Quantum Electronics **38** (7) 613 – 614 (2008)

LETTERS

PACS numbers: 42.62.Eh; 42.72.Ai; 42.55.Lt; 42.55.Wd
DOI: 10.1070/QE2008v038n07ABEH013914

Realisation of a compact methane optical clock

M.A. Gubin, A.N. Kireev, A.V. Konyashchenko, P.G. Kryukov,
A.V. Tausenev, D.A. Tyurikov, A.S. Shelkovnikov

***Abstract*. A compact optical clock based on a double-mode He – Ne/CH_4 optical frequency standard and a femtosecond Er^{3+} fibre laser is realised and its stability against a commercial hydrogen frequency standard is measured.**

Keywords: *optical clock, fibre femtosecond laser, frequency difference generation, methan, helium – neon laser.*

Compact optical clocks with a low phase noise, high short-term stability ($10^{-14} - 10^{-15}$) and a long-term stability close to that of a hydrogen maser (H-maser) are needed for the further development of time – frequency measuring methods in radioastronomy, navigation, for the development of frequency standards on laser cooled atoms or ions, etc.

A new generation of compact double-mode 3.39-μm He – Ne lasers stabilised to saturation absorption/dispersion resonances in methane [He – Ne/CH_4 optical frequency standard (OFS)] with a short-term stability 1×10^{-14} for 1 s [1] is one of the candidates as a master oscillator in such clocks. An increase in a passive resonator stability by two – three orders of magnitude and control of external conditions, which is possible with the monoblock sitall cavity, can also improve the long-term stability of the methane OFS up to required values.

Since 2000 passively mode-locked femtosecond lasers have been used to transfer the high stability of optical standards to the microwave domain, and optical clocks of a new generation have been realised for the first time in Garsching and in Boulder with the help of a femtosecond 0.8-μm Ti : sapphire laser [2]. The emission spectrum of such lasers consists of a comb of equidistant optical components with the frequencies $\nu_m = mf_{\rm rep} + f_0$, where $m \sim 10^6$ is an integer; $f_{\rm rep}$ is the pulse repetition rate; f_0 is the comb frequency offset with respect to the zero frequency; $f_{\rm rep}$ and f_0 lie within the radiofrequency (RF) range. This expression provides a direct optical – microwave phase-coherent relation by controlling two comb parameters – $f_{\rm rep}$ and f_0 [2].

If the optical standard frequency $\nu_{\rm st}$ is smaller than the comb width, the optical clock scheme can be significantly simplified by eliminating the quantity f_0 by converting the comb spectrum in a nonlinear crystal [3, 4]. If the crystal is phase-matched for the comb components with a frequency difference close to $\nu_{\rm st}$, a new comb can be obtained at difference frequencies in the mid IR range overlapping with the frequency $\nu_{\rm st}$. Because the frequencies of two regions of the initial comb are $\nu_m = (mf_{\rm rep} + f_0)$ and $\nu_n = (nf_{\rm rep} + f_0$, we have the frequencies of the new IR comb $\nu_k = kf_{\rm rep}$, where $k = m - n$. There is no dependence on f_0 in this relation and by generating a beat signal between the IR comb and the optical standard, we establish direct phase coherence between the frequencies $f_{\rm rep}$ and $\nu_{\rm st}$: $f_{\rm b} = \nu_{\rm st} - kf_{\rm rep}$, where $f_{\rm b}$ is the beat signal frequency also falling to the RF range.

An optical clock based on the He – Ne/CH_4 OFS and a femtosecond Ti : sapphire laser with application of difference frequency generation (DFG) is described in [4], where the prospects of such a clock as a master microwave oscillator with a low level of phase noise are shown. However, serious drawbacks of femtosecond Ti : sapphire lasers (a bulky and expensive pump laser, a problem of maintenance of stable long-term operation, etc.) stimulated the development of a ‘clockwork’ based on reliable and relatively low cost femtosecond fibre lasers [5].

In the present work we realise for the first time to our knowledge a compact optical methane clock based on the following scheme: master oscillator (double-mode He – Ne/CH_4 OFS), frequency converter (femtosecond Er^{3+} fibre laser system) and an interface between them [periodically poled lithium niobate (PPLN) crystal].

