Generation of cw-THz waves with high frequency accuracy by Mach-Zehnder-modulator-based flat comb generator for phase-locking of THz-QCLs

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***Abstract*— Generation of cw-THz waves with high frequency accuracy was demonstrated by using a Mach-Zehnder-modulator-based flat comb generator (MZ-FCG). A combination of the MZ-FCG and a highly nonlinear dispersion shifted fiber generated broadband optical combs, and cw-THz waves in the range of 3 THz were generated by photonic down-conversion of two-tone signals extracted from the broadband combs.**

I. Introduction

In the THz region, cw source devices such as resonant tunneling diodes, quantum cascade lasers (QCLs) and so forth, are key components. They are being used in various applications such as imaging, spectroscopy, and high speed wireless communications. However, the stability of their operation frequencies is insufficient for such applications. For example, the long-term linewidth of QCLs is generally several megahertzes. Stabilization of their operation frequencies using phase-lock techniques is now being attempted [1-3].

Optical combs provide equally-spaced cw lights with high accuracy, which are used in frequency standards. By linking the THz frequency with optical combs, the THz source devices can be highly stabilized. Although conventional optical comb sources are based on mode-locked lasers, optical-modulator-based optical comb sources are good candidates for flexible and stable sources [4]. In this source, the frequency spacing of optical comb signals is decided by the microwave signal driving the modulator, so that the modulator-based comb source enables to multiply the frequency of the microwave signal to the THz range. In our previous work, generation of THz waves in the range of 0.7 THz has been demonstrated by photonic down-conversion using a Mach-Zehnder-modulator-based flat comb generator (MZ-FCG) [5], which had a frequency-stability in the order of 10^{-11}. In this paper, we report on generation of cw-THz waves in the 3 THz range with high frequency accuracy and broadband tunability by using the MZ-FCG, which can be used as a reference signal for phase-locking of QCLs.

II. Basic Concept of Phase-Locking of THz Sources

Figure 1 shows our basic concept for frequency-stabilized THz source using a phase-locked loop (PLL) system. Optical frequency comb sources are used for a reference source in the PLL system. The comb source is locked to a frequency standard, which leads to high stability of the repetition frequency (or the comb spacing). The optical combs illuminate an optical-to-THz converter such as high-speed photodiodes or nonlinear optical materials, generating THz combs. Because the THz comb is created from the highly-stabilized optical comb, the THz comb has high frequency accuracy and stability. The THz comb is launched into a frequency mixer along with a THz signal generated from a THz source device. The frequency difference between the THz comb and the THz signal is detected as an error signal by the PLL system, and the error signal is fed back to the THz source. As a result, the operation frequency of the THz source is highly stabilized.

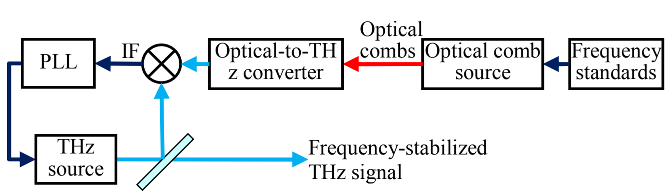

Fig. 1. The block diagram of the frequency stabilization of THz source devices.

III. Broadband Optical Comb Generation

Figure 2 shows the configuration of the broadband comb source. To generate broadband combs, a combination of the MZ-FCG and a highly nonlinear dispersion shifted fiber (HNL-DSF)

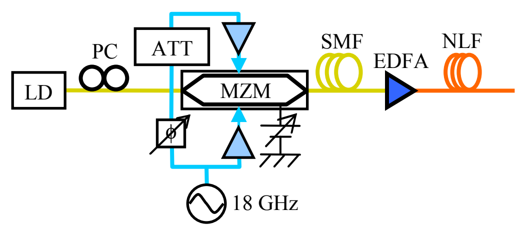

Fig. 2. Schematic illustration of the configuration of the broadband comb source composed of the MZ-FCG.

