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Generation of Coherent cw-Terahertz Radiation Using a Tunable Dual-Wavelength External Cavity Laser Diode

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A tunable dual-wavelength external cavity laser diode (2-λ-ECL) was used to generate tunable coherent cw-terahertz (THz) radiation by photomixing in a biased photoconductive antenna fabricated on a low-temperature-grown (LTG)-GaAs film. The 2-λ-ECL oscillated at the two output modes simultaneously with a frequency separation from 250 GHz to 2.1 THz in the same cavity. We demonstrated that the frequency of the emitted THz radiation corresponded to the difference frequency between the two modes of the diode laser. The tunable 2-λ-ECL, due to its compact design and ease of optical alignment, is a promising laser source for the generation of tunable cw-THz radiation by photomixing.

KEYWORDS: tunable dual-wavelength external cavity laser diode, tunable cw-THz radiation, LTG-GaAs, photomixing

A tunable, compact, stable and inexpensive coherent cw-THz source is highly desirable for high-resolution THz spectroscopic measurements and other potential applications in the terahertz frequency region.[1–3] Recently, a technique for generating tunable coherent cw-THz radiation by mixing two independently tunable lasers in a biased photoconductive antenna fabricated on a low-temperature-grown (LTG) GaAs film has been used by several groups.[4–6] By changing the difference frequency between the two lasers, a tunable coherent cw-THz source was realized at frequencies up to 5 THz.[7] In this method, the stability of the two excitation lasers determines the stability of the THz radiation. Further, the excitation efficiency critically depends on the spatial mode matching of the two lasers.[8] Alternatively, one can employ a laser simultaneously oscillating in two modes with complete spatial overlap. Previously, we explored photomixing using a two-longitudinal-mode distributed Bragg reflector (DBR) laser diode to generate 162.5 GHz radiation.[9] We found that the linewidth of the radiation was much narrower than that of each laser mode due to the common-mode rejection effect between the two modes oscillating in the same cavity.[10] The frequency separation of the two modes, however, cannot be easily tuned due to the monolithic device structure. In this work, to our knowledge we demonstrate for the first time the generation of tunable coherent cw-THz radiation by photomixing the output of a tunable dual-wavelength laser diode in an external cavity (2-λ-ECL). The experimental configuration is very simple and compact compared with the conventional photomixing method using two independent lasers.

Figure 1 shows the experimental setup. The configuration of the 2-λ-ECL is similar to that in our previous work.[11] A broad-area laser diode chip (SDL-2630C) with a nominal wavelength $\lambda_o = 830$ nm was used as the gain medium. It has a high-reflectivity (HR) coating ($R > 95\%$) on the rear facet and an antireflection (AR) coating of about 0.1% reflectivity on the front facet. A 2000 line/mm diffraction grating is used for wavelength selection and for output coupling of the laser cavity. The emission of the diode array from the AR-coated facet is collimated by a 40x, 0.5 NA microscope objective lens and is incident on the grating at an angle of 79°. The first-order diffracted light is then focused on a V-shaped double-stripe end mirror by a lens ($f = 250$ mm).

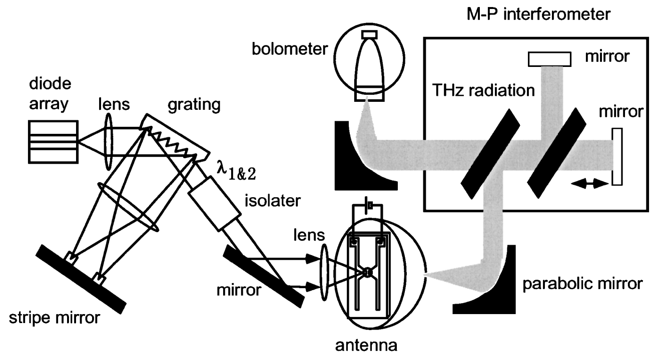

Fig. 1. Experimental setup of a tunable coherent cw-THz radiation system.

The V-shaped double-stripe end mirror is used to select the two oscillation wavelengths simultaneously. The length and width of each stripe is 10 mm and 0.120 mm, respectively. The angle between them is 15°. The width of the stripes is sufficient to suppress the other modes than the two selected laser modes. The two-separated single mode is coaxial, has the same polarization, and oscillates in the same cavity. The wavelength separation is determined by the separation of the V-shape double-stripe mirrors. By adjusting the horizontal position of the stripe with respect to the optical axis or tilting the end mirror to select the equal gain of two laser modes on opposite slopes of the gain profile, the laser can oscillate at equal output powers for the two wavelengths. Because the two laser modes utilize a different gain section of the broad-area laser diode, the competition or crosstalk between the two modes is weak.[12] The main laser output was from the zeroth-order diffracted light from the grating. The zeroth-order reflection of the grating was about 60% of the incident light from the diode chip. The threshold bias current of the 2-λ-ECL was 420 mA. The spectral separation of the two output wavelengths can be tuned from 0.58 to 4.82 nm (250 GHz to 2.1 THz) by vertically translating the V-shaped double-stripe end mirror. The total output power over the tunable spectral separation at a bias current of 430 mA and a temperature of 20°C is almost 8 mW, as shown in Fig. 2. The inset of Fig. 2 shows a typical output spectrum of the 2-λ laser with the wavelength separation at $\Delta\lambda = 1.2$ nm measured using an optical spectrum analyzer. The linewidth of each mode was less than 10 MHz, estimated using a scanning Fabry-Perot interferometer. The side mode suppression ratio is over 20 dB

