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Femtosecond laser comb based subterahertz synthesizer

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Functioning layout of a frequency comb-based subterahertz synthesizer is demonstrated. A primary subterahertz oscillator was phase-locked against the Ti:Sapphire femtosecond laser frequency comb down-converted to the subterahertz range by the semiconductor mixer. Synthesizer operation is demonstrated through Fabri-Perot resonator response curve recording experiment. Spectral purity of the synthesizer was estimated. The advantage of the comb-based synthesizer over the synthesizer based on the Agilent E8257D device was shown. © *2014 AIP Publishing LLC*.
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Frequency combs of femtosecond lasers, providing a large amount of highly coherent and uniformly spaced spectral peaks potentially covering up to one octave interval,[1,2] are used as reference sources for optical and infrared continuous wave oscillators (CW-oscillators)[3–5] or as a base for low-power terahertz and subterahertz CW-radiation sources[6–9] and spectrum analyzers[10] by means of difference frequency generation. Considerable advantages of the comb-assistant signals in comparison to traditionally generated signals in millimeter-wave (MW) range were demonstrated earlier.[11] Using frequency combs as a reference source allows transferring spectral purity of the comb components to the one of stabilized oscillator. The possibility of primary subterahertz oscillator frequency phase-locking against down-converted femtosecond laser frequency comb was demonstrated in our previous paper.[12] The current paper reports on the operating specimen of the subterahertz synthesized radiation source built using the mentioned technique (a backward wave oscillator (BWO) was used as a primary source). Precise digital frequency control of the constructed synthesizer is illustrated by means of step-by-step recording of a narrow response curve of the Fabri-Perot resonator near the eigenfrequency of the transverse electromagnetic mode TEM_{00q}. Spectral purity of the radiation source based on the femtosecond laser comb as a reference source was estimated and compared to one of the same radiation source phase-locked against the harmonic of the microwave synthesizer. The latest technique of frequency synthesis is widely used for subterahertz spectroscopy[13–15] and, hereinafter, is referred to as "traditional."

The block-diagram of the subterahertz synthesizer is shown in Fig. 1. The optical frequency comb is generated by a Ti:sapphire femtosecond laser with a wavelength of ~790 nm, pulse length ~50 fs, average laser power ~100 mW, and pulse repetition rate ~92 MHz.[12] The pulse repetition rate of the femtosecond laser is stabilized by the phase-locked loop against a radiofrequency synthesizer. The drift of the pulse repetition rate f_{pulse} in usual conditions is mainly caused by variation of the pulse path optical length due to the thermal expansion of the optical elements. The optical path length is kept stable by placing one of the laser mirrors on the piezoceramic element driven by the phase-locked system.

A planar Schottky GaAs diode is used as a mixer which maintains two processes simultaneously. The first process is down-conversion of the femtosecond-laser frequency comb to the subterahertz range. The second one is non-linear generation of a difference frequency, i.e., generation of the beatnotes between the BWO frequency f_{BWO} (and harmonics $n \times f_{BWO}$) and the down-converted comb components $m \times f_{pulse}$. The difference between f_{BWO} and the nearest comb component having frequency less than $0.5 f_{pulse}$ is filtered and transferred to the phase detector to phase-lock the BWO frequency using a traditional synchronization technique[14] by means of two reference sources (down-converted comb and radiofrequency synthesizer ♯2 (PTS x10B3O2AE) according to Fig. 1), similar technique was used in Refs. 5 and 8 with the only difference that subterahertz comb generation and mixing it with the primary source were separated in space. To ensure the long term stability (which was not really assessed in this work), one may use a quantum frequency standard to synchronize all the synthesizers used in the layout. However, stability of the synthesizers' internal quartz generators was sufficient for this work.

It is also possible to observe beatnotes between the BWO frequency harmonics $n \times f_{BWO}$ and the corresponding nearest comb components in the filtered signal up to $n = 5$ with lower magnitude (as in our previous paper,[14] where beatnote for $n = 7$ was observed). These beatnotes are not necessary for phase-locking the synthesizer frequency, and their magnitude can be decreased so that they do not affect the phase detector. Nevertheless, beatnotes demonstrate a

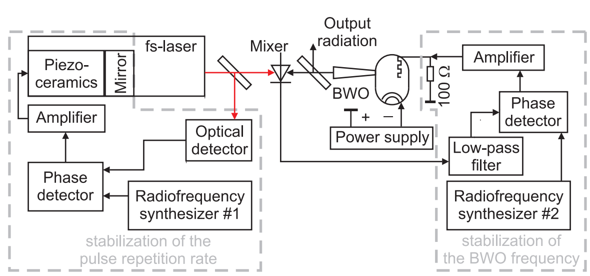

FIG. 1. Block-diagram of the synthesizer.