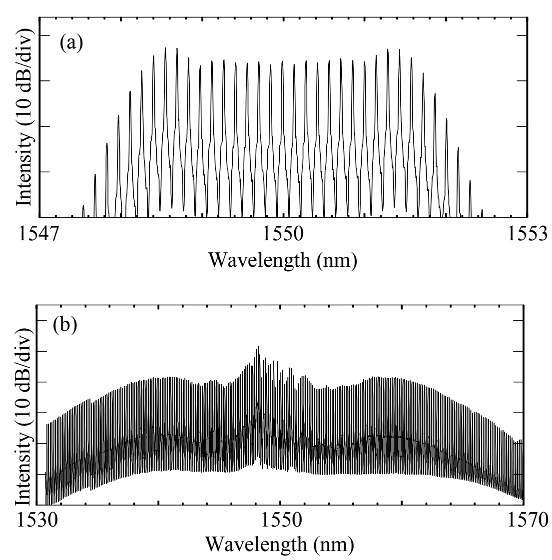

Fig. 3. Spectra of broadband combs generated by (a) the MZ-FCG, and (b) broadened by the HNL-DSF.

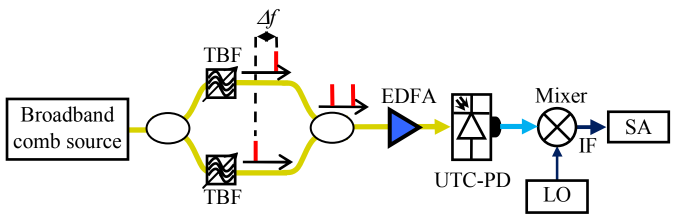

Fig. 4. Schematic illustration of the experimental setup for cw-THz wave generation.

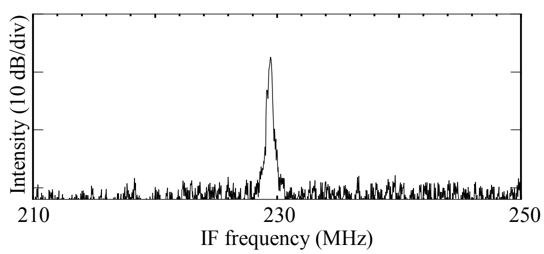

Fig. 5. A spectrum of generated THz wave by photomixing of the two-tone signal. The center frequency was 3.095 THz.

were used. The MZ-FCG was driven with an 18 GHz rf signal. By setting the driving condition of the MZ-FCG to the comb flattening condition [4], a cw light fed into the MZ-FCG was converted to an 18 GHz-spaced ultraflat comb. Figure 3(a) shows a spectrum of a comb generated by the MZ-FCG. An ultraflat comb with a 10 dB-reduction bandwidth of 468 GHz was generated. After chirp compensation using a 200 m-long single-mode fiber, the comb signal was conducted to the HNL-DSF to generate broadband comb signal. Figure 3(b) shows a spectrum of a broadband comb signal. The comb signal spanned over 40 nm (> 5 THz) was generated.

IV. Highly Accurate THz Wave Generation

Figure 4 shows the setup for THz wave generation. Two optical modes were extracted from the broadband optical comb by a pair of tunable bandpass filters (TBFs). The frequency separation between the two modes is set to the desired frequency of THz waves. By photomixing of the two-mode signal, cw-THz waves are generated. Merits of this method are (i) the frequency of THz signals is precisely controlled by both the mode spacing of the two-mode signal and the driving the MZM, (ii) the stability of the mode spacing of the comb signal is depends on the accuracy of the rf signal.

To generate THz waves by photonic down-conversion, a two-mode signal with a frequency separation of 3 THz was extracted from the broadband comb signal by using TBPs with a minimum pass-bandwidth of 6 GHz. The extracted modes were launched into an antenna-integrated-type uni-traveling carrier photodiode (UTC-PD), radiating THz waves. The THz waves were launched into a hot electron bolometer mixer (HEBM) along with a THz signal emitted from a QCL [4]. The QCL is operated in the 3 THz range. The intermediate frequency (IF) signal of the HEBM was measured by an rf spectrum analyzer. Figure 5 shows a spectrum of a generate THz signal. A THz wave with the center frequency was 3.095 THz and the C/N ratio was over 25 dB was successfully generated.

V. Conclusions

Generation of cw-THz waves with high frequency accuracy was demonstrated by using the MZ-FCG. A combination of the MZ-FCG and a highly nonlinear dispersion shifted fiber generated broadband optical combs, and cw-THz waves in the range of 3 THz were generated by photonic down-conversion of two-tone signals extracted from the broadband combs. The generated THz waves had a C/N ratio of over 25 dB.

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