Distributed feedback laser diode integrated with distributed Bragg reflector for continuous-wave terahertz generation

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Abstract: A widely tunable dual mode laser diode with a single cavity structure is demonstrated. This novel device consists of a distributed feedback (DFB) laser diode and distributed Bragg reflector (DBR). Micro-heaters are integrated on the top of each section for continuous and independent wavelength tuning of each mode. By using a single gain medium in the DFB section, an effective common optical cavity and common modes are realized. The laser diode shows a wide tunability of the optical beat frequency, from 0.48 THz to over 2.36 THz. Continuous wave THz radiation is also successfully generated with low-temperature grown InGaAs photomixers from 0.48 GHz to 1.5 THz.

OCIS codes: (140.5960) Semiconductor lasers; (140.3600) Lasers, tunable; (300.6495) Spectroscopy, terahertz.

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1. Introduction

Continuous wave (CW) terahertz (THz) systems have attracted great interest owing to their wide range of applications in fields such as wireless communications, spectroscopy, and sensing [1, 2]. Frequency-domain THz CW systems are superior to THz time-domain spectroscopy (THz-TDS) systems in terms of frequency resolution, compactness, and a wide range of field applications [3, 4]. Therefore, a compact and widely tunable CW THz emitter based on photonics technology can be used in new fields of application. A single-chip and frequency-tunable THz emitter can be realized by combining an optical beat source and a fast opto-electronic (OE) converter such as a waveguide-type photomixer or fast photodiode. With this approach, an efficient and compact optical beat source becomes a key component of the single chip THz emitter.

Optical beat sources have been widely reported for CW THz systems. Two solitary distributed feedback (DFB) laser diodes (LDs) or external cavity lasers are typically used in commercially available CW-THz systems [5, 6]. They use bulk optics in case of 780 nm system, and a polarization maintaining fiber to match the polarization of the two laser beams in case of 1550 nm system. Also, fiber-based laser systems have been developed to have a rapid frequency sweep and a wide tuning range [7, 8]. However, fiber lasers have problems in longitudinal multi-modes and gain competition of erbium-doped fiber. Additionally, a monolithically integrated dual-mode DFB LD has been reported [9, 10]. Although a single cavity structure is realized and its tuning range exceeds 1.34 THz, the compound cavity modes limit the output power.

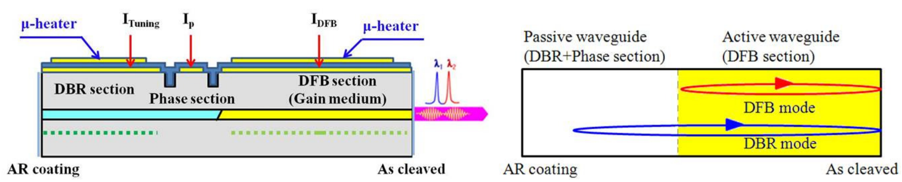
Regarding the optical characteristics, the parameters related to the spectral purity of optical beat sources, such as linewidth, relative intensity noise (RIN), and phase noise between two modes, determine the characteristics of the generated THz radiation. This implies that if two lasing modes are emitted from a single resonator, the generated THz radiation via photomixing would be sufficiently narrow and stable [11]. The system configuration is also greatly simplified when it is combined with a heterodyne receiver, such as a Schottky diode [12], and field-effect transistors [13]. However, development of a widely tunable dual-mode laser with a single cavity structure is technically challenging. Because typical tuning methods, such as thermal and electrical tuning via plasma effect, affect both lasing modes, the beat frequency cannot be tuned over a wide range of wavelengths. Furthermore, the gain competition between two lasing modes also prevents the optical beat source with a single active medium from performing dual-mode operation [14].

So far, DFB LD based beat sources have utilized a thermal tuning method to change the optical beat frequency. However, linewidth broadening at high temperatures due to the thermal effect deteriorates the spectral purity of the generated CW-THz radiation [15, 16]. Furthermore, the gain peak shift decreases the output power of optical beat sources. From the standpoint of tunability, distributed Bragg reflector laser diodes (DBR LDs) with a passive waveguide are likely to be the best solution for widely tunable dual mode LDs. A wide wavelength tuning range could be achieved by using thermal tuning and plasma effect via carrier injection [17]. However, it is not easy to match the optical phase of two lasing modes for continuous, independent, and simultaneous wavelength tuning.

