Microwave synthesis from a continuous-wave terahertz oscillator using a photocarrier terahertz frequency comb

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We report low-noise microwave synthesis from radiation with a frequency of 0.3 THz using a photocarrier frequency comb in a photoconductive antenna. The synthesized microwave signal at 1 GHz is phase coherent to the 0.3 THz radiation and has a fractional instability of 1×10^{-15} within 300 s averaging times and single-sideband phase noise of −105 dB/Hz at a 100 Hz offset from the carrier. This terahertz (THz)-to-microwave synthesizer is capable of being a THz frequency divider, which would be indispensable to not only THz metrology but also future high-speed wireless networks.

OCIS codes: (120.3940) Metrology; (140.4050) Mode-locked lasers; (040.2235) Far infrared or terahertz; (060.5625) Radio frequency photonics.

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Recent technological progress in the terahertz (THz) domain of 0.1–10 THz has yielded novel ideas in many scientific and industrial fields such as astronomy, biology, material analysis, and information and communication technology [1,2]. A frequency comb in the THz region is a powerful tool and has been used in microwave-to-THz broadband synthesizers for counting absolute THz frequencies [3–5] and providing a grid of frequency reference for stabilizing quantum cascade lasers [6–8]. However, no approach has been developed yet to transfer information from THz radiation directly to the microwave region. We demonstrate the generation of low-phase-noise microwave signal synthesized from THz radiation by using a THz frequency comb produced in a photoconductive antenna (PCA). This THz-to-microwave synthesizer allows precise comparison with the present frequency standard and THz oscillators in the microwave region. It will be also essential for establishing a new THz frequency standard with an expected uncertainty of 10^{-16} [9], which can test the so-called Standard Model by detecting the time evolution of fundamental constants [10]. It can also help to characterize the extent of the breakdown of the Born–Oppenheimer approximation [11]. Moreover, the THz-to-microwave synthesizer serves as a *THz frequency divider* and is potentially useful for future high-speed wireless networks employing cognitive radio technology, which changes the transmission parameters to efficiently use the limited available spectrum band [12,13].

The principle of THz-to-microwave synthesis is illustrated in Fig. 1. The spectral components of the femtosecond (fs) laser frequency combs (FLFCs) are regularly spaced by the pulse repetition rate $f_{\rm rep}$ and shifted by the carrier-envelope offset frequency $f_{\rm ceo}$ [14]. The frequency of the n th component f_n of the FLFC is fully determined by the two frequencies and is described by $f_n = nf_{\rm rep} + f_{\rm ceo}$, where n is an integer. Combining the FLFCs with the photoconductive process can extend the concept of the frequency comb into the THz region. A sequence of photocarrier generation is induced in the PCA by introducing a fs optical pulse train into it. This constructs the frequency comb structure of the photocarrier $f_k^{\rm (PC)}$ in the THz region, where k is an integer and the superscript (PC) indicates the photocarrier. Unlike the FLFC, this photocarrier THz comb has no offset frequency. Since the spectral components of the FLFCs are mixed in the PCA, regarded as a nonlinear wavelength conversion device, the spectral components of the THz comb are produced by the difference frequency generation process: $f_k^{\rm (PC)} = f_n - f_m = (n-m) \times f_{\rm rep}$ when $k = n - m$. The photocarrier $f_{\rm cw}^{\rm (PC)}$ produced by the cw-THz radiation in the PCA is downconverted by the THz comb into the accessible rf region as a photocarrier beat signal $f_{\rm beat}^{\rm (PC)}$, and consequently $f_{\rm beat}^{\rm (PC)} = f_{\rm cw}^{\rm (PC)} - f_k^{\rm (PC)}$. In the THz-to-microwave synthesizer, $f_k^{\rm (PC)}$ is stabilized to $f_{\rm cw}^{\rm (PC)}$ via the $f_{\rm beat}$ phase-locked loop (PLL). Then

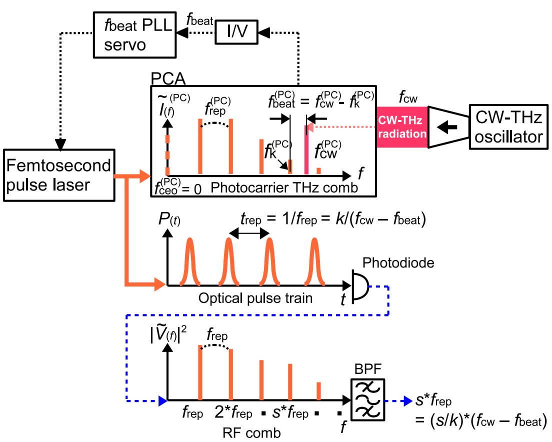

Fig. 1. Principle of THz-to-microwave synthesis. PCA, photoconductive antenna; I/V, current-to-voltage converter; PLL, phase-locked loop; BPF, band-pass filter; f, frequency; t, time; I, current; P, light power; and V, voltage. The superscript (PC) indicates the photocarrier.