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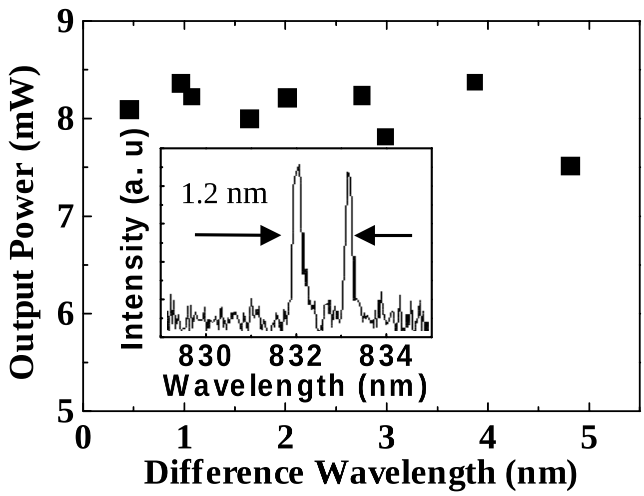

Fig. 2. Output power of the tunable dual-wavelength operation diode laser system measured at a bias current of 430 mA and at 20°C. The inset shows a typical dual-wavelength output spectrum.

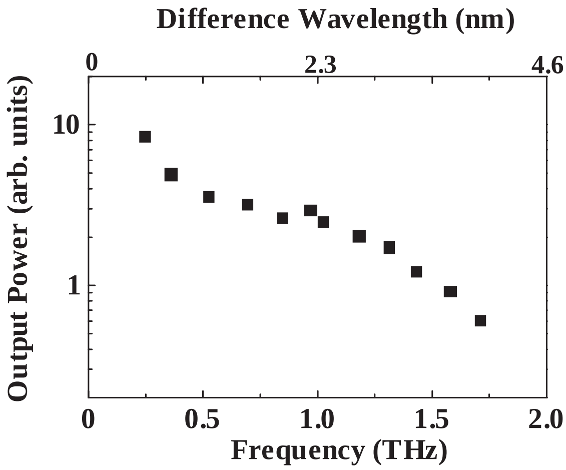

Fig. 3. Output spectrum of the cw-THz radiation from a 1-mm-long dipole antenna measured with an InSb hot-electron bolometer cooled to 4.2 K.

and 10 dB for the minimum and maximum separation, respectively.

The output of the 2-λ-ECL was focused on the biased electrode gap of a 1-mm-long dipole photoconductive antenna with a set of collimating and focusing optics. The photoconductive antenna (AuGe/Ni/Au) was fabricated on the LTG-GaAs layer. The LTG-GaAs has a short (sub-ps) photocarrier lifetime, a high photocarrier mobility (200 $cm^2 \cdot V^{-1} \cdot s^{-1}$), and a high DC breakdown field that is larger than 5×10^5 V/cm.[13] These properties of the LTG-GaAs are desirable to use as a substrate of a photomixer to emit THz radiation. A hemispherical silicon lens with a diameter of 3 mm is attached to the backside of the GaAs substrate of the antenna device in order to reduce the reflection loss at the air-substrate interface and to increase the radiation collection efficiency. The cw-THz radiation emitted from the dipole antenna is linearly polarized in the dipole direction. The THz radiation was first collimated with a parabolic mirror, then passed through a Martin-Puplett polarizing interferometer[14] and was finally focused onto a 4.2 K InSb hot electron bolometer with another parabolic mirror to detect the THz radiation power and spectrum, as shown in Fig. 1.

Figure 3 shows an output power of the cw-THz radiation as a function of the difference wavelength between the two modes. An optical spectrum analyzer was used to monitor the difference wevelength (corresponding to the frequency of the detected THz radiation) of the two modes. A trend of decreasing THz radiation power with increasing radiation frequency is evident in Fig. 3. This can be explained as follows. It is well known that the photoconductive antenna has a tendency to suppress the power emission at high frequencies because of the photocarrier lifetime of the LTG-GaAs and photomixer antenna RC time constant, where R is the radiation impedance and C is the electrode capacitance.[8] We used a 1-mm-long antenna with a resonance frequency of 120 GHz, at which the antenna emitted the highest radiation power. The radiation power of the antenna falls in frequency regions lower and higher than 120 GHz. Furthermore, the sensitivity of the InSb bolometer is roughly inversely proportional to the detection frequency.[15] The sensitivity of the bolometer used in our experiment is two times higher at 250 GHz than that at 1 THz, and the cutoff frequency is almost 2 THz. Therefore, we cannot measure radiation power above 1.75 THz with a good signal-to-noise ratio using the InSb bolometer. For these reasons, we observed THz radiation power which decreased with increasing radiation frequency as can be seen in Fig. 3. The radiation power from the antenna was estimated to be about 2 nW at 250 GHz.

