Quantum Electronics **50** (12) 1155–1159 (2020)

LASER FREQUENCY STANDARDS

https://doi.org/10.1070/QEL17437

Radiofrequency synthesiser with an intrinsic instability of 5×10^{-15} at the averaging time of 1 s based on a femtosecond erbium-doped fibre laser

A.N. Kireev, A.S. Shelkovnikov, A.V. Tausenev, D.A. Tyurikov, M.A. Gubin

Abstract. **A radio-optical synthesiser intended for operation in a radio-frequency master oscillator with an optical He–Ne/CH$_4$ frequency standard (λ = 3.39 μm) is developed on the basis of a femtosecond erbium-doped fibre laser. The synthesiser generates equidistant harmonics in the frequency range of 1–10 GHz with stability determined by the optical frequency standard. A stable supercontinuum spectrum is formed in the range around 1.06 μm, which provides stable 24-hour operation of the synthesiser and is important for practical applications in off-laboratory conditions. A direct comparison of the output frequencies of two synthesisers shows that the up-grade of the fibre laser and detection system of femtosecond pulses results in the synthesiser intrinsic instability of 5×10^{-15} at the averaging time of 1 s. Such a value is by an order of magnitude less than that obtained in our earlier works.**

Keywords: *femtosecond synthesiser, fibre laser, He–Ne/CH$_4$ frequency standard, ultra-low phase noise microwave generator.*

1. Introduction

Synthesisers of optical- and radio-frequencies based on femtosecond lasers have been actively developed in the last 20 years [1, 2] and have now become a necessary laboratory instrument in precision frequency-time and spectroscopic measurements. These have proved the ability to efficiently transfer the accuracy and stability of an optical oscillator frequency both within the optical range and from this range to the radio-frequency spectral range [3–7]. The requirements to femtosecond synthesiser parameters (the intrinsic noise and introduced frequency–phase inaccuracy) and its structural scheme are mainly related to particular applications, the operation frequency range, and the standard that defines the frequency stability and accuracy.

Femtosecond synthesisers are complicated laser optical systems, which often require laboratory conditions; therefore, one way of their improvement is to provide the reliability, compactness, and transportability particularly. In any case, the main requirement is that the intrinsic instability of a femtosecond synthesiser should not noticeably contribute into the process of transferring the frequency stability of the standard considered.

The greatest progress in the development of femtosecond synthesisers is obtained in the optical spectral range. In [8], the time scale based completely on optical technologies was demonstrated. It comprised an optical frequency standard on ^{87}Sr atoms in an optical lattice with a stability of $3.5 \times 10^{-17}/\tau^{1/2}$, where τ is the averaging time in seconds. The included femtosecond synthesiser, which locks the optical frequencies employed (or wavelengths of 0.698 and 1.542 μm) has an intrinsic instability of 1.6×10^{-18} at $\tau = 1$ s [6].

One more important application of femtosecond lasers is the development of radio-frequency sources on their basis. The transfer from the optical to radio-frequency range occurs through photodetection of an instantaneous series of femtosecond light pulses with the following selection of microwave spectral harmonics. An interval between the harmonics is defined by the pulse repetition rate, and the width of the observed spectrum is related to the photodetector response time. The frequency stability of harmonics at the photodetector output is substantially lower than that of components of the femtosecond synthesiser optical spectrum. The reduction in the stability is related to photodetector saturation by high-energy pulses and conversion of femtosecond laser amplitude noise to radio-frequency phase noise in the process of photodetection [9].

Femtosecond radio-frequency synthesisers having the highest stability level ($\sim 6 \times 10^{-16}$ at $\tau = 1$ s) are complicated optical systems that operate in laboratory conditions [7, 10]. Measurements of their characteristics is a particular problem that requires the development of unique specialised radio-frequency devices.

However, there are applications, which require femtosecond synthesisers of lower stability (10^{-14}–10^{-15} at $\tau = 1$ s), capable of operating in off-laboratory conditions for replacing conventional quartz oscillators and masers. These are transportable time and frequency standards on ‘fountains’ of cold atoms, next-generation fast communication lines, coherent radars, radioastronomy, and other applications [11–14].

