CW Terahertz-Wave Source Based on Photonic Millimeter-wave Generation and Its Application for Spectroscopic Measurement

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***Abstract*—This paper describes a CW terahertz-wave source with narrow spectral linewidth and high frequency accuracy. This source uses a photonic millimeter-wave generation as a primary source of radiation. We succeeded in observing a rotational transition line of N_2O gas molecules with the source. This proves that the source has the high frequency accuracy and narrow linewidth required for the spectroscopic applications.**

I. Introduction

Terahertz and sub-terahertz electromagnetic waves has attracted much attention for possible applications in biological and medical sciences, industrial non-destructive evaluations, security, wireless communication, and radio astronomy [1]-[5]. After several years of fundamental study, some of the research is undergoing a transition to practical use. Important features for CW terahertz-wave sources required in such practical applications are narrow spectral line width, high accuracy and controllability of the oscillation frequency. Our photonic millimeter-wave generator [6] meets such requirements, although its operation frequency is slightly lower than the terahertz range. Therefore, a way to extend its operation frequency is required. However, the instability of the level in higher-order modes of the optical sideband and a lack of optimum frequency-tunable optical-mode-selection filter make this difficult [7].

In this work, we used the photonic millimeter-wave generator as a primary source of radiation and extended its operation frequency with a frequency multiplier. Advantages of this configuration include compactness and stability of the solid-state electronics and a narrow spectral linewidth, high accuracy and controllability of the oscillation frequency of the photonic millimeter-wave generation. Moreover, delivery of a primary signal through low-loss optical fibers makes highly sensitive coherent detection possible [5]. The developed CW terahertz-wave source based on this technique operates between 390 and 500 GHz. The narrow linewidth and high frequency accuracy of the CW terahertz-wave source was confirmed from its application to spectroscopic measurement of a sample gas.

II. CW terahertz-wave source

Figure 1 schematically shows the terahertz-wave source developed in this study. A CW lightwave from a single-mode laser at the wavelength of 1.55 μm is intensity-modulated via a $LiNbO_3$ Mach-Zehnder intensity modulator (LN-MZM). The LN-MZM is biased at an extinction point and driven by a millimeter-wave signal with the frequency f_{mmw} ranging from 39 to 50 GHz. As shown in Fig. 2, upper and lower side band modes are dominant in the LN-MZM output, while the carrier signal is completely suppressed. Therefore, the LN-MZM output coincides with an optical beat signal with the beat frequency $2f_{mmw}$. The output is once amplified by an erbium-doped fiber amplifier and fed into a W-band photomixer [8]. This signal is amplified by a W-band amplifier and converted into a terahertz wave with a quintupler. The frequency of the quintupler's output fall between 390 and 500 GHz with the maximum output power of about 1 μW at 450 GHz. The frequency of the generated terahertz wave is quite accurate since it is completely independent of the laser oscillation frequency and determined by that of the signal driving the LN-MZM, f_{mmw}.

In order to estimate the linewidth of the generated terahertz wave, we converted it to 14.2-GHz signal with a sub-harmonic mixer. Figure 3 shows the RF spectra of the mixer IF signal. The linewidth of the down-convert signal is less than 400 Hz. Therefore, the generated terahertz wave inherits the narrow line width of the RF source besides its frequency accuracy.

Noteworthy is that small amount of carrier signal passing

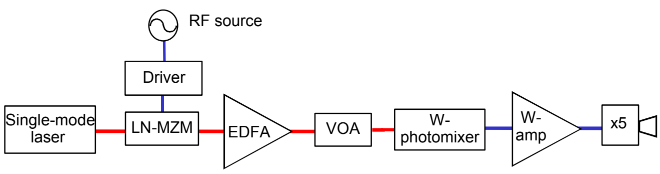

Fig. 1: Schematic of the terahertz-wave source.

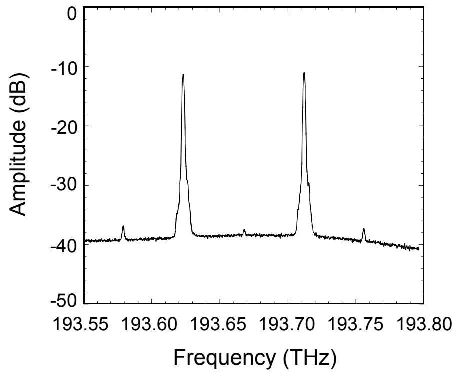

Fig. 2: Optical spectra of LN-MZM output.

through the LN-MZM and higher-order modes generated in the LN-MZM as shown in Fig. 2 scarcely degrade the signal quality of the terahertz wave. This is because the mixing of the main and these spurious signals doesn't generate W-band signal. The limited operation bandwidth of the W-band components therefore eliminates the need for an optical band-pass filter that rejects the spurious signal after the MZM-IM, which leads to a simple system configuration while ensuring frequency tunability.

III. Spectroscopic application

Using this CW terahertz source, spectroscopic measurements were carried out for N_2O gas mixed with N_2 gas in the ratio of one to one per volume. A gas cell with a length of 0.5 or 1 m was filled with the gas mixture at atmospheric pressure. Terahertz wave radiated from the quintupler was once collimated with an off-axis parabolic mirror and irradiated to one end of the gas cell. Then, another off-axis parabolic mirror placed at the other end of the cell focused the terahertz wave onto the detector. In this measurement, a Schottky barrier diode or Golay cell were used as a terahertz detector. The intensity of the transmitted terahertz wave was measured as a function of its frequency. We also prepared gas cell filled with pure N_2 gas. By normalizing the transmitted intensity of the N_2O + N_2 cell with that of the pure-N_2 cell, we derived the transmittance for N_2O gas.

The result for the 1-m long cell is shown in Fig. 4. The absorption peak of the terahertz wave was observed at the frequency of 452.5 GHz that agrees well with that of the rotational transition from *J'* = 18 to *J''* = 17 of N_2O gas molecules, 452.6 GHz, although there are residual ripples in the background due to the imperfect calibration procedure for frequency-dependent transmission characteristics of gas cells. The absorption peak was also observed for the 0.5-m cell at the same frequency with its peak depth half of that for 1-m cell. The broken line is the Lorentzian function fitted to the experimental data. The full-width at half maximum of the absorption line 4.0 GHz obtained from this curve fitting agrees with calculated one, 5.6 GHz. Therefore, it is concluded that the observed absorption peaks originate from a rotational transition of N_2O gas molecules. This result indicates that the developed CW terahertz-wave source based on photonic millimeter-wave generation has the high frequency accuracy and narrow linewidth required for the spectroscopic applications.

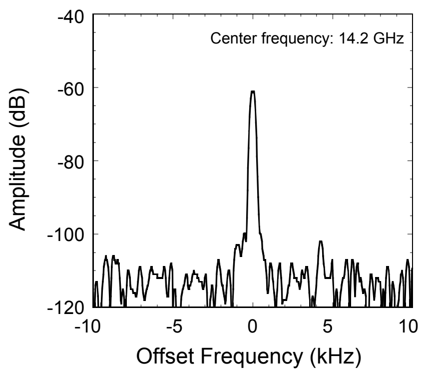

Fig. 3: Spectra of the mixer IF signal.

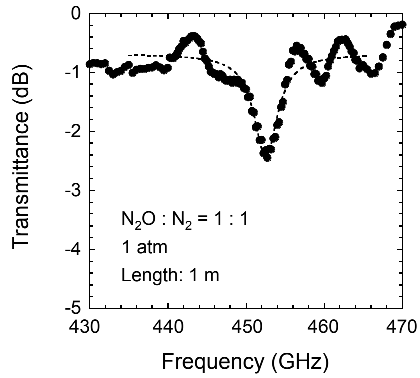

Fig. 4: THz transmission characteristics.

IV. Conclusion

A CW terahertz-wave source operating from 390-500 GHz was developed based on a photonic millimeter-wave generation technique. The generated terahertz wave inherits the narrow linewidth and high frequency accuracy of the RF source. From the gas absorption line measurements, we confirmed the applicability of the system to spectroscopic applications.

Acknowledgment

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