$$f_{\mathrm{rep}}^{(\mathrm{PC})} = \left(f_{\mathrm{cw}}^{(\mathrm{PC})} - f_{\mathrm{beat}}^{(\mathrm{PC})}\right)/k, \quad (1)$$

where $f_{\mathrm{rep}}^{(\mathrm{PC})}$ is the mode interval of the photocarrier THz comb. Since f_{rep} in the optical domain is equivalent to $f_{\mathrm{rep}}^{(\mathrm{PC})}$ in principle, the microwave signal coherently linked to the THz radiation can be obtained by directly detecting the optical pulse train from the fs laser. The output signal from the detection photodiode forms a frequency comb structure in the rf domain; thus the sth harmonics of f_{rep} can be obtained as a microwave signal phase-coherent to the THz radiation as illustrated in Fig. 1, where s is an integer.

The experimental setup for the THz-to-microwave synthesis is depicted in Fig. 2. The cw-THz radiation was emitted from a frequency multiplier chain with low-noise rf synthesizer 1 (Virginia Diodes, Inc). Its frequency was 0.3 THz with an output power of 2 mW. The THz radiation propagating in free space was incident on the THz detection PCA. It had a bowtie antenna pattern, which is suitable for sub-THz detection with high efficiency. The 1.5 μm erbium-doped-fiber laser had two fiber-coupled outputs with 50 mW average power. Both had a 100 MHz repetition rate and 55 fs pulse width. One output was used to generate the photocarrier THz comb, and the other to synthesize the microwave signal. The cw-THz radiation and THz comb produced a heterodyne beat signal as a photoconductive current in the PCA. The beat signal was amplified by a low-noise amplifier with a transimpedance gain of 10^9 V/A (FEMTO Messtechnik DLPCA-200). To obtain a high signal-to-noise ratio (SNR) of the beat signal with the amplifier, the signal frequency was set to 60 kHz by slightly changing the frequency of the rf synthesizer 1. The SNR of the beat signal was 45 dB with a resolution bandwidth (RBW) of 100 Hz [Fig. 3(a)]. The beat signal was compared with the output of a direct digital synthesizer by a digital mixer to extract the control signal of the f_{beat} PLL. The control signal was fed back to a PZT actuator of the fs laser for modulating the cavity length. The control bandwidth of the PLL was about 1.5 kHz. The relative frequency instability of the PLL was 3×10^{-14} at the 1 s averaging time τ down to the 10^{-16} level with a dependence of τ^{-1} as plotted in Fig. 4, plot (c). This measurement was implemented by the

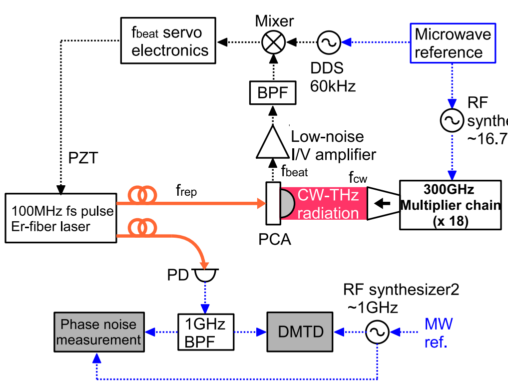

Fig. 2. Experimental setup for THz-to-microwave synthesis. PCA, photoconductive antenna; LNA, low-noise amplifier; PD, photodiode; BPF, band-pass filter; PZT, piezo-electric transducer; and DDS, direct digital synthesizer.

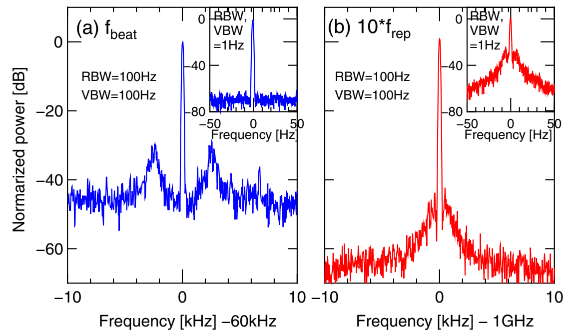

Fig. 3. (a) Spectra of the heterodyne beat signal between the 0.3 THz oscillator and THz comb, and (b) 1 GHz microwave signal synthesized from the 0.3 THz cw radiation. The insets show each spectrum in higher resolution. Note that the THz oscillator and THz comb have a common microwave reference.

dual-mixer time difference technique with a bandwidth of 10 Hz [15]. The optical pulse train from the fs laser was directly detected by a fiber-coupled fast InGaAs photodiode. The tenth mode of the rf comb was selected by a narrow bandpass filter with a center frequency of 1 GHz [Fig. 3(b)]. This corresponds to dividing the 0.3 THz cw radiation down to f_{rep} by a factor k of 3000 and then multiplying it up to 1 GHz by a factor s of 10. The 1 GHz signal synthesized was used to measure the frequency instability and single-sideband (SSB) phase noise to characterize the THz-to-microwave conversion.

Since $f_{\mathrm{beat}}^{(\mathrm{PC})}$ is phase-locked to the low-frequency reference with fluctuations below 1 mHz at 1 s, the phase noise of f_{cw} is expected to become the dominant noise source of the microwave signal synthesized. Figure 4 plot a) shows the instability of the 1 GHz signal synthesized from the 0.3 THz cw oscillator. The dual-mixer time difference technique was employed for this measurement with the aid of another low-noise rf synthesizer, 2. The instability achieved was 2×10^{-13} at 1 s and averaged down to the 10^{-16} level within 300 s. This measurement is currently restricted by the instabilities of rf synthesizers 1 and 2 as plotted in Fig. 4(b). Figure 5 shows the SSB phase-noise spectra of several microwave signals at 1 GHz relative to the output of rf synthesizer 2.

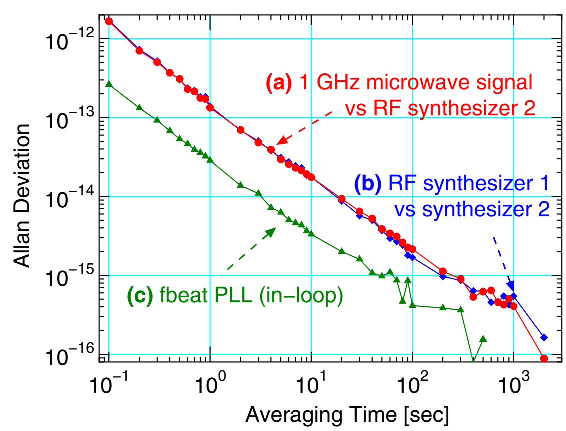

Fig. 4. (a) Allan standard deviation of the instability of the 1 GHz microwave signal synthesized from the cw-THz radiation and (c) that of f_{beat} phase-locked loop (c). (b) The relative instability of two rf synthesizers is also plotted for comparison.

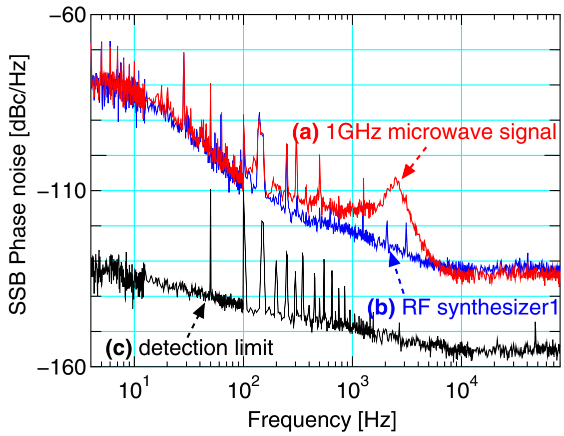

Fig. 5. SSB phase noise spectra of various microwave signals relative to rf synthesizer 2. (a) 1 GHz signal synthesized from 0.3 THz cw radiation, (b) rf synthesizer 1 used in frequency multiplier chain, and (c) detection limit measured by using common 1 GHz signal from synthesizer 2.

They were determined by phase comparison using a double-balanced microwave mixer. The output of the mixer was low-pass filtered, amplified and then sent to a fast Fourier transform analyzer. Figure 5, plot (a) is a plot of the 1 GHz signal that is phase coherent with the cw-THz oscillator. The THz-to-microwave conversion did not result in significant excess noise below 200 Hz, since the relative SSB phase noise of the 1 GHz signal synthesized is in good agreement with that of the rf synthesizers used in this experiment [Fig. 5, plot (b)]. The bump around 2 kHz was caused by the lack of a phase margin of the f_{beat} PLL. The SSB phase noise levels were −105 and −134 dBc/Hz at 100 Hz and 10 kHz from the 1 GHz carrier frequency, respectively. It should be noted that the noise level above 7 kHz is lower than that of rf synthesizer 1 because of the intrinsically low noise of the optical-pulse timing jitter at the high Fourier frequencies.

In conclusion, low-noise microwave synthesis from the cw-THz oscillator was demonstrated by using the photocarrier THz comb in the PCA. The synthesized microwave signal with a 1 GHz frequency, which was coherently linked to 0.3 THz cw radiation, had a measured fractional instability of 10^{-16} within 300 s and an SSB phase noise level of −105 dBc/Hz at a 100 Hz offset from the carrier frequency. The THz-to-microwave division imposed no significant excess noise within the stability of the low-noise rf synthesizers used. Our theoretical estimate indicates that this microwave synthesis technique can function above 1 THz. The THz-to-microwave synthesizer will be important for future THz metrology and is a potential THz frequency divider for next-generation high-speed wireless communications.

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