The present work is aimed at studying the intrinsic instability of femtosecond erbium-doped fibre synthesisers developed for transferring the frequency stability of a compact He–Ne/CH$_4$ laser from the optical to radio-frequency spectral range.

Paper [15], which is the most close to the subject, describes a compact, transportable radio-optical oscillator based on a low-noise femtosecond erbium synthesiser stabilised by an optical resonator fabricated from ULE glass. Presently, this

---

A.N. Kireev, A.S. Shelkovnikov, A.V. Tausenev, D.A. Tyurikov Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: shelkov@lebedev.ru;
M.A. Gubin Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; Federal State Unitary Enterprise ‘All-Russian Scientific Research Institute of Physical-Technical and Radiotechnical Measurements’, 141570 Mendeleevo, Moscow region, Russia

Received 14 September 2020; revision received 12 October 2020
Kvantovaya Elektronika **50** (12) 1155–1159 (2020)
Translated by N.A. Raspopov

system synthesising high-stable microwave signals in the frequency range of 2–12 GHz is suggested as a commercial product [16]. Its important feature is a compact system, which occupies part of the instrument rack, and softer requirements to stability of external conditions as compared to stationary laboratory devices arranged on optical tables in rooms equipped with conditioners.

In our paper [17], a femtosecond erbium-doped fibre synthesiser has been described with a frequency instability (Allan deviation) around 5×10^{-14} at $\tau = 1$ s at a carrying frequency of 1.5 GHz. In measurements, a filter with a 100-Hz band was placed at the frequency counter input. The synthesiser is included into the radio-optical master oscillator based on a stabilised He–Ne/CH_4 laser. The experiment with the employment of a 'methane' master oscillator as a reference 100-MHz frequency source was performed on a complex of caesium and rubidium 'fountains' at VNIIFTRI [18]. The stability of a 100-MHz output frequency of the master oscillator was limited by a commercial radio-synthesiser employed and was 3×10^{-14} ($\tau = 1$ s) according to measurements on a comparator with a bandwidth of 3 Hz.

While carrying out long measurements at VNIIFTRI we have observed nonstationary occasional spikes in the frequency of the femtosecond synthesiser, which limited the stability of the methane radio-oscillator as a whole. In the present work, the intrinsic short-term frequency stability and operation stability of the femtosecond erbium-doped fibre synthesisers are substantially improved due to modification of the latter.

2. Design and operation features of femtosecond erbium synthesiser

A schematic of a synthesiser is shown in Fig. 1. The synthesiser is based on a femtosecond erbium-doped fibre laser (λ = 1.55 μm), the repetition rate of which is stabilised by an optical He–Ne/CH_4 frequency standard (λ = 3.39 μm). To this end, the erbium laser spectrum is transferred to the range λ = 3.39 μm by difference frequency generation of the radiations with wavelengths of 1.06 and 1.55 μm, which are formed at the synthesiser optical output [19, 20]. The difference frequency is generated in a periodically poled lithium niobate crystal with a period of 30.45 μm.

The femtosecond erbium laser is fabricated by using only polarisation-maintaining fibres. The mode locking regime is realised due to Kerr nonlinearity in a Sagnac interferometer (a nonlinearly reflecting loop mirror). The pulse repetition rate of the laser is 58.9 MHz, spectrum width is 38 nm, average power is 40 mW, and pulse duration is 110 fs. For stabilising the pulse repetition rate, the end mirror of the cavity is arranged on a piezoelectric transducer capable of moving the mirror by 10 μm and realises the feedback in a bandwidth of 20 kHz. An electro-optical phase modulator fabricated from lithium niobate is arranged on a linear part of the cavity, which extends the feedback bandwidth to 400 kHz. Long-term fluctuations of the pulse repetition rate are compensated for by varying the temperature of a small part of the fibre with the help of a Peltier element.

The erbium laser radiation is divided into two parts of equal power. One part is amplified to a power of 20 mW and is used for generating a radio-frequency output signal of the synthesiser. The other part of radiation is used for forming an optical signal of the synthesiser. For this purpose, it is amplified in a fibre amplifier to a power of 250 mW and split by a fibre power splitter with an 80/20 ratio. The pulses from the 20% splitter output are compressed in a fibre with negative dispersion to a duration of 150 fs and serve as the optical output signal at λ = 1.55 μm. Pulses from the 80% output are compressed to a duration of 300 fs and pass to a germanium-silicate fibre possessing a high nonlinearity, where supercontinuum is generated with a peak at λ = 1.06 μm.

