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Frequency Stabilization of a Primary Subterahertz Oscillator by a Frequency Comb of a Femtosecond Laser

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The frequency of a primary subterahertz oscillator has been phase locked with the use of the equidistant components of a broad spectrum produced by a femtosecond laser. The optical-to-terahertz down-conversion of the laser pulse train and its mixing with subterahertz radiation has been performed at a Schottky diode. This work provides the opportunity of creating a principally new generation of frequency synthesizers with the desired power and phase noise a few orders of magnitude lower than that of their traditional analogues.

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Laser frequency combs generated by femtosecond lasers have opened new horizons in the accuracy of frequency and time standards. The laser combs provide the most accurate frequency measurement from the RF to near ultraviolet range with the use of nonlinear sum and difference frequency generation [1]. As was shown in [2, 3], the implementation of fast phase-locked loop provides the intrinsic width of each component of the optical comb, which is two orders of magnitude narrower than the limit specified by the quantum noise of the laser. The absolute width of the component spectrum and its frequency stability are given by the respective parameters of the reference oscillator to which the entire comb is phase-locked. Such a source may be provided by, e.g., an optical frequency standard [4], which has a radiation spectrum width of ~0.6 Hz with an averaging period of 32 s and a 1-s frequency stability of $\sim 3 \times 10^{-16}$.

It should be mentioned that laser combs have already been used for both precision measurements and the generation of a coherent CW subterahertz/submillimeter radiation. Goyette et al. [5] and Yasui et al. [6] showed that an optical comb with a width of several terahertz may be converted to the submillimeter range with the use of a GaAs-based photoconductive antenna (PCA) and that the components of the comb can be used for high-resolution spectroscopy. Yasui et al. [7] also reported the implementation of a terahertz spectrum analyzer, which uses the components of a frequency comb generated by a fiber-optic femtosecond laser in the photoconductive antenna as a heterodyne. They further demonstrated the opportunity of analyzing signals with about one-hertz spectrum width and demonstrated that the accuracy of the frequency measurement of these signals is determined by the precision of the used frequency standard. Song et al. [8] presented a high-coherency tunable broadband CW subterahertz (0.1–1 THz) source based on a laser comb, the required components of which were selected by arrayed waveguide gratings and the subterahertz difference frequency was reemitted by a photoconductive antenna; a high spectral purity and low phase noise of the generated signals were demonstrated. Mouret et al. [9] synthesized terahertz radiation from a PCA-produced difference frequency of two CW diode lasers phase-locked to the respective components of the femtosecond laser comb. Owing to the low efficiency of the optical-to-subterahertz down-conversion, the power of the generated radiation in both setups [8, 9] was about one microwatt in the low-frequency part of the operation range and hundreds of nanowatts near one terahertz. In many applications (high-precision spectroscopy, radars, active remote sensing, etc.), this low power would cause the loss of the usability of such sources.

The laser comb components can be used as reference signals for the frequency stabilization of CW oscillators. In this case, the ultimate spectral purity and stability of the comb are transferred to the radiation of the CW source. In this work, we report the application of the frequency comb produced by a femtosecond laser for phase-locking a primary CW subterahertz oscillator with a sufficient power. This requires the conversion of the optical comb to the terahertz range and the use of one of the produced terahertz comb components for the phase-locking of the terahertz source.

The block diagram of the setup based on the above idea is shown in Fig. 1. The commercial OB-71 backward wave oscillator (BWO) (Istok, Fryazino, Moscow region) with a typical power of about 10 mW and an operation frequency of 78–118 GHz was used as a CW

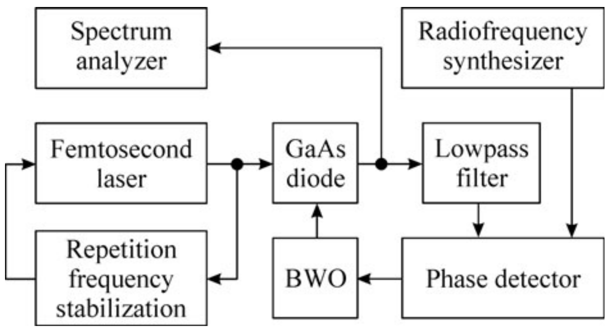

Fig. 1. Block diagram of the experimental setup.

