Multiple-Frequency Generation of Sub-Terahertz Radiation by Multimode LD Excitation of Photoconductive Antenna

Masahiko Tani, Shuji Matsuura, Kiyomi Sakai, and Masanori Hangyo

***Abstract*— Multiple-frequency coherent radiation in the sub-terahertz region was generated by excitation of a photoconductive antenna with a commercially available multimode laser diode (LD). The origin of the radiation was the current modulations in the photoconductive antenna caused by the optical beats between the longitudinal modes of the LD. An interferometric spectral measurement showed line spectra at frequency multiples of 52 GHz beyond 400 GHz. This result indicates that the photoconductive antenna with a multimode LD excitation can achieve a wavelength-selectable coherent radiation source in the sub-terahertz region with a very simple and compact device configuration.**

***Index Terms*—Multimode LD, photoconductive antenna, photomixing, sub-terahertz radiation.**

I. Introduction

THE generation of coherent terahertz radiation with photoconductive antennas excited by cw laser light modulated at terahertz beat-frequencies has recently been reported by Brown *et al.* [1], [2]. This technique, referred to as "photomixing," uses optical intensity beats resulting from two lasers to drive the biased photoconductive antenna based on high-speed semiconductors, such as low-temperature-grown (LTG) GaAs. Brown *et al.* used two independently operated lasers (Ti: sapphire lasers [1] or single-mode LD's [2]), whose wavelengths were shifted a little toward each other and were spatially coupled in order to produce optical intensity beats in terahertz frequencies. The main advantage in using two independent lasers is the tunability of the difference frequency over a wide frequency range. However, sophisticated techniques are needed for stabilization and spatial mode matching of the two lasers. In addition, a 3-dB loss of laser power at the laser beam coupling is inevitable. Hyodo *et al.* [3] reported a photomixing experiment using a microchip laser which operated in two longitudinal laser modes. They demonstrated very stable and narrow-band (430 Hz) millimeter-wave generation at a frequency corresponding to the mode separation (101 GHz). The advantages in using a monolithic dual-mode laser are the compactness of the laser source and the stability of the difference frequency between the laser modes originating from the common-mode rejection effects [3]. However, the frequency tunability is largely sacrificed.

In this letter we report the generation of multiple-frequency coherent radiation in the sub-terahertz region with a very simple and compact device configuration, that is, the excitation of a photoconductive antenna with an LD operating in multimode. Since a multimode LD has many laser modes, the laser intensity is expected to be modulated with multiple beat-frequencies between those laser modes. When the biased photoconductive gap in a photoconductive antenna was irradiated with a multimode laser, the photo-induced current in the antenna is modulated according to the laser intensity modulation if the carrier lifetime in the photoconductor is short enough compared to the shortest modulation period. The modulated current in the photoconductive antenna will then emit multimode frequency radiation corresponding to the multiple laser beats.

II. Experiment

The experimental setup was similar to that in the experiment of Hyodo *et al.* except that we used a multimode LD for the excitation instead of the dual-mode microchip laser. We also used a Martin–Puplett polarizing interferometer to characterize the radiation spectra instead of the radio frequency (RF) spectrum analyzer. We used a commercially available multimode LD (SDL-2432-P1) operating at a constant current and temperature. Fig. 1 shows the spectrum of the multimode LD measured using a spectrometer with a spectral resolution of 0.0055 nm (≅2.6 GHz). The bias current and operating temperature of the LD was 500 mA and 10.9 °C. The spectral peaks almost equally spaced by about 0.11 nm (corresponding to about 50 GHz) are due to the longitudinal modes of the laser, and the additional peaks observed around the longitudinal modes are attributed to the transverse modes. The width of the spectral peaks are 6–15 GHz, depending on the peaks.

The multimode laser beam was focused on the biased photoconductive gap of the photoconductive antenna with a set of collimating and focusing optics. The photoconductive antenna consisted of a metalized 2-mm-long bow-tie antenna on LTG-GaAs [4] with a 60° bow-angle and a photoconductive gap (10×10 μm) at the center of the bow-tie (Fig. 2). The carrier lifetime of the LTG-GaAs observed in a standard pump-probe photo-reflectance measurement was 0.6 ps. A hemispherical silicon lens with a diameter of 13.5 mm was attached to

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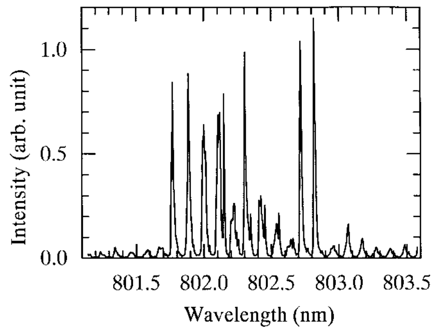

Fig. 1. Emission spectrum of the multimode LD (SDL-2432-P1).

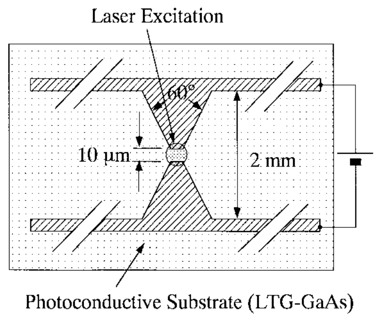

Fig. 2. Structure of the photoconductive bow-tie antenna.

the backside of the GaAs substrate of the device in order to reduce the reflection loss at the air-substrate interface and increase the radiation collection efficiency. The radiation from the photoconductive bow-tie antenna was linearly polarized in the bow direction and its polarization was oriented so as to pass through the wire-grid polarizer at the input port of the interferometer. The interferogram of the radiation was detected with an InSb hot-electron bolometer cooled to 4.2 K. The laser beam was chopped at 450 Hz and the modulated signal voltage from the bolometer was detected with a lock-in amplifier. The spectral resolution of the interferometer, which was limited by the maximum path difference of the moving mirror (30 cm), was about 1 GHz.

III. Results and Discussion

Fig. 3 shows the radiation spectrum measured with the interferometer. The input laser power was 50 mW and the applied bias voltage was 50 V. The bias current of the LD was 500 mA and the operating temperature was kept at 7 °C. Spectral peaks are observed at multiple frequencies of 52 GHz beyond 400 GHz, corresponding to the beat frequencies between the longitudinal modes of the LD. The total radiation power detected just in front of the photoconductive source was about 15 nW. The spectral intensity for the lowest frequency mode (52 GHz) is the strongest, as expected from the highest number of the laser modes contributing to the fundamental beat frequency and the decreasing efficiency of the photoconductive bow-tie antenna for higher frequencies [5]. The linewidths of the spectral peaks are 3–5 GHz, which is much narrower than that of the pumping laser modes (6–15 GHz). This can be explained by the common-mode rejection effect, by which a large part of the frequency fluctuations of the beats

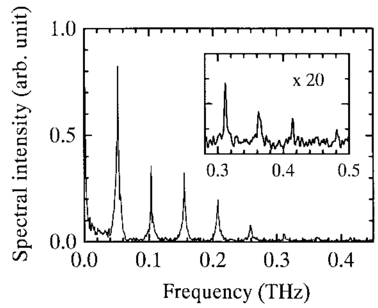

Fig. 3. Radiation spectrum for the photoconductive bow-tie antenna excited with the multimode LD. The spectral resolution was about 1 GHz. The inset is the magnified spectrum for the higher frequency modes.

are canceled out and thus the beat frequencies of the laser are stabilized as demonstrated in [3]. The frequencies of the radiation peaks were stable throughout the experiment: no detectable shift was observed even if the operating temperature of the LD was changed from 7 °C to 15 °C.

The radiation power increased quadratically with both bias voltage and pump laser power. This indicates that the amplitude of the radiation field was proportional to the modulation amplitude of the photo-current in the photoconductive antenna as expected from the simple radiation theory of antennas [5]. From the quadratic dependence of the radiation power on the pump laser intensity, a high-power pulsed LD is expected to be useful to increase the radiation power avoiding the damage of the photoconductive device by the laser power. For example, a pulsed laser excitation with 5-W peak power and 1% duty ratio will increase the total radiation power by a factor of 100 with the same averaged laser power as in the present experiment (50 mW), making it possible to have a radiation power beyond 1 μW. The line broadening of the radiation due to the pulsed excitation will be negligible when the duration of the laser pulses are on the order of hundreds of nanoseconds. The resonant antennas, such as dipole antennas, are also useful to increase the radiation power at a specific frequency range [5].

IV. Conclusion

We have demonstrated multiple-frequency generation of sub-terahertz coherent radiation by the excitation of a photoconductive bow-tie antenna with a commercially available multimode LD. The equally spaced spectral lines corresponding to the beats of the longitudinal modes of the LD were observed below 500 GHz. The linewidths of the radiation are narrower than those of the laser lines indicating the common-mode rejection effect.

In order to get a narrower linewidth and to select a particular harmonic mode of the radiation, we can use the optical filtering to cut out sharp laser lines with a desired mode spacing by using a Fabry–Perot (F–P) interferometer, whose transmission peaks and free spectral range are adjusted to the peaks and the spacing of the desired laser modes, respectively [6]. The remaining higher order harmonic components of the radiation can be rejected by using an appropriate far-infrared low-pass or bandpass filter for the relevant frequency range. The linewidth of the radiation will be determined by the finesse of the

F–P interferometer. An increase of the emission efficiency for the radiation is also expected from the increased modulation depth of the optical beat with the decreased numbers of the interfering laser modes [6]. Thus, our experimental results indicate that, when combined with appropriate optical filters (i.e., a F–P interferometer and a far-infrared low-pass filter), a photoconductive antenna excited by a multimode LD with a very simple and compact device configuration can be a stable and wavelength-selectable source of coherent radiation in the sub-terahertz frequency region.

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