A particular attention was paid to the stability of a supercontinuum spectrum in the range of 1.06 μm. The shift of supercontinuum peak to the short-wavelength side depends on both fibre parameters (dispersion, its slope, and others) and parameters of input pulses (power, duration, and chirp) [21]. If the fibre parameters are not optimal, the spectrum can be shifted to a desired wavelength by varying the power of a pulse introduced into the fibre; however, a power excess results in a non-smooth structure of the spectrum obtained. Finally, small variations of the parameters of input pulses result in hopping variations of the spectrum shape, which stipulates non-stationary pulsed spikes of the output radiofrequency. Typical examples of two unstable spectra of supercontinuum are given in Fig. 2.

With a fibre thoroughly chosen to optimally match the parameters of the optical pulses, a stable smooth supercontinuum spectrum has been realised with a clearly defined peak at λ = 1.06 μm and absent interfering oscillations (Fig. 3). The peak amplitude and position of the centre wavelength smoothly (without spikes) varied by varying laser parameters. The nonlinear fibre has the following characteristics: the dispersion is 10 ps km^{-1} nm^{-1}, mode field diameter is 3.75 μm at a wavelength of 1.55 μm, zero-dispersion wave-

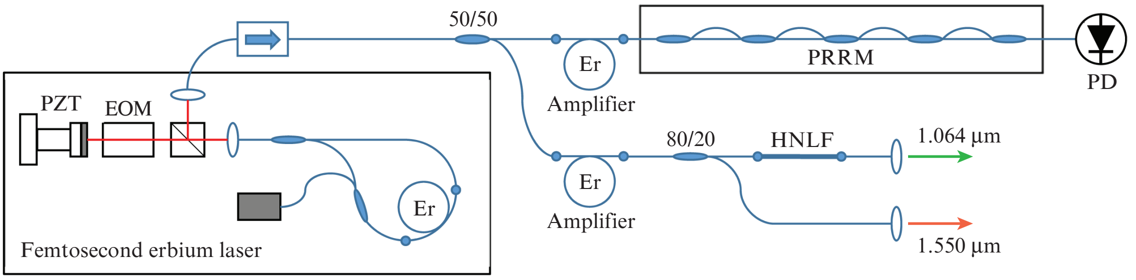

Figure 1. Schematic of a femtosecond synthesiser:
(PZT) piezoelectric transducer; (EOM) electro-optical modulator; (HNLF) highly nonlinear fibre; (PRRM) pulse repetition rate multiplier (a set of four Mach–Zehnder interferometers); (PD) photodetector.

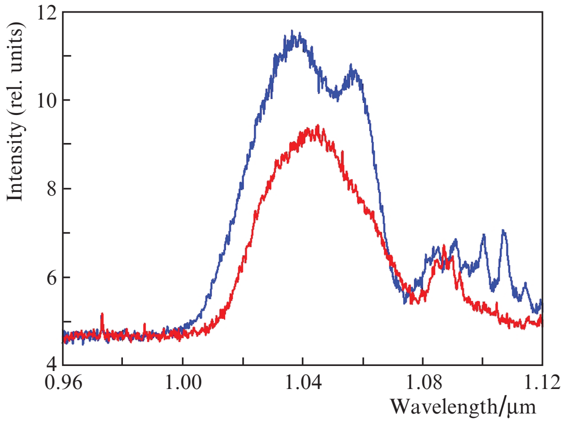

Figure 2. Typical examples of two unstable supercontinuum spectra in the range of 1.06 μm with a non-smooth structure. Random jumps from one spectrum to another lead to pulse spikes in the output radio-frequency.

length is 1.32 μm, and dispersion slope is 0.07 ps km^{-1} nm^{-1}. This modification allowed one to reliably make long-term measurements and obtain stable results at long averaging times.