To further investigate the properties of cw-THz radiation from the antenna, we fixed the difference wavelength of the tunable two-mode diode laser operating at 0.58 nm (250 GHz), and measured the radiation frequency using a Martin-Puplett polarizing interferometer. The polarization of the THz radiation through the silicon hemispherical substrate lens is oriented to pass through the wire-grid polarizer at the input port of the Martin-Puplett polarizing interferometer. The interference signal at the output port was measured with an InSb hot-electron bolometer cooled to 4.2 K. The laser beam is chopped at 200 Hz and the modulated signal voltage from the bolometer is detected with a lock-in amplifier. Figure 4(a) shows the interference signal of the radiation. Figure 4(b) shows the Fast Fourier Transform (FFT) of the interferogram (a). The radiation frequency was 250 GHz, corresponding to the wavelength difference of 0.58 nm. The emission of radiation with the same frequency as the beat frequency of the tunable 2-λ-ECL indicates that the radiation originates from the photocurrent modulated by the tunable 2-λ-ECL. The spectral resolution of the interferometer, which is limited by the maximum path difference of the scanning mirror (5 cm), is approximately 6 GHz. Therefore, we could measure the linewidth of the radiation directly. However, in the previous work we showed that the linewidth of the beat frequency of the two modes in the same laser cavity was narrower than that of individual laser modes.[9,10] This is because a large part of the frequency fluctuations of the two laser modes was canceled out due to the two-mode oscillation in the same cavity. It was established that the linewidth of the cw-THz radiation generated by the photomixing method was almost the same as the beat linewidth of the two excitation lasers. We suggest that the tunable two-mode operation diode laser using as the excitation source can generate a stable and compact tunable cw-THz radiation. We are currently studying the stabilizer of the tunable two-mode operation diode laser in order to gener-

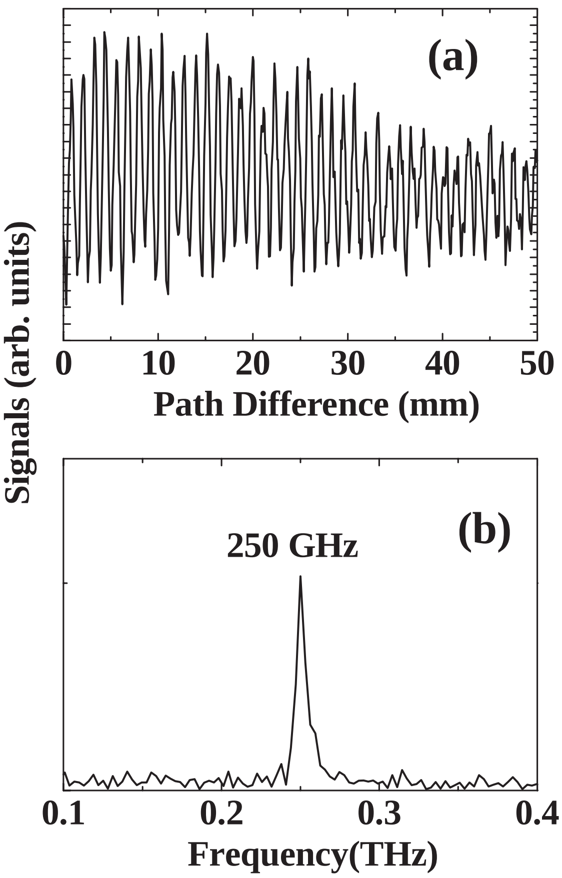

Fig. 4. (a) Interferogram (b) the corresponding Fourier spectrum of the THz signal with the wavelength separation of the laser at $\Delta\lambda = 0.58$ nm.

ate more stable cw-THz radiation. Improvement in the spectral purity of the THz radiation is expected by achieving the frequency stabilization of the laser.[16] The laser output can be increased by techniques such as injection locking.

In summary, tunable coherent cw-THz radiation is generated by exciting the photoconductive antenna fabricated on an LTG-GaAs layer using a tunable dual-wavelength external cavity laser diode (2-λ-ECL). The system is simpler and more compact than that using two independent lasers. Our results indicate that the tunable 2-λ-ECL is a promising laser source for photomixing, which will enable us to build a stable and compact tunable coherent cw-THz radiation source.

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