In this paper, we report a novel dual-mode laser diode having a single cavity geometry and exhibiting compound cavity mode free operation with enhanced output power characteristics as well as a broad tuning range.

2. Tunable dual-mode laser

Figure 1(a) shows a schematic diagram of the DBR-integrated DFB dual mode LD (DFB-DBR). It consists of a λ/4 phase-shifted DFB LD as a single gain medium, a phase section, and a DBR section. The phase and DBR sections are composed of a passive waveguide of comprising 1.3Q InGaAsP fabricated via the butt coupling process. The length of the DFB LD, phase, and DBR sections are 400 µm, 50 µm, and 250 µm, respectively. A buried hetero-structure with a pnp current blocking layer is used and a deep trench between each section is introduced for electrical and thermal isolation. Coupling coefficient κ is precisely controlled by adjusting the duty cycle of a grating during the e-beam lithography step for stable operation of the DFB mode and single mode operation of the DBR mode. In order to increase the tuning range of the optical beat frequency, we set the DBR mode to a longer wavelength as compared to that of the DFB mode by controlling the grating period. Micro-heaters (µ-heaters) are integrated on the DFB and DBR mirror sections for continuous wavelength tuning of each mode. Even though the µ-heater provides continuous wavelength tuning without mode hopping, the spectral purity parameters such as linewidth and RIN are rapidly deteriorated in the case of high µ-heater power [16]. We introduce an electrode in the DBR section to reduce the required µ-heater power for wavelength tuning; thus, plasma effect of the DBR mode by means of current injection into the DBR section also widens the tuning range of the DBR mode.



(a) (b)

Fig. 1. Structure of the DFB-DBR LD. (a) Schematic diagram of the device structure, and (b) lasing modes

The cavity structure of the DFB-DBR can be analyzed as shown in Fig. 1(b). One mode oscillates in the phase shifted DFB LD section (DFB mode), and the other mode is generated by the optical cavity formed by the as-cleaved front facet and DBR (DBR mode). Consequently, the dual mode LD can be considered a kind of monolithically integrated device with a DFB and DBR LD occupying the same gain medium, and two lasing modes are effectively emitted from a single resonator.

Figure 2 shows the output spectrum of the initial operating state, which shows that any operating current flowing into the DBR section and µ-heaters is not injected. The current is only applied to the DFB section (gain section). Clear mode behaviors are shown for each

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mode. The DFB mode has a stopband of 2.05 nm, and the DBR mode has a mode spacing of 0.6 nm. To reduce gain competition between the two lasing modes, we set the optical gain peak to 1543 nm. The large wavelength differences above 300 GHz and inhomogeneous properties of the active medium at the low energy side of the gain peak reduce gain competition and enable the dual-mode operation over a wide range.

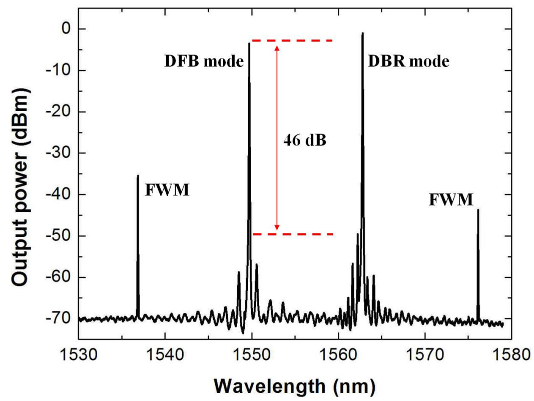

Fig. 2. Output spectrum of the initial operating state. Current is injected into the DFB section only. Side mode suppression ratio is 46 dB.