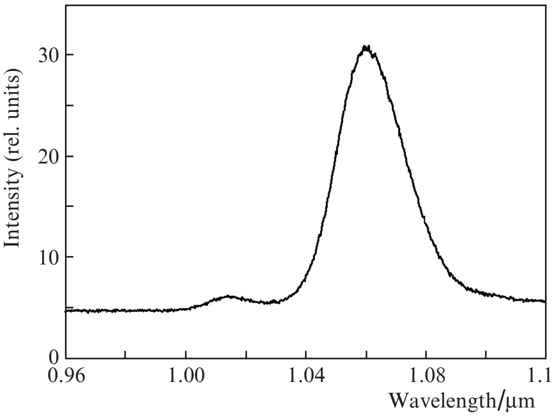

Figure 3. Stable smooth spectrum of a supercontinuum in the range of 1.06 μm.

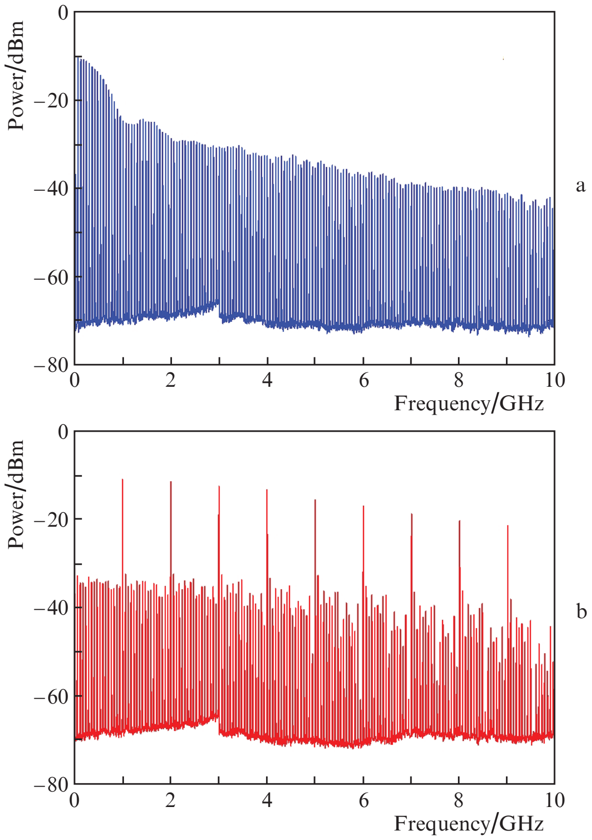

Figure 4. Spectra of the radio-signal at photodetector output (a) without optical filtering and (b) with the optical filtering. The spectrum analyser bandwidth is 1 MHz.

The synthesiser output radio-signal formed by an optical radiation on a photodetector (see Fig.1) is an instantaneous series of picosecond-duration pulses with a stabilised pulse repetition rate. A spectrum of an instantaneous pulse series is a radio-frequency comb with the interval equal to the pulse repetition rate (Fig. 4a) and width determined by the photodetector bandwidth, which in our case is 10 GHz (DSC50S, Discovery Semiconductors). Any spectral component can be used as the synthesiser output signal. One should keep in mind that the signal power is distributed over all spectral components and due to a relatively low pulse repetition rate of the fibre oscillator it is difficult to obtain the required signal-to-noise ratio for a separate component. A simple increase in the radiation power results in photodetector saturation. The saturation problem is solved by employing a highly linear photodetector and the off-cavity multiplication of the femtosecond pulse repetition rate, which results in decimation of the radio-frequency spectrum with energy redistribution between components [22].

In the present work, for increasing the pulse repetition rate (with the corresponding reduction of the energy of a single pulse) and spectrum decimation, the radiation of the femtosecond erbium laser passed through four Mach–Zehnder fibre interferometers (see Fig. 1). For further employment of the synthesiser, its output frequencies should be harmonics that are multiples of 1 GHz, in our case, multiples of the 17th harmonic of the pulse repetition rate. The most efficient filtering is attained for the 16th harmonic; however, the 17th harmonic made it possible to employ the femtosecond laser without substantial construction changes. Filtering was realised by choosing the corresponding delays in arms of the Mach–Zehnder interferometers. Suppression of other harmonics of the repetition rate did not exceed 24 dB because the number of the selected harmonic was not divisible by 16. A subsampled spectrum after the cascade of the fibre interferometers is shown in Fig. 4b. This procedure reduced photodetector saturation and increased the power of selected (multiple of the frequency of 1 GHz) harmonics of a radio-frequency spectrum, which raised the signal-to-noise ratio by at least 20 dB.