The femtosecond fibre laser system used in our experiment is similar to that described in [6]. It includes a 1.55-μm femtosecond Er^{3+} fibre oscillator with a pulse repetition rate $f_{\rm rep} = 62$ MHz, an Er^{3+} fibre amplifier and a 0.5-m piece of a highly nonlinear fibre where a supercontinuum in the 1.0 – 2.0 μm range is generated (Fig. 1a). A DFG comb was obtained in the PPLN crystal during the interaction of radiation from two spectral regions (1.06 and 1.55 μm) of the initial comb. The resulting emission appeared at ~ 3.4 μm and had the spectral width of ~ 50 nm

---

M.A. Gubin, A.N. Kireev, D.A. Tyurikov, A.S. Shelkovnikov
P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia;
e-mail: gubin@sci.lebedev.ru, kireev@okb.lpi.troitsk.ru;
A.V. Konyashchenko P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; Avesta-Project Ltd., ul. Solnechnaya 12, 142190 Troitsk, Moscow region, Russia;
P.G. Kryukov P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia; e-mail: kryukov@fo.gpi.ru;
A.V. Tausenev P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; Fiber Optics Research Center, Russian Academy of Sciences, ul. Vavilova 38, 119333 Moscow, Russia; Avesta-Project Ltd., ul. Solnechnaya 12, 142190 Troitsk, Moscow region, Russia

Received 3 June 2008
Kvantovaya Elektronika **38** (7) 613 – 614 (2008)
Translated by A.N. Kireev

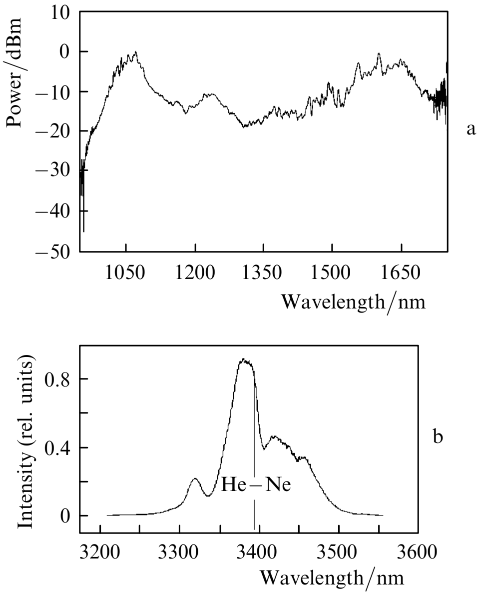

Figure 1. Supercontinuum emission spectrum in a highly nonlinear fibre (spectral resolution 2 nm) (a) and the emission spectrum of the DFG comb after the PPLN crystal (resolution 4 nm) (b).

(Fig. 1b). The total power of the IR comb was about 20 μW, corresponding to the power P_k of a single spectral component ~ 1 nW.

The phase locking of the Er^{3+} fibre laser was performed by using a 1.3-mW single mode He–Ne heterodyne laser, which was phase coherently locked to the He–Ne/CH_4 standard. A beat signal between the radiation frequencies of the He–Ne laser and the kth component of the IR comb was recorded with a photodetector at the beat frequency $f_{\mathrm{b}} = kf_{\mathrm{rep}} - \nu_{\mathrm{He-Ne}}$ with a signal-to-noise ratio 25–30 dB in the 100-kHz bandwidth (Fig. 2). The beat signal was filtered, amplified and phase locked to a quartz oscillator at the frequency 4 MHz. A phase-lock loop feedback bandwidth was limited to ~ 50 kHz by resonances of a piezoelectric transducer used to control the Er^{3+} laser cavity length.

In the case of the phase locked regime the radiofrequency f_{rep} is directly expressed in terms of the optical frequency $\nu_{\mathrm{He-Ne}}$: $f_{\mathrm{rep}} = (\nu_{\mathrm{He-Ne}} + 4\ \mathrm{MHz})/k$, and because the frequency $\nu_{\mathrm{He-Ne}}$ is locked to the frequency ν_{st} of the He–Ne/CH_4 standard f_{rep} in its turn is stabilised to the He–Ne/CH4 OFS. By knowing k (in our case $k = 1415468$) and measuring f_{rep} against a microwave frequency standard one can determine the He–Ne laser absolute frequency $\nu_{\mathrm{He-Ne}}$ from the expression for f_{rep} with accuracy provided by this standard.