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wide bandwidth of the subterahertz comb provided by the mixer and, consequently, a possibility of building synthesizers operating at the corresponding frequency range. Thus, having $f_{BWO} = 100$ GHz, beatnotes with comb components having frequency from 500 to 700 GHz (for $n = 5$ and $n = 7$ respectively) are observed despite the fact that used planar Schottky diode was not designed for optical radiation detecting. Specified by the manufacturer, cutoff frequency of the diode is of 2–5 THz which could be compared to the terahertz comb width from the article by Consolino *et al.*[8]

Having set f_{pulse} and the reference synthesizer frequency f_{ref}, f_{BWO} is locked to the value of $m \times f_{pulse} + f_{ref}$ or $m \times f_{pulse} - f_{ref}$ according to the synchronization system settings. Frequency scanning is performed like in traditional synthesizers, i.e., by scanning f_{ref}, which allows setting the frequency in the vicinity of the chosen comb component and, if necessary, switching between the comb components.

Spectral purity of the radiation source is usually demonstrated by analyzing the beatnotes between the radiation generated by two identical and independently referenced sources.[1,2] Having no opportunity to assemble a second synthesizer setup, a sample spectrum was analyzed using a single synthesizer. Demanding a smaller amount of hardware, this technique is more valuable and demonstrative in terms of spectroscopy: slopes of the narrow spectral profile work as a frequency discriminator transforming phase noise of the radiation source frequency to the output signal noise that is proportional to radiation frequency variation and response profile derivative. The similar method was used previously (e.g., see Fig. 2 in Ref. 16). A hi-quality Fabri-Perot resonator response profile was chosen as a sample spectrum. The resonator technique is currently brought to perfection and widely used for precise measurements.[17] The response profile of the resonator can be mathematically described as a Lorentz function with width proportional to radiation losses. The resonator length was 70 cm, and its Q-factor was near 1.5×10^6. At the eigenfrequency near 100 GHz, the response profile width value is about 60 kHz, which is a typical value of the width of the Lamb-dips on the top of Doppler broadened molecular lines studied by ultrahigh resolution spectrometers.[18]

All the synthesizer setup, including a femtosecond laser and a primary subterahertz oscillator, was placed on a single optical table together with the resonator. In addition, the resonator was covered with a thin film transparent for the subterahertz radiation and isolating the resonator from ambient air fluctuations. Despite this fact, weak temperature fluctuations, air fluxes, and mechanical vibration in the laboratory were able to cause additional noise or jitter of the resonator response curve. That jitter could also result in additional phase noise that did not depend on the frequency stabilization technique because, in terms of resonator response profile recording, the resonator eigen-frequency instability is equivalent to radiation frequency instability.

A resonator spectrometer automated data recording system was used.[17] Two series of measurements were carried out. The first one was performed with stabilizing BWO frequency to the femtosecond laser comb as described above and the second one was performed with a traditional technique of frequency synthesis using reference harmonics of microwave synthesizer Agilent E8257D (operating frequency up to 40 GHz) The synthesizer frequency harmonics were generated by the same mixer (operating in this case as a multiplier (multiplier-mixer or harmonic mixer)) and were used instead of subterahertz frequency comb components. The details of the resonator spectrometer functioning and measurement procedure may be found in Ref. 17.

In both cases, a large number of resonator response profile recordings were obtained. Data were recorded in batches of 32 scans (16 forward and 16 backward). Each scan contained 512 signal-versus-frequency points, time per scan was 30 ms. All profiles within a single batch were drawn to reconcile the peak positions and then averaged to reduce the intrinsic detector noise masking the phase noise on the profile slopes. The model function,

$$y(x) = \frac{A(1 + D(x - C))}{B^2 + (x - C)^2} + E + F(x - C), \qquad (1)$$

was fitted to the averaged profile to extract the profile parameters: amplitude A, center C, and width B. The multiplicative term $(1 + D(x - C))$ is used to account for the dependence of the radiation power on frequency and linear additive term $(E + F(x - C))$ is used to account for the baseline.

Figure 2 shows typical recorded and averaged profiles together with the residuals of the fit (i.e., difference between measured and fitted profiles).

To evaluate the spectral purity of the radiation source used for resonator excitation, fit residuals of the measured resonator responses were analyzed.

To show the general difference in the spectral width between the subterahertz radiation source referenced by the microwave synthesizer and the femtosecond laser comb, 152

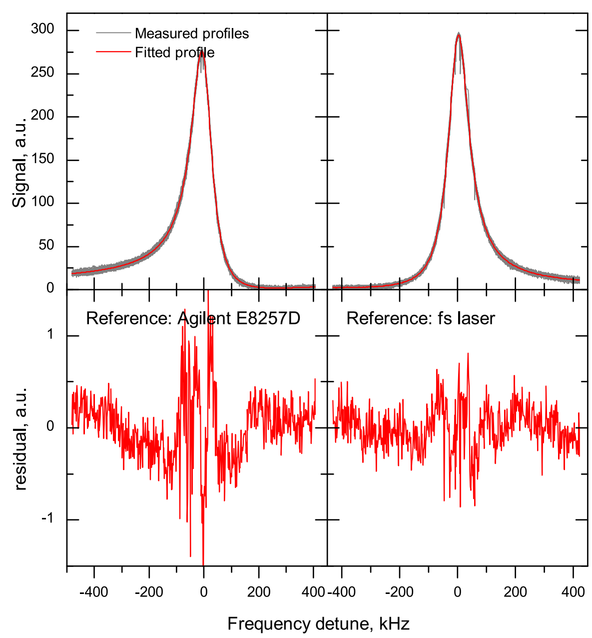

FIG. 2. Top panels: Results of resonator response curve recording with the same radiation source phase-locked against two different reference signals: harmonic of the Agilent E8257D synthesizer (left panel) and component of down-converted femtosecond laser frequency comb (right). Bottom panels: residuals of the model profile fitted to the corresponding averaged records displayed on the top.

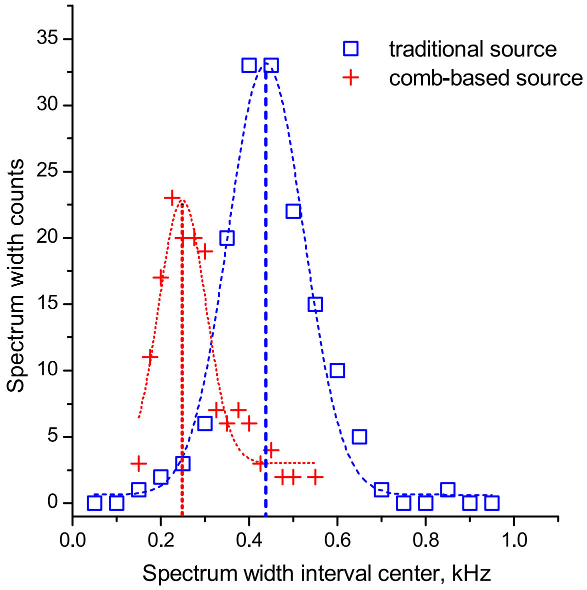

FIG. 3. Distribution of the estimated spectral width of the discussed subterahertz synthesizer with femtosecond laser comb (red crosses) and traditional synthesizer (blue squares) used as a reference source. Lines of the corresponding color show Gauss functions fitted to the experimental points and central values derived from the fit.

profile recordings obtained with each reference source were processed. As the upper limit of the spectral width, maximum observable deviation of the radiation frequency from the set value was taken. Maximum signal deviation caused by frequency instability is observed at maximum slope of the response profile. In these terms, upper bound of spectral width may be roughly estimated as a ratio of maximum fit residual to the maximum model response profile derivative.

In Ref. 19, wideband detector (bandwidth is 200 MHz) was used for the phase noise analysis, whereas the maximum bandwidth of the detection channel in the resonator spectrometer is 100 kHz.[17] This allowed only observation of the cumulative effect of signal instability caused by the radiation source frequency instability within the detector bandwidth. However, comparing spectrum width of the primary source referenced by the subterahertz comb and by microwave CW-synthesizer, all other details of the setup were kept the same, which allowed to consider all the observed difference in the recorded resonator profiles as provided by the reference source.

The calculated spectral width values distributions are shown in Fig. 3. Both distributions are close to Gauss one. Central values obtained from fit of the Gauss function to the distributions are also shown in the figure. Comparing these two values, it should be concluded that using a femtosecond laser frequency comb down-converted to the subterahertz range as a reference source provides better spectral purity than the traditional method of frequency synthesis using harmonics of a microwave CW synthesizer. The esteemed spectral width of the comb-based subterahertz source is in agreement with measurements of one of the terahertz sources[16,19] (but it is worth to notice that we estimate possible frequency deviation within the detector bandwidth, not spectrum half-width at half-maximum). In conclusion, it should be noted that further improvement of the synthesizer spectral purity can be obtained by means of f–2f pulse repetition rate stabilization.[1,2] In this case, repetition rate instability does not scale with the comb peak number.

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