3. Comparison of signals from two synthesisers

The intrinsic instability of an output frequency of a femtosecond synthesiser was found from direct comparison of two identical systems. The pulse repetition rates of the femtosecond lasers comprised in the systems differed by approximately 120 Hz. A scheme of the experiment (Fig. 5) is similar to that from [17], where signals from the two heterodyne lasers ‘locked’ to a single stabilised He–Ne/CH_4 laser passed to inputs of the synthesisers. The present experiment differs in that an erbium amplifier and fibre multiplier of the pulse repetition rate are arranged at the output of the femtosecond laser. For a synthesiser output signal, the second harmonic of the multiplied frequency (2.0 GHz or the 34th harmonic of the pulse repetition rate of the femtosecond erbium laser) selected by a narrow-band filter was used. Then, the signals of two synthesisers were amplified and passed to a mixer. The difference frequency of 4 kHz after amplification and filtration (by a filter with bandwidth of 200 Hz) was measured by a frequency counter HP53132A. The intrinsic instability of the femtosecond erbium synthesisers was determined from these measurements. Since the reference source of a stable frequency for two synthesisers was the same He–Ne/CH_4 laser, a contribution of its own instability can be neglected.

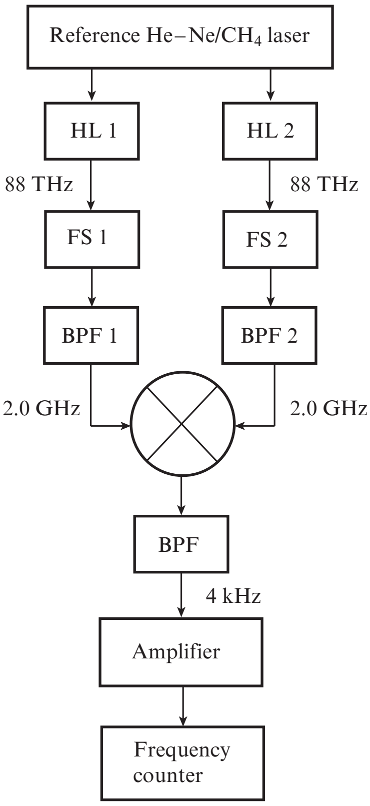

Figure 5. Scheme of the experiment:
(HL) heterodyne laser; (FS) femtosecond synthesiser; (BPF) band-pass filter.

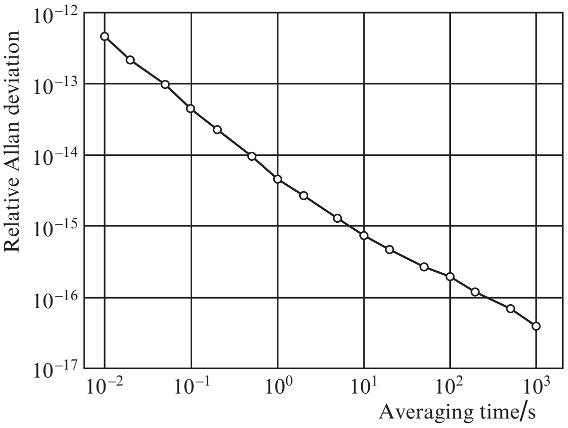

Figure 6. Relative Allan deviation for the femtosecond synthesiser output frequency of 2 GHz.

The instability of the output frequency of 2 GHz (Allan deviation) of a femtosecond erbium laser recalculated to a single system is presented in Fig. 6. The calculation was made under the assumption that the two systems are independent and similar. Each point on the Allan deviation curve corresponds to a data series with at least 80 samples at averaging times greater than 100 s. For example, a series with the averaging time of 1000 s has 82 samples of measured frequency, that is, the measurements lasted for almost 24 hours.

As compared to the previous variant of a femtosecond erbium synthesiser [17], the substantially lower relative Allan deviation was observed, which was 5×10^{-15} at the averaging time of 1 s in the present experiment.