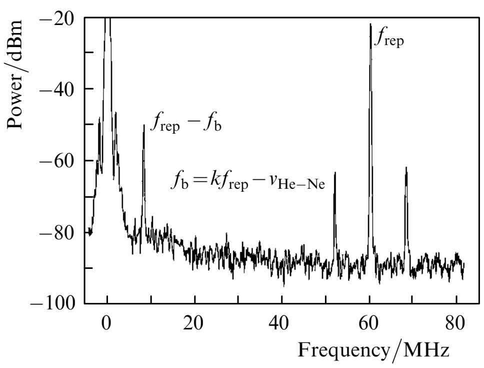

Figure 2. Radiofrequency beat spectrum of the He–Ne heterodyne radiation frequency and a neighbouring mode of the IR comb (resolution bandwidth 100 kHz).

The optical clock signal at the frequency f_{rep} or its harmonics was detected independently from the fibre output of the Er^{3+} laser. Stability of the optical clock signal represented by f_{rep} was compared with a signal of the Ch1-1006 hydrogen maser. The maser and the optical clock signals were mixed resulting in the difference frequency ~ 28 kHz. The instability of this difference frequency is shown in Fig. 3 by triangles. The squares correspond to the maser intrinsic instability. Also, the result of comparison of two He–Ne/CH_4 OFS, one of which is used in this experiment, is shown (circles) [1]. One can see from these data that for averaging times $\tau \leqslant 30$ s, the methane clock instability is determined by the frequency instability of the H-maser and is $6 \times 10^{-13}\tau^{-1/2}$. For longer averaging times, frequency drifts of the He–Ne/CH_4 OFS dominate.

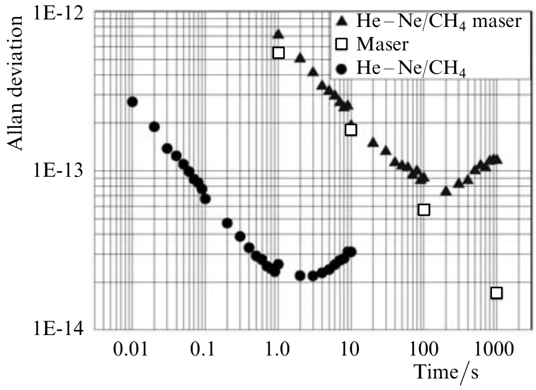

Figure 3. Allan deviations for the optical clock radiofrequency signal against the maser (▲), the maser intrinsic instability (■), the He–Ne/CH_4 OFS intrinsic instability (●).

Acknowledgements. The authors thank V.N. Sorokin for providing the hydrogen maser. This work was partially supported the Russian Foundation for Basic Research (Grant No. 06-02-16999), the Presidium of the Russian Academy of Sciences (Femtosecond Optics and New Optical Materials Program), and the Department of General Physics, Russian Academy of Sciences (Spectroscopy and Quantum Frequency Standards Program).

References

1. Gubin M.A., Shelkovnikov A.S., Kovalchuk E.V., Krylova D.D., et al., in *Proc. 1999 Joint Meeting EFTF/IEEE IFCS* (Besancon, France, 1999) p. 710.
2. Hall J.L. *Usp. Fiz. Nauk*, **176** (12), 1353 (2006); Hänsch T.W. *Usp. Fiz. Nauk*, **176** (12), 1368 (2006).
3. Zimmermann M., Gohle C., Holzwarth R., Udem T., Hänsch T.W. *Opt. Lett.*, **29**, 310 (2004).
4. Foreman S., Marian A., Ye J., Petrukhin E., Gubin M., Mücke O., Wong F., Ippen E., Kaertner F. *Opt. Lett.*, **30**, 570 (2005).
5. Washburn B.R., Diddams S.A., Newbury N.R., Nicholson J.W., Yan M.F., Jorgensen C.G. *Opt. Lett.*, **29**, 250 (2004).
6. Gubin M.A., Kireev A.N., Tausenev A.V., Konyashchenko A.V., Kryukov P.G., Tyurikov D.A., Shelkovnikov A.S. *Laser Phys.*, **17**, 1286 (2007).