A Terahertz Source with High Frequency Accuracy Using a Mach-Zehnder-modulator-based Flat Comb Generator for High Resolution Spectroscopy

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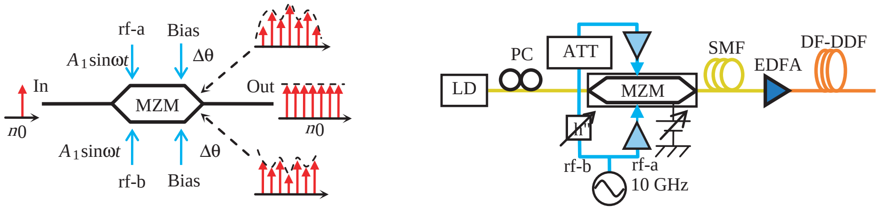
Abstract— In this paper, we repot on generation of THz waves with high accuracy and precise controllability of the frequency using a photonic down-conversion technique. A 2.5 THz-spanned optical comb signal was generated by a combination of a Mach-Zehnder-modulator-based flat comb generator and a dispersion-flattened dispersion-decreasing fiber. By mixing a two-tone signal extracted from the comb signal, THz signals have generated, in which the C/N ratio of them was greater than 30 dB.

Terahertz (THz) waves attract great deal of attention in material research, gas sensing and so forth [1]. For these applications, time-domain spectroscopy (TDS) is widely used. Although the THz-TDS can simultaneously acquire amplitude and phase spectra, the frequency resolution is limited by the temporal window of signal waveforms. Photonic down-conversion techniques are a good candidate for THz sources with precise frequency tuning, because the frequency of THz signals can be precisely controlled by the frequency separation of two-tone signals. Optical combs generated by a modulator-based source are suitable for creating the two-tone signals, because of high frequency accuracy and controllability [2]. Recently, a Mach-Zehnder-modulator (MZM)-based flat comb generator (MZ-FCG) has proposed and demonstrated [3, 4]. The MZ-FCG can generate ultraflat comb signals using single MZM. In addition, the MZ-FCG can operate with alignment-free and turn-key starting. In our previous work, we have demonstrated generation of millimeter waves with narrow linewidth and low phase noise by using the MZ-FCG [5]. In this paper, we repot on generation of THz waves with high frequency accuracy using the MZ-FCG.

Figure 1(a) shows the mechanism of comb generation using the MZ-FCG. A dual-drive-type MZM fabricated on a $\mathrm{LiNbO_3}$ crystal was used. The MZM is driven by two large-amplitude rf sinusoidal signals with slightly different amplitudes. A continuous-wave (cw) light led to the MZM is converted to a comb signal. The spectral spacing is directly related to the rf frequency, and the number of sidebands depends on the rf power. Thus, the bandwidth of the comb signal is decided by the frequency and the power of the rf signal. When the condition of $\Delta A \pm \Delta\theta = \pi/2$ is satisfied (comb flattening condition), the amplitudes of the comb modes are flattened out, where ΔA is the amplitude difference between the rf signals, and $\Delta\theta$ is the optical phase difference between the two arms of the MZM [4, 6]. In the comb flattening condition, the generated comb signal has linear chirp, so that it can be formed to a picosecond pulse train in the time domain by compensating the chirp using a standard single-mode fiber (SMF). Figure 1(b) shows the configuration of the MZ-FCG. The MZ-FCG was driven by a 10 GHz rf signal. A cw light incident into the MZ-FCG is converted to an ultraflat comb signal. The comb signal was launched into a 1.2 km-long single-mode fiber to form picosecond pulse trains. The picosecond pulse train was conducted to a dispersion-flattened dispersion-decreasing fiber (DF-DDF) to generate broadband comb signal by an adiabatic soliton



(a) (b)

Figure 1: (a) The mechanism of comb generation by the MZ-FCG. (b) The experimental configuration of broadband comb generation. ϕ, rf phase shifter; ATT, rf attenuator; PC, polarization controller; DF-DDF, dispersion-flattened dispersion-decreasing fiber.

