Femtosecond laser for metrological applications

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Present situation of new applications of a femtosecond comb as metrological tool is discussed. Some of last results of worldwide investigation in this field are presented.

We have been observing reliable progress in the field of stable lasers and measurement of their frequencies. By now, there is a lot kinds of standards; lasers are controlled in the $\triangle f$/f$\sim 10^{-15}$ domain using numerous attractive quantum resonators, including Yb^+, In^+, Sr^+, Hg^+, and Mg, Ca, Sr, I_2, CH_4, OsO_4, C_2HD, and C_2H_2 [1]. In the past, standards labs had to develop complex chains of phase-related oscillators, organized to phase-coherently connect optical oscillators locked to these narrow optical resonances with frequency standards in the microwave radio frequency domain [2]. Fortunately, later, another way to link optical and radio domains was suggested. It was revolutionary new concept in frequency metrology [3]. The idea is based on use of an equidistant frequency comb generated by a mode-locked laser [4]. But in fact, it became completely realizabled recently when for the first time frequency comb of octave bandwidth was produced by propagation femtosecond radiation through an optical fibre [5,6]. Such comb contains over million components of well-known frequencies. For measuring optical frequencies, this single-laser self-calibrating frequency synthesizer can be ideal, both for metrologists interested in frequency standards and as well for the physicist interested in the properties of some special quantum transition in a special element [7]. At present several famous labs do investigations in this field by similar ways. The main difference may be contained in the kind of fibre extending comb and in the kind of reference frequency standard. One of the laser systems allowing high-precision frequency measurements to be implemented includes a mode-locked Ti:Sapphire laser, a methane-stabilized He-Ne laser, and a tapered (holey) fiber. It is being developed by ac.Bagayev‘s Russian group. As the principle of such systems is based on the operational characteristics of mode locked laser they must be highly stable. So special attention in their experiments was given to the analysis of spectral characteristics of the femtosecond frequency comb and the stability of intermode beat frequency. The servo-control system developed by them provides extremely high long term stability of the repetition rate of femtosecond pulses i.e. the frequency of intermode beats (up to x10^{-14}) [8, 9]. As mentioned above, they managed to span wave band over more than 200 nm (in accordance with frequency of HeNe/CH_4 standard $\sim$ 88.5 THz) by use of tapered fibre. The spectrum width of output of Ti:Sapphire laser was 20 nm ($\sim$ 10 THz). The present goal of their investigation is complete transmission of stability of HeNe/CH_4 to comb of Ti:Sapphire laser [10]. Author was happy by taking a little and humble part in this investigation. We should also note great results achieved by other labs. The "self-referencing" method for servo-control the repetition rate and the absolute frequency offset independently inside optical clockwork was developed at JILA and MPQ [7, 11, 12]. Thanks to their efforts, an independent research community can perform optical frequency measurements using stable femtosecond combs [13, 14].

In conclusion: It is clear at present we observe just a start of a new metrological field using ultrabroadband femtosecond combs. The stability of frequency parameters surely will be improved for future. For this it will be better if a researcher has two identical stabilized comb in order to get complete information about stability by intercomparison. Another part of present and future investigations should be a development new laser producing femtosecond comb applied at metrology in order to make more compact and more efficient optical clockworks than traditional one based on the Ti:Sapphire.

References:

[1] Bagayev S.N., Chebotaiev V.P., *Frequency Stability and Reproducibility of the 3.39 μm He-Ne Laser Stabilized on the Methane Line* (Appl. Phys., 1975, v. 7, p.71).

[2] Evenson K.M., Jennings D.A., Peterson F.R. et al. *Laser Frequency Measurements: A Review, Limitations, Extension to 197 Thz* (Springer Ser. Opt. Sci., 1977, v.7, p.56.).

[3] Bagayev S.N., Chebotaev V.P., Klementyev V.M., Pyltsin O.I. (1991, Proc. of 10th Int. Conf. on Laser Spectroscop (Font-Romeo), p.91.).

[4] Udem Th., Reichert J., Holzwarth R., Hansch T.W, *Accurate measurement of large optical frequency differences with a mode-locked laser.* (Opt. Lett., vol.24, N 13, 991 (1999).

[5] Jones D.J., Diddams S.A,. Taubman M.S, Cundiff S.T, Ma L.S., and Hall J.L., *Frequency comb generation using femtosecond pulses and cross-phase modulation in optical fiber at arbitrary center frequencies* (Opt. Lett., vol. 25, pp. 308310, 2000).

[6] Diddams S.A., Jones D.J., Ye J., Cundiff S.T.,. Hall J.L, Ranka J.K., Windeler R.S., Holzwarth R., Udem T., and Hansch T.W. *Direct link between microwave and optical frequencies with a 300 THz femtosecond laser comb* (Phys. Rev. Lett., vol. 84, pp. 51025105, 2000.).

[7] Holzwarth R., Udem T., Hansch T.W., Knight, Wadsworth W.J.,Russel P.St.J., *Optical frequency synthesizer for precision spectroscopy.* (Phys. Rev. Lett., vol. 85, pp. 22642267, 2000).

[8] S.N. Bagayev, S.V. Chepurov, V.M. Klementyev, S.A. Kuznetsov, V.S. Pivtsov, V.V. Pokasov, V.F. Zakharyash, *A femtosecond self-mode-locked Ti:sapphire laser with high stability of pulse-repetition frequency and its applications* (Appl. Phys. B, 70, 375-378 (2000).).

[9] S.N. Bagayev, S.V. Chepurov, V.M. Klementyev, D.B. Kolker, S.A. Kuznetsov, Y.A. Matyugin, V.S. Pivtsov, V.F. Zakharyash *Application of Femtosecond Lasers for the Frequency Synthesis in Radio-Optical Ranges and for the Creation of an Optical Clock.* (Laser Phys. V.11, n10, pp. 1094-1097, 2001.). 70, 375-378 (2000).).

[10] S.N. Bagayev, A.K. Dmitriev, S.V. Chepurov, A.S. Dychkov, V.M. Klementyev, D.B. Kolker, S.A. Kuznetsov, Y.A. Matyugin, M.V. Okhapkin, V.S. Pivtsov, M.N. Skvortsov,V.F. Zakharyash, T.A. Birks, W.J. Wadsworth, P.St.J. Russel, A.M. Zheltikov, *Femtosecond Frequency Combs Stabilized with a He-Ne/CH4 Laser: Toward a Femtosecond Optical Clock.* (Laser Phys. V.12, n10, pp. 1094-1097, 2001.).

[11] Jones D.J., Diddams S.A., Ranka J.K., Stentz A., Windeler R.S., Hall J.L., Cundiff S.T., *Carrier-envelope phase control of femtosecond mode-locked laser and direct optical frequency synthesis.* (Science, vol.288, pp.635-639, 2000.). 70, 375-378 (2000).).

[12] John L. Hall, Jun Ye, Scott A. Diddams, Long-Sheng Ma, Steven T. Cundiff, and David J.

Jones, *Ultrasensitive Spectroscopy, the Ultrastable Lasers, the Ultrafast Lasers, and the Seriously Nonlinear Fiber: A New Alliance for Physics and Metrology* (IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 37, NO. 12, DECEMBER 2001).

[13] Leo Hollberg, Associate Member, IEEE, Chris W. Oates, E. Anne Curtis, Eugene N. Ivanov, Scott A Diddamas, Thomas Udem, Hugh G. Robinson, James C. Bergquist, Robert J. Rafac, Wayne M. Itano, Robert E. Drullinger, and David J. Wineland., *Optical Frequency Standards and Measurements* (IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 37, NO. 12, DECEMBER 2001).