Quantum Electronics **46** (3) 281 – 282 (2016)

OPTICAL FREQUENCY STANDARDS

DOI: 10.1070/QEL15987

Stabilisation of a femtosecond frequency standard using a Michelson interferometer*

E.V. Baklanov, A.K. Dmitriev

Abstract. **We propose an optical frequency standard based on a femtosecond laser, in which the shift of the frequency comb is controlled using a Michelson interferometer.**

Keywords: *quantum metrology, femtosecond laser, optical frequency synthesiser, Michelson interferometer.*

1. Introduction

At present many frequency standards make use of femtosecond lasers that generate a periodic train of short pulses in the mode-locking regime. Since the pulse repetition rate is mastered by an etalon microwave oscillator, the optical frequencies of the laser appear to be precisely calibrated in the units of its frequency. A large number of laser equidistant modes overlap the frequency range from microwave to visible light. In fact, we obtain an optical scale for the absolute measurement of frequencies in the above range. One of the main problems in the implementation of such a scale is to remove the offset common for all frequencies, which is often referred to as the CEO (carrier-envelope offset). Therefore, for precise knowledge of the optical frequency scale one has to stabilise the pulse repetition rate and eliminate the CEO of the frequency comb.

One of the main problems in constructing femtosecond frequency standards is the phase locking of the frequency of the etalon microwave oscillator to the frequency comb of the femtosecond laser. Commonly this problem is solved by means of an optical frequency synthesiser using a f–$2f$ interferometer [1, 2]. Another method of controlling the frequency comb is based on using an external high-Q resonator [3, 4]. In this case, the repetition rate and the CEO are stabilised simultaneously. This method provides a high short-term stability, but the absolute values of the laser frequencies remain undetermined.

In our papers [5, 6] we proposed to control the frequency comb offset using an external high-Q interferometer with the CEO determined from the interference pattern. In the present paper, the control of the frequency comb offset is implemented using a Michelson interferometer that detects the phase difference between the pulses and, therefore, determines the CEO. After the CEO elimination, one should stabilise only one parameter, i.e. the pulse repetition rate. This makes the implementation of the frequency standard essentially simpler as compared to the existing femtosecond standards.

2. Elimination of the CEO

The radiation in a femtosecond frequency standard is a periodic train of pulses with the spectrum consisting of a set of frequencies

$$\omega_m = m\Omega + \text{CEO}, \tag{1}$$

where m is an integer positive number; and Ω is the intermode frequency, stabilised by the microwave etalon. The origin of the CEO is related to the difference between the phase velocity and the group velocity of the pulse during the laser cavity roundtrip. The group velocity is determined by the pulse repetition rate Ω, while the phase velocity is determined by the dispersion elements in the laser cavity. Therefore, in general periodic laser pulses differ from each other, i.e., the radiation field is not a rigorously periodic function. Let i be the number of the pulse in the train. Then the shape of each pulse will be conserved, but the carrier frequency will acquire the phase shift φ_i with respect to the pulse peak, proportional to the CEO. When we measure the interference signal produced by two pulses by means of the Michelson interferometer, the additional term appears on the detector proportional to

$$\cos(\Delta\varphi)\exp(-\Delta t^2/\tau^2), \tag{2}$$

where τ is the pulse duration, $\Delta\varphi = \varphi_i - \varphi_k$ is the phase difference between the pulses, and Δt is the time delay between the pulses determined by the interferometer; for simplicity, the shape of the pulses was chosen Gaussian. For recording the signal, one can make use of the scheme, analogous to the scheme of the Hänsch – Couillaud detector [7], which is widely used in highly sensitive polarisation methods of laser frequency stabilisation [8].

Note that when the CEO equals zero, all pulses are similar and, therefore, $\Delta\varphi = 0$. Thus, the elimination of the CEO is

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[*] Reported at the Fifth Russian-Chinese Workshop and School for Young Scientists on Laser Physics and Photonics (RCWLP&P, Novosibirsk, August 26 – 30, 2015).

E.V. Baklanov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia; e-mail: baklanov.ev@gmail.com;
A.K. Dmitriev Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; Novosibirsk State Technical University, prosp. K. Marksa 20, 630073 Novosibirsk, Russia

Received 7 December 2015
Kvantovaya Elektronika **46** (3) 281 – 282 (2016)
Translated by V.L. Derbov

implemented in the following way. First, the interferometer is tuned to the signal maximum, for which $\Delta t = 0$. Then the dispersion in the laser cavity is varied to change the phase velocity of the pulses and to provide $\Delta\varphi = 0$. Usually this is achieved by varying the laser pump current.

3. Scheme of the standard

Consider the frequency standard in which the COE is eliminated using the above method. Figure 1 presents a simplified schematic of the setup. The scheme includes two control loops. The first loop is fast and keeps the repetition rate of the femtosecond laser pulses constant. It operates as follows. The radiation of a femtosecond laser (*1*) reflected from a semitransparent mirror (*2*) arrives at a high-frequency photodetector (*3*), where the intermode beats are selected, and then is passed to one of the inputs of a phase frequency locking (PFL) unit (*4*). The other input of this unit receives the signal from a synthesiser (*5*), the frequency of which is locked to a microwave etalon (*6*). The error signal from the PFL unit output is applied to a laser (*1*) piezoceramic plate that varies the length of the laser cavity and, therefore, the laser pulse repetition rate.

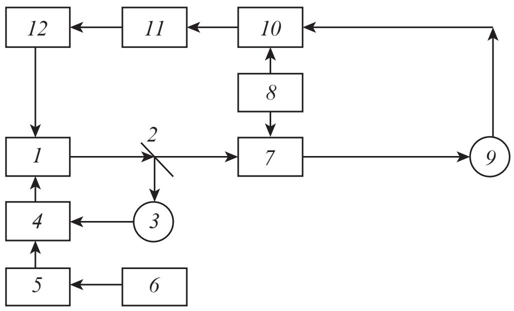

Figure 1. Stabilisation scheme for the frequency comb of the femtosecond laser:
(*1*) femtosecond laser; (*2*) beam splitter; (*3*) broad-band photodetector; (*4*) frequency reference unit; (*5*) frequency synthesiser; (*6*) microwave frequency standard; (*7*) Michelson interferometer; (*8*) saw-shaped voltage generator; (*9*) photodetector; (*10*) computer; (*11*) digital-to-analogue converter; (*12*) laser power supply.

The second control loop is slow as compared to the first one and intended to eliminate the CEO. Part of the radiation passes through the beam splitter (*2*) to the Michelson interferometer (*7*), in which the path length difference between the arms is scanned by means of a saw-shaped voltage generator (*8*) within nearly a wavelength around a specified value. The beat signal from the interferometer is recorded by a photodetector (*9*) and then processed by a computer (*10*). The feedback loop is closed by a digital-to-analogue converter (*11*) and a power supply unit (*12*) that controls the laser cavity dispersion and, therefore, the CEO.

4. Conclusions

At present the high-precision measurement of frequency is implemented using the femtosecond laser with the *f*–2*f* interferometer [1, 2]. However, for the operation of this interferometer it is necessary to have a spectral width greater than an octave. However, there are many commercial nanosecond and picosecond self-mode-locked lasers, in which the *f*–2*f* interferometer cannot be used because of a small spectral width. The simple scheme of a frequency standard proposed here is applicable for different widths of the laser radiation spectrum, which allows the extension of the considered method over the nano- and picosecond-range self-mode-locked lasers.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant Nos 15-02-02557, 14-02-00408) and the Ministry of Education and Science of the Russian Federation within the project part of the State Research Task (Project Code 1316).

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