compression process. Figure 2 shows a spectrum of a generated comb signal. In Figure 2(a), 40 modes were clearly observed, and the 10 dB-reduction bandwidth was 340 GHz. By compensating the chirp of the comb signal using the single-mode fiber, a 2.8 ps-width pulse was generated. The picosecond pulse was amplified by the EDFA, and launched into the DF-DDF. Figure 2(b) shows a spectrum of a broadband comb signal. The comb signal spanned over 20 nm, which corresponds to a bandwidth of 2.5 THz.

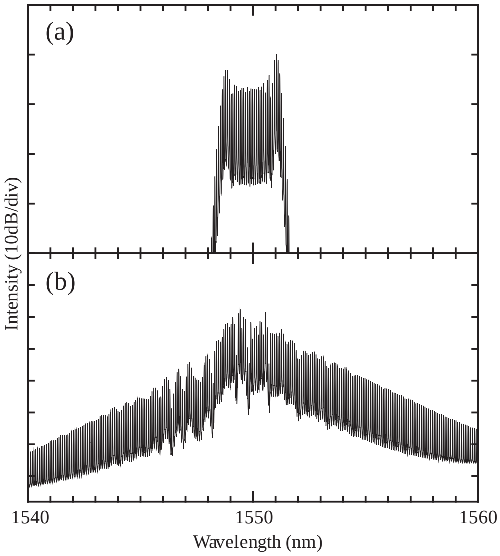


Figure 2: The optical spectrum of a 10 GHz-spaced comb signal generated by the MZ-FCG.

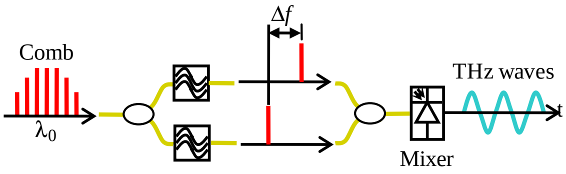


Figure 3: The basic concept of MMW generation using comb signals generated by the MZ-FCG.

Figure 4 shows the basic concept of THz wave generation. Two optical modes are extracted from the broadband comb signal by using a pair of optical filters. The extracted modes are launched into a photomixer such as uni-traveling carrier photodiodes (UTC-PDs). In this scheme, there are two methods for the frequency tuning of THz signals; one is a coarse adjustment by tuning the frequency of the filters which changes the selection of the comb modes. The other is fine tuning by changing the frequency of rf signal driving the MZ-FCG, f_m, which can precisely tune the THz frequency. The frequency stability of the THz signal is depends on that of the rf signal.

Figure 4 shows experimental setup for THz wave generation. The comb signal generated by the MZ-FCG was halved by a 3 dB optical coupler. An optical two-mode signal for photomixing was extracted from the comb signal by using a pair of optical tunable bandpass filters (TBFs) with the minimum pass-bandwidth of 6 GHz. The extracted two modes are combined by another 3 dB

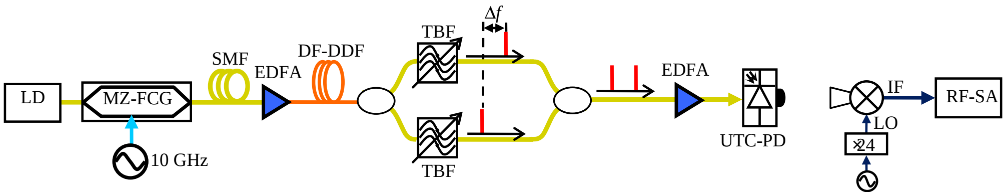


Figure 4: Schematic illustration of the experimental setup for MMW signal generation. TBF, optical tunable bandpass filter; RF-SA, rf spectrum analyzer.

coupler. Figures 5(a)–(c) show optical spectra of the two-tone signals. A two-tone signal with the high extinction ratio was successfully extracted, in which the frequency separations were 600, 700, and 750 GHz, respectively. The two-tone signals were launched into an antenna-integrated-type UTC-PD with a nominal bandwidth of greater than 1 THz. The UTC-PD radiated THz signals into air via silicon hemispherical lens. This generated THz signals were characterized by the down-conversion technique. The THz signals were coupled to a 24-multiplying harmonic mixer and down-converted to a RF signal. The intermediate frequency (IF) signal of the mixer was measured by a spectrum analyzer. Figures 5(d)–(f) show an rf spectra of generated THz signals. A THz signal centered at 600, 700, and 750 GHz, which correspond to the frequency separation of the two-tone signals, were successfully generated. The C/N ratios of THz signals were greater than 30 dB at the resolution bandwidth of 1 Hz.

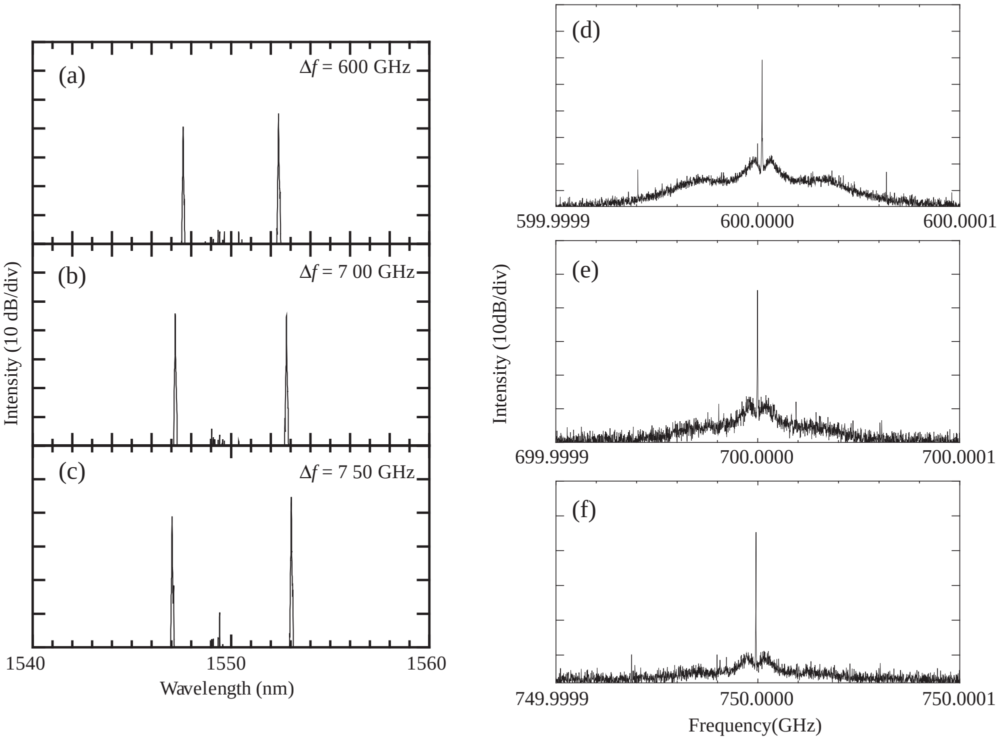


Figure 5: (a)–(c) The optical spectra of the two-tone signals, and (d)–(f) the spectra of the generated THz signals.

In conclusion, we have successfully generated THz signal by using the combination of the MZ-FCG and the DF-DDF. By extracting arbitrary two modes from the optical frequency comb broadening over 2.5 THz, high stable and accurate THz-cw was generated. In the generation of THz signals, we have confirmed that the signal has the C/N ratio of greater than 30 dB. Photonics down-conversion technique using optical two-tone signals of the optical comb is a good candidate for a THz source with high accuracy and precise frequency tuning.

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