4. Conclusions

A radio-frequency synthesiser was developed in the range of 1–10 GHz on the basis of a femtosecond erbium-doped fibre laser. Stable 24-hour synthesiser operation without frequency spikes was demonstrated. The intrinsic instability (Allan deviation) measured at the output frequency of 2 GHz was 5×10^{-15} at an averaging time of 1 s. It proved to be less by an order of magnitude than the value from [17]. The instability of the femtosecond radio-frequency synthesiser was less than that of the He–Ne/CH_4 optical frequency standard and did not prevent the obtaining of the short-term instability of 1×10^{-14} (τ = 1 s) for a methane master oscillator, which is important for its off-laboratory applications.

References

1. Hall J.L. *Rev. Mod. Phys.*, **78**, 1279 (2006).
2. Hänsch T.W. *Rev. Mod. Phys.*, **78**, 1297 (2006).
3. Udem T., Holzwarth R., Hänsch T.W. *Nature*, **416**, 233 (2002).
4. Diddams S.A., Jones D.J., Ye J., Cundiff S.T., Hall J.L., Ranka J.K., Windeler R.S., Holzwarth R., Udem T., Hänsch T.W. *Phys. Rev. Lett.*, **84**, 5102 (2000).
5. Diddams S.A., Bartels A., Ramond T.M., Oates C.W., Bize S., Curtis E.A., Bergquist J.C., Hollberg L. *IEEE J. Sel. Top. Quantum Electron.*, **9**, 1072 (2003).
6. Oelker E. et al. *Nat. Photonics*, **13**, 714 (2019).
7. Xie X. et al. *Nat. Photonics*, **11**, 44 (2017).
8. Milner W.R. et al. *Phys. Rev. Lett.*, **123**, 173201 (2019).
9. Zhang W., Li T., Lours M., Seidelin S., Santarelli G., Le Coq Y. *Appl. Phys. B*, **106**, 301 (2012).
10. Zhang W., Seidelin S., Joshi A., Datta S., Santarelli G., Le Coq Y. *Opt. Lett.*, **39**, 1204 (2014).
11. Ghelfi P. et al. *Nature*, **507**, 341 (2014).
12. Sinclair L.C. et al. *Appl. Phys. Lett.*, **109**, 151104 (2016).
13. Millo J., Abgrall M., Lours M., English E.M.L., Jiang H., Gúna J., Clairon A., Tobar M.E., Bize S., Le Coq Y., Santarelli G. *Appl. Phys. Lett.*, **94**, 141105 (2009).

14. Nand N.R., Hartnett J.G., Ivanov E.N., Santarelli G. *IEEE Trans. Microwave Theory Tech.*, **59**, 2978 (2011).
15. Giunta M., Yu J., Lessing M., Fischer M., Lezius M., Xie X., Santarelli G., Le Coq Y., Holzwarth R. *Opt. Lett.*, **45**, 1140 (2020).
16. http://www.menlosystems.com/products/ultrastable-microwaves/pmwg-1500/.
17. Kireev A.N. et al. *Quantum Electron.*, **46**, 1139 (2016) [*Kvantovaya Elektron.*, **46**, 1139 (2016)].
18. Shelkovnikov A.S. et al. *Quantum Electron.*, **49**, 272 (2019) [*Kvantovaya Elektron.*, **49**, 272 (2019)].
19. Gubin M.A., Kireev A.N., Tausenev A.V., Konyashchenko A.V., Kryukov P.G., Tyurikov D.A., Shelkovikov A.S. *Laser Phys.*, **17**, 1286 (2007).
20. Gubin M.A., Kireev A.N., Konyashchenko A.V., Kryukov P.G., Shelkovikov A.S., Tausenev A.V., Tyurikov D.A. *Appl. Phys. B*, **95**, 661 (2009).
21. Herrmann J., Griebner U., Zhavoronkov N., Husakou A., Nickel D., Knight J.C., Wadsworth W.J., Russell P.St.J., Korn G. *Phys. Rev. Lett.*, **88**, 173901 (2002).
22. Haboucha A., Zhang W., Li T., Lours M., Luiten A.N., Le Coq Y., Santarelli G. *Opt. Lett.*, **36**, 3654 (2011).