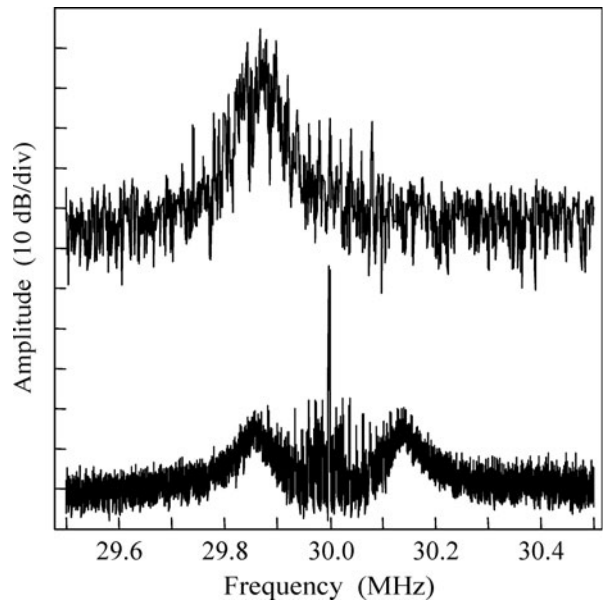

Fig. 2. Spectra of the intermediate frequency signal of the phase-locked loop, which correspond to the mutual beating of the BWO signal at a frequency of about 100 GHz and the 1092nd component of the terahertz comb (lower spectrum) with and (upper spectrum) without the frequency stabilization.

submillimeter source. The optical frequency comb was produced by the radiation of a Ti:Sapphire femtosecond laser with a pulse length of ~50 fs, an average power of ~100 mW, and a stabilized pulse repetition rate. The repetition rate of 91 577000.000 Hz was stabilized by the phase-locked loop against the Agilent E8257D microwave signal generator synchronized with the rubidium frequency standard. The optical-to-terahertz down-conversion of the laser comb to the millimeter/submillimeter range was performed with the use of a commercial Salyut A91147 planar microwave Schottky diode with a guaranteed cutoff frequency of 2–5 THz. The laser radiation was focused onto a GaAs semiconductor in the contact region of the diode, which led to the appearance of subpicosecond pulses in the concentration of photoinduced carriers. The concentration and, consequently, conductivity pulses formed the comb of reference terahertz frequencies, whereas the stability of the optical comb period assured the stability of the terahertz comb [6]. The diode was mounted at the open edge of the waveguide of the wideband submillimeter mixer/multiplier (see review [10] and references therein). The radiation from the BWO was supplied through the waveguide to the rare side of the diode, whose leads worked as a receiving antenna. Since the current through the diode was proportional to the product of the conductivity and intensity of the BWO radiation, the beating between the BWO signal and the respective component of the terahertz comb appeared at the diode [11]. The amplitude of the beating signal was sufficient for phase locking the BWO radiation frequency with the use of the previously developed synchronizer [12], which we modified for the present experiment. In particular, the operating beating frequency (the intermediate frequency of the phase-locked loop) was reduced to 30 MHz and the phase detector of the synchronizer worked at the same frequency. In addition, the low-pass filter with a cutoff frequency of 80 MHz was mounted at the input of the synchronizer to prevent the terahertz comb components from entering the phase detector. The bandwidth of the input beating signal amplifier was about 10 MHz, which provided a sufficient decoupling from the mirror channel beating and the beatings with other components of the terahertz comb. A Kvarz Ch6-66 radiofrequency synthesizer synchronized with the signal of the frequency standard was used as the source of the high-stability reference signal for the phase detector.

Figure 2 shows the mutual beating spectra of the BWO emitting at a frequency of about 100 GHz and the 1092nd component of the terahertz comb; the lower (upper) spectrum was recorded with (without) the stabilization. The emission spectrum of the free-running BWO is mainly determined by the quality of the power supply voltages and has a bandwidth of about 200 kHz in our case (upper spectrum). When the phase stabilization loop is locked, one can see a very narrow (the observed peak width exactly corresponded to the minimum 10-Hz bandwidth of the available spectrum analyzer) central component, which exceeds the noise level by more than 35 dB, and specific noise amplification at the edges of the control band (lower spectrum).

The BWO frequency was swept within the bandwidth of the input beating amplifier by stepping the Ch6-66 synthesizer frequency. If necessary, the sweep range can be extended to the entire BWO operation range with the use of the traditional phase-locking methods [13]. The implementation of the frequency sweep with a continuous radiation phase under switching is also possible [14].

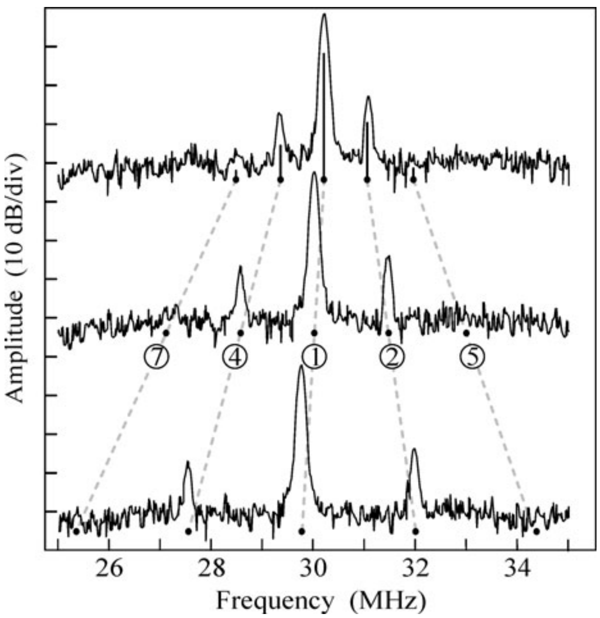

Fig. 3. Beating spectra between the BWO harmonics and the components of the terahertz comb recorded (from top to bottom) at a monotonically decreasing BWO frequency. The calculated positions of various harmonics are shown by the vertical lines and heavy points and the peak displacements are indicated by the dashed lines. The harmonic numbers are marked below the second spectrum.

Thus, we experimentally demonstrated the possibility of phase locking the CW subterahertz radiation to the frequency comb produced by a femtosecond laser. It is of interest to analyze the potential and prospects of this stabilization technique and to compare it with the traditional approach.

First, let us determine the frequencies to which the components of the reference frequency comb are resolved in our setup. This can be done, e.g., with the use of the BWO frequency harmonics formed at the diode mixer/multiplier. Under the chosen ratio of the repetition rate (the terahertz comb period) to the intermediate frequency of the BWO phase-locked loop, which is approximately three in our case, one can always find the radiation frequency F_{BWO} such that its beating frequency with the Nth component of the comb is approximately equal to the beating frequency of the $2F_{\text{BWO}}$, $4F_{\text{BWO}}$, $5F_{\text{BWO}}$, $7F_{\text{BWO}}$, etc., BWO harmonics with the corresponding $2N + 1$, $4N + 1$, $5N + 2$, $7N + 2$, etc., comb components. Figure 3 presents the typical spectra of such beatings detected without the frequency stabilization. The central peak corresponds to the beating of the fundamental BWO radiation frequency with the 1092nd comb component, the right and left satellites are due to the beating of the second and fourth BWO harmonics with the 2185th and 4369th comb components, respectively. The amplitude of the beating corresponding to the fifth and seventh BWO harmonics is comparable with the noise level and the respective peaks are not as well resolved as the other ones because the harmonic intensity decreases rapidly with an increase in N and the sensitivity of the receiving circuit becomes insufficient. The relative amplitudes of the peaks and, primarily, their relative positions in the frequency axis exclude misidentification. All of the peaks are shifted in exact agreement with the calculation under a change in the BWO frequency. The experiment indicates that the comb components up to at least 400 GHz are present in the diode mixer. Similar beating spectra were observed at all BWO frequencies within the entire operating range of 78–118 GHz.

Let us now analyze the spectral purity of the BWO radiation stabilized with the use of the above technique. As well known, the radiation spectrum of the oscillator in the phase-locked mode under the optimal choice of the operation parameters of the phase-locked loop almost exactly corresponds to the spectrum of the reference signal. In the case of BWO, this was confirmed in, e.g., [15]. However, in the traditional method of subterahertz frequency generation [12, 15, 16], the reference signal is the harmonic of the microwave signal generator. When the signal frequency is multiplied by N, the amplitude of its instability increases by the same factor, whereas the instability power increases by a factor of N^2. That is, the phase noise of the multiplied signal increases by $20\log(N)$. As a result, even very high-stability terahertz [12, 15, 16] and subterahertz [17] signals produced by the traditional method, in which the frequency multiplication factor is several tens (up to 43 in [16] and up to 72 in [17]), may have quite limited applications. In the proposed synthesis technique, the reference signals are the components of the comb produced by femtosecond laser radiation. The formation of the high-stability comb in our technique requires a microwave or radiofrequency synthesizer as in [2, 3, 5–9], but its frequency is not multiplied and, consequently, the spectral purity of each comb component will be approximately (to an imperfectness of the employed phase-locked loop) the same as that of the synthesizer signal [8]. The high-stability RF signal required for the operation of the phase detector in the phase-locked loop of the BWO is also not multiplied and has a sufficient spectral purity. Thus, the power of the phase noise of the terahertz source stabilized with the use of the proposed method appears to be a few orders of magnitude lower than in the traditional approach.

As mentioned above, the power of subterahertz synthesizers based on femtosecond laser combs is no more than one microwatt [8, 9]. In the traditional method of frequency generation with the use of primary oscillators, the output power can be four (Gunn diodes, BWOs, klystrons, etc.) to eight (gyrotrons) orders of magnitude greater. The proposed technique provides the combination of the advantages of both approaches, i.e., the ultimate spectral purity featured by the components of the laser combs and a high output power of the traditional subterahertz synthesizers with primary oscillators.

To conclude, this work provides the opportunity of creating a new generation of frequency synthesizers with a sufficient power and a low level of the phase noise.

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REFERENCES

1. R. J. Glauber, D. L. Holl, and T. V. Hansh, Usp. Fiz. Nauk **176**, 1341 (2006).
2. T. R. Schibli, I. Hartl, D. C. Yost, et al., Nature Photon. **2**, 355 (2008).
3. M. J. Martin, S. M. Foreman, T. R. Schibli, and J. Ye, Opt. Express **17**, 558 (2009).
4. B. C. Young, F. C. Cruz, W. M. Itano, and J. C. Bergquist, Phys. Rev. Lett. **82**, 3799 (1999).
5. T. M. Goyette, W. Guo, F. C. De Lucia, et al., Appl. Phys. Lett. **67**, 3810 (1995).
6. T. Yasui, Y. Kabetani, E. Saneyoshi, et al., Appl. Phys. Lett. **88**, 241104 (2006).
7. T. Yasui, R. Nakamura, K. Kawamoto, et al., Opt. Express **17**, 17034 (2009).
8. H.-J. Song, N. Shimizu, T. Furuta, et al., J. Lightwave Technol. **26**, 2521 (2008).
9. G. Mouret, F. Hindle, A. Cuisset, et al., Opt. Express **17**, 22031 (2009).
10. A. F. Krupnov, Spectrochim. Acta A **52**, 967 (1996).
11. S. Yokoyama, R. Nakamura, M. Nose, et al., Opt. Express **16**, 13052 (2008).
12. A. F. Krupnov, Int. J. Infrared Millim. Waves **22**, 1 (2001).
13. T. R. Schibli, K. Minoshima, F.-L. Hong, et al., Opt. Lett. **30**, 2323 (2005).
14. M. Yu. Tretyakov, V. V. Parshin, M. A. Koshelev, et al., J. Mol. Spectrosc. **238**, 91 (2006).
15. M. Schäfer, M. Andrist, H. Schmutz, et al., J. Phys. B: At. Mol. Opt. Phys. **39**, 831 (2006).
16. V. L. Vaks, Yu. I. Koshurinov, D. G. Pavel'ev, and A. N. Panin, Izv. Vyssh. Uchebn. Zaved., Ser. Radiofiz. **48**, 933 (2005).
17. S. Schiller, B. Roth, F. Lewen, et al., Appl. Phys. B **95**, 55 (2009).

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