed interference for 1550 nm femtosecond pulsed beam in the output of the optical resonator. The profile of the interference is shown in Fig. 7. It was recorded with respect to expression:

$$L_x = L_{cav} + \Delta L_{FP},$$

where ΔL_{FP} is small change of the cavity length with using of the piezo-electric transducer. Then we tuned the repetition frequency of the mode-lock laser to a maximum of the interference. The frequency f_{rep} = 99.9398 MHz was readout for the maximum.

After calculation of the true number k we obtain $k = \nu_x / f_{rep}$ = 399.7500/99.9398 = 3.99991. The deviation from the experimentally measured $k = 4$ is caused probably by dispersion of the refractive index of air inside the cavity [7]. The measurement of the inter-mode frequency was done at 633 nm wavelength and the mode-lock laser works at 1550 nm. The refractive index at each of wavelengths differs due to dispersion so that the small deviation is tolerable.

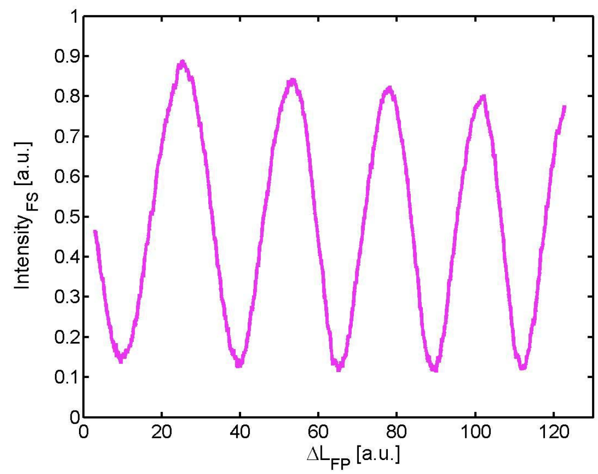

Figure 7. The record of the course of the interference in the output of the optical resonator.

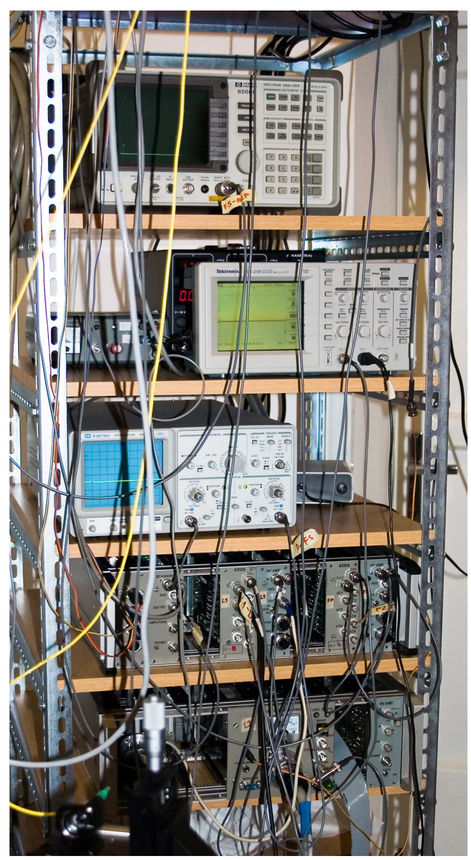

Figure 8. The arrangement of the control, stabilization, and measuring electronics.

The arrangement of our control and stabilization electronics is shown in Fig. 8. The servo-loop controllers for locking of tunable lasers *L1* and *L2*, locking of the optical resonator to the mode-lock laser are made by us. The electronics is based completely on the digital signal processors. For the first harmonics detection we have used the technique of a direct digital mixing at the modulation frequency 1 kHz. The data transfer and remote control of the electronics is via Controller Area Network (CAN) [8]. The whole experiment is under control of LabView software.

V. Conclusion

Our experiments proved the possibility of direct transfer between highly precise and stable radio frequency etalons (ev. optical frequency etalons) into discrete lengths. The mode-lock femtosecond laser based optical synthesizer serves here not only for bridging the gap between rf and optical domain but also into direct length measurement. We adjusted the passive cavity length into the repetition frequency of the mode-lock laser by the help of two lasers locked to neighboring longitudinal modes of the cavity. This allowed us to measure, control and adjust precisely the cavity mode spacing by monitoring of the beat frequency between the two lasers. The cavity following resonant frequencies of the pulsed femtosecond laser allowed positioning over precise discrete distances.

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