3. Wavelength tuning

Wavelength tuning is mainly achieved by controlling the refractive index of DBR section. The plasma effect of DBR section via current injection tunes the DBR mode to the short wavelength side, and thermal tuning of lasing modes via integrated μ-heaters moves the lasing modes to the long wavelength side. For a low optical beat frequency, we inject the current into the DBR section for plasma effect tuning of the DBR mode and integrate a μ-heater on the DFB section for thermal tuning. Then, the mode beat frequency can be tuned from 1.65 THz to 0.48 THz. The dissipated power of the μ-heater on the DFB section is 0.21 W. This regime is clearly shown at the bottom of Fig. 3(a). In this configuration, the stopband of the DFB mode limits the tuning range since the overlap of the + 1 mode of the DFB LD and one of the DBR modes results in the deterioration of the DFB LD characteristics due to high optical feedback [18]. To increase the mode beat frequency from the initial operating state, we use the μ-heater on the DBR section; consequently, the DBR mode shows a red-shift due to the thermal effect. The optical mode beat frequency can be tuned from 1.65 THz to 2.36 THz, as shown in Fig. 3(a). Because the thermal tuning of the DBR mode is independent of the gain peak shift in the DFB section, it provides a wider tuning range for the DBR mode than for the DFB mode. In case of high optical beat frequency tuning, the gain bandwidth of the active medium determines the maximum tuning range. We also measured the thermal tuning speed via μ-heater by using the dual-mode laser in [4]. It shows a fast tuning speed of about 10 ms/0.5 W. In the case of DBR mode tuning in the DFB-DBR, the maximum dissipated power of the μ-heater is 1.3 W. As shown in Fig. 3(a), the tuning characteristic of the DBR mode does not remain continuous if the optical phase is not controlled. However, by introducing the current to the phase section between the gain and DBR sections, continuous wavelength tuning is successfully obtained, as shown in Fig. 3(b). The optical beat source should provide continuous-mode beat frequency tuning in the application of a CW-THz spectrometer. However, because many materials applicable to CW-THz spectroscopy have wide absorption spectra, coarse and fine mode tuning can be applied to the spectroscopic application in the THz regime. The DFB-DBR configuration operates in a fast coarse mode without controlling the operating condition of the phase section and in the fine mode with phase adjustment. It should be noted that the DFB mode maintains its wavelength and spectral purity very well

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during DBR mode tuning. This assures easy operation and wide and stable beat frequency tuning. We have measured the frequency setting resolution of the optical beat by using a heterodyne setup with the external tunable LD. Although the thermal fluctuation of un-packaged device causes difficulties in measuring the exact value, we confirmed that the frequency setting resolution of the optical beat is below 300 MHz. We believe that thermal stabilization with a packaged device, and optimization of the DBR LD structure will improve the frequency setting resolution below 100 MHz.

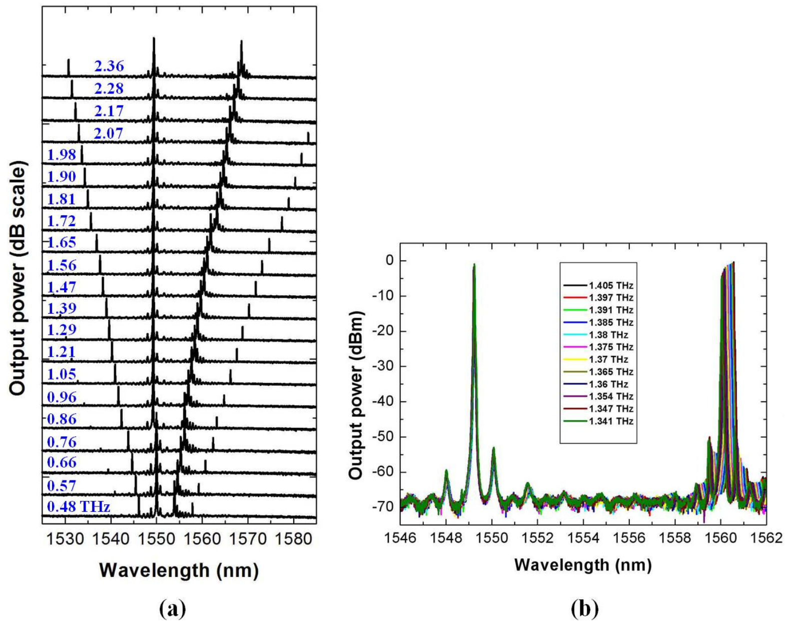

Fig. 3. Wavelength tuning spectra of the DFB-DBR LD. (a) Optical beat frequency can be tuned from 0.48 THz to over 2.36 THz, and (b) tuning spectra in fine tuning mode.

Since each mode is selected by the Bragg grating, the other modes do not appear. Although this device is a kind of monolithically integrated laser, the operating characteristics do not depend on the compound cavity modes [9]. The output power of the dual-mode laser in [4] is limited near 3 mW by the compound cavity modes. We successfully increase the output power of the dual-mode laser up to 17 mW by realizing the compound-cavity-mode free operation. The output power slightly decreases to 15 mW when changing the operating wavelength of DBR mode. When the optical beat frequency decreases, the free-carrier loss in the passive waveguide reduces the power of the DBR mode. When the optical beat frequency increases, the reduced optical gain decreases the output power of the DBR mode. Consequently, the output power can be increased by increasing the operating current of the gain section; the device shows a wide operating window while maintaining dual-mode operation.

The four-wave mixing (FWM) signal with power level over 30 dB from the amplified spontaneous emission level indicates high mode correlation and efficient mode beating. The physical origin of the FWM is related to optical mode beating in terms of high power, beam overlap, polarization, and phase noise [19]. Furthermore, at the high detuning frequency over 100 GHz, the phase noise between two lasing modes is main factor of the efficiency of the FWM [20]. The strong FWM signals through whole tuning range over 2 THz means low phase noise of optical beat signal. We measured autocorrelation traces by changing the optical beat frequency, as shown in Fig. 4(a). The efficient mode beats are measured in each tuning step. The beat frequencies of the plasma, initial, and thermal tuning regions are 1.31 THz,

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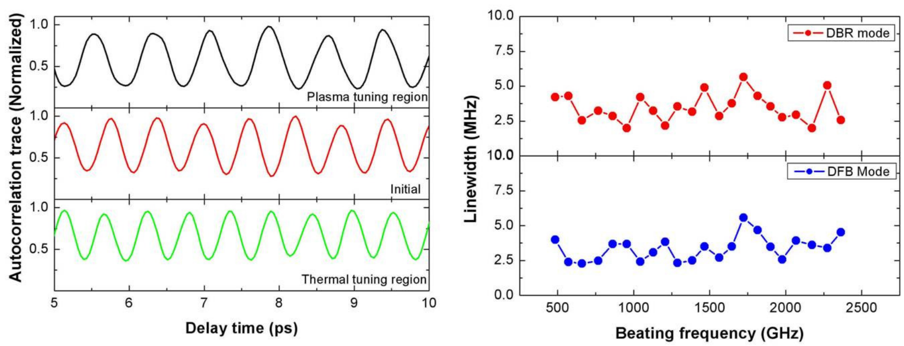
1.65 THz, and 1.84 THz, respectively. We should address noise characteristics such as the linewidth of lasing modes, which determines the linewidth of the generated THz radiation via photomixing. We measured the optical linewidth of the lasing mode using a delayed self-homodyne method with 25 μs optical time delay [21]. A narrow grating filter was used to select each mode. As shown in Fig. 4(b), the optical linewidth of each mode ranges from 2 MHz to 5.6 MHz depending on the operating conditions. However, they are sufficiently narrow to serve as an optical beat source. When high μ-heater power is applied to the gain medium directly, the reduced gain at the lasing wavelength causes a degradation of the linewidth and RIN [17]. By introducing the DBR laser structure, we can reduce the required power of the μ-heater on top of the gain medium and increase the mode beat frequency without any deterioration in spectral purity of the lasing modes. We currently cannot measure the linewidth of the CW THz radiation, however, we believe that the single cavity geometry, low phase noise between two lasing modes, and narrow optical linewidth indicate high spectral purity of the generated CW THz radiation [22].



(a) (b)

Fig. 4. (a) Autocorrelation traces for plasma effect tuning, initial state, and thermal tuning region, and (b) measured optical linewidth of each mode in wavelength tuning.

4. CW THz generation

To verify the device characteristics of the optical beat source in the CW THz system, we measured the CW THz spectrum [9]. A typical homodyne method was used with low-temperature-grown (LTG) InGaAs photomixers. A mesa structure was utilized to reduce the dark current of the photomixer. The log-spiral antenna and interdigitated finger were defined by the stepper system. Detailed characteristics of the log-spiral-antenna-integrated photomixers are reported elsewhere [23]. The measured CW THz spectrum is shown in Fig. 5. We successfully measured CW THz radiation from 488 GHz to 1.5 THz. The inset shows the waveform of the generated THz radiation at a frequency of 488 GHz obtained by using the thermal tuning of the DFB mode and electrical tuning of DBR mode simultaneously. It means that the operating condition of DFB-DBR laser as the optical beat source at 488 GHz can be deteriorated. However, we can measure the clear and stable CW THz waveform as shