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# The low-dispersive optical cavity as a length sensor using radiation of an optical frequency comb

Lenka Pravdová, Adam Lešundák, Václav Hucl, Martin Čížek, Břetislav Mikel, Jan Hrabina, Radek Šmíd, Šimon Řeřucha, Josef Lazar, Ondřej Číp

*Institute of Scientific Instruments of the CAS, Královopolská 147, 612 64 Brno, Czech Republic*

*E-mail: ocip@isibrno.cz*

**Abstract**

New lasers, special digital signal processing electronics, algorithms and new materials for optics enabled development of new absolute distance measurement methods. The phenomenon of the mode-lock of the femtosecond pulse laser increased a number of potential applications with distance surveying where a stable generator of very short and periodically repeated coherent pulses can be used. The aim of the work is a presentation of our unique measuring method which determines the length of unknown distance with direct traceability to a time standard. The principle is based on a passive optical cavity with mirrors keeping distance to be measured. Time spacing of short femtosecond pulses generated by optical frequency comb is optically phase locked to the cavity free spectral range. A value of the repetition frequency of the laser determines the measured distance in that case. The exact value of the frequency/period of the femtosecond pulse train is detected by a frequency counter. The counting gate of the counter is synchronized with a highly stable oscillator disciplined by H-maser. This measuring technique is demonstrated in the work on length characterization of the piezoelectric transducers which belongs to high-resolution positioning actuators.

Keywords: Optical cavity, femtosecond, optical frequency comb, distance measurement

## 1. Background

The ultra-precise measurement of lengths is a domain of laser interferometers. Many configurations of counting two-beam laser interferometers based on Michelson or Mach-Zehnder scheme allow length measurement in the nanometer scale. These devices mainly measure a relative displacement from a zero position where the interferometer fringe counter is reset. In some cases, the absolute value of measured distance has to be surveyed. The multi-wavelength interferometry with a synthetic wavelength is the traditional way, indeed with loss of superb precision. Therefore different methods are necessary to fulfill the needs of the absolute scale measurement and nanometer resolution at the same time. A passive optical cavity represents the ultimate precise measuring interferometer where the laser beam passes the cavity many times and each pass interferes with others in the output of the cavity [1]. The small displacement of the cavity length causes big change of mutual phase of the interfering beams. The phase shift can be monitored with a tracking single-frequency laser locked to any selected resonant peak of the cavity comb spectrum. The displacement is converted to optical frequency change of the tracking laser and is monitored with a wave-meter or beat-note with an optical frequency standard. This scheme let us to measure the distance relatively as well as the counting interferometers, but the following method extends the measurement to absolute scale.

The recent progress in the field of optical frequency standards is oriented to femtosecond mode-lock lasers stabilized by a technique of the optical frequency comb [2]. Such a laser produces a supercontinuum light composing from a cluster of coherent frequency components in certain interval of wavelengths. A value of the repetition frequency of femtosecond pulses determines (in the frequency domain) spacing of these coherent components. If we control the mode-lock laser by means of i.e. atomic clocks we ensure frequency of these components very stable.

## 2. Methods

### *2.1 The method of the absolute length measurement*

The combination of stabilized optical frequency comb and passive cavity presented here is useful measuring tool to distance surveying with the absolute scale.

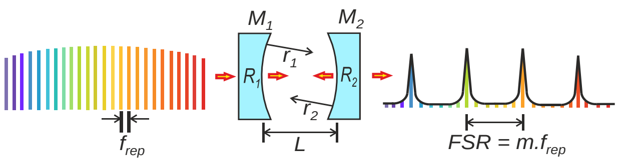


**Figure 1.** Scheme of coupling the cavity onto the supercontinuum beam. The resonant transmission modes are separated by *FSR*. The repetition frequency of the comb is $f_{rep}$. The cavity mirrors $M_1$, $M_2$ have radius of curvature $r_1$, $r_2$ and reflectivity $R_1$, $R_2$.

The passive cavity (see Figure 1.) identifies the value of unknown distance *L* by its free spectral range *FSR*. The distance is discovered with position of mirrors $M_1$ and $M_2$ of the cavity. The cavity is illuminated with the supercontinuum beam generated with the mode-locked laser characterized the repetition frequency of femtosecond pulses $f_{rep}$. If the $f_{rep}$ frequency is $m^{th}$ integer multiple of the cavity *FSR* (in accordance $FSR = m \cdot f_{rep}$) then the cavity is on resonance and it filters each $m^{th}$ component of the supercontinuum beam. The frequency $f_{rep}$ of the optical frequency comb can be locked to the *FSR* by a 1st harmonic detection technique for range of the cavity length *L*. In this case, the measuring system works as the converter of the absolute distance $L$ to the value of the repetition frequency $f_{rep}$ which can be counted by a frequency counter.

### *2.2 The low-dispersive cavity for distance measurement*

The design of the cavity has to respect the criterion of zero dispersion for the range of spectral components discovering supercontinuum beam. In the case of a dispersive cavity, the resonance condition can't be fulfilled because each $m^{th}$ component will have a different phase shift on dispersive mirrors discovering the cavity. Thus the resonance of each $m^{th}$ component will be valid for different *FSR* (thus length) of the cavity. The low dispersion of the cavity can be achieved with using the silver coating the cavity mirrors [3].

## 3. Experimental setup

The femtosecond laser working at the central wavelength 1550 nm and stabilized with the optical frequency comb technique is employed for surveying *FSR* of designed passive cavity, see Figure 2. The stabilization of the carrier to envelope offset frequency $f_{ceo}$ of the optical frequency comb is provided with *f-2f* interferometer (not shown in the figure).

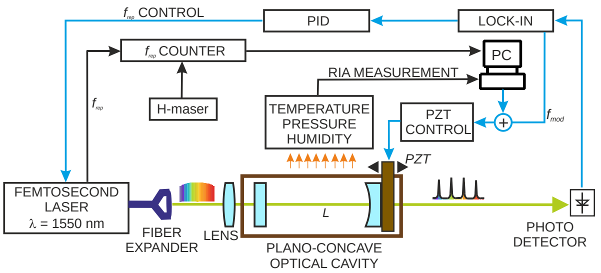


**Figure 2.** The setup for the length measurement with the absolute scale. *PID* is servo-loop controller, *PZT* is piezoelectric transducer.

The cavity is designed in plano-concave configuration ($r_1 = \infty$, $r_2 = -$ 500 mm) and with a nominal cavity length $L \approx 150$ mm. Both mirrors are coated with silver providing very low-dispersion of the cavity for the spectrum of the comb. The cavity length $L$ is controlled with *PZT* transducer.

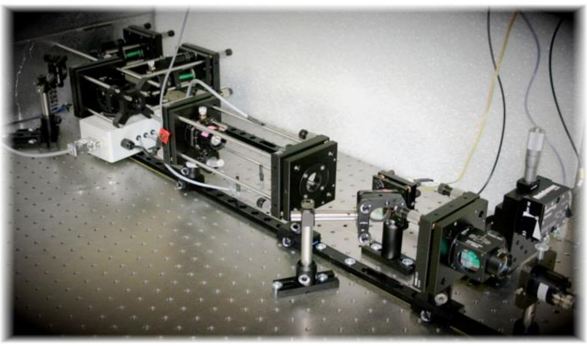

**Figure 3.** The setup photo: the cavity in the middle, the laser beam delivering optics on the left, the detection part on the right.

The 1[st] harmonic detection technique is used to locking the repetition frequency $f_{rep}$ of the femtosecond laser to the cavity length $L$. The measurement of the refractive index of air occupying the cavity is done with the weather station measuring air temperature, humidity and pressure. The station is also equipped with material probes measuring the temperature of the cavity spacer. The refractive index of air and thermal expansion of the cavity are calculated simultaneously and both values are used for correction of the measured cavity length $L$. The view of the setup is in Figure 3. The setup has been tested experimentally on displacement measurement of the *PZT* carrying mirror $M_2$. The measurement procedure has based on periodical sweeping *PZT* bias voltage. The value of the cavity length $L$ has been monitored with the frequency counter and corrected by signal processing of all measured values from the weather station. The example of one cycle of the *PZT* sweeping is shown in Figure 4. The standard deviation of the measured length is 0.46 nm for integration time 1 s while *PZT* bias voltage was kept at 0 V.

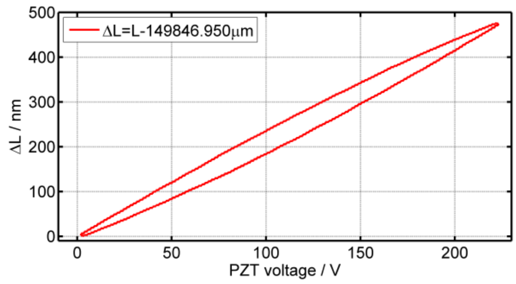


**Figure 4.** Displacement measurement of the PZT with the low-dispersive cavity and the optical frequency comb radiation.

## 4. Conclusion

We have assembled an experimental low-dispersive cavity for length measurement with absolute scale. The principle of conversion *FSR* representing the surveyed length $L$ of the measuring to the repetition frequency of the mode-locked laser has been demonstrated on *PZT* transducer displacement. The principle gives the unique possibility to measure mesoscale lengths with the absolute scale and nanometer resolution at the same time.

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### References

[1] O. Cip at al., Meas. Sci. Technol., 18:2005-2013, 2007
[2] T. Udem et al., Topics in Applied Physics: Few-Cycle Pulse Generation and its Application, Springer Verlag Berlin, Heidelberg 95: 295-316, 2004
[3] L. Pravdova et al. SPIE MEASUREMENT SYSTEMS FOR INDUSTRIAL INSPECTION IX Book Series: Proceedings of SPIE Volume: 9525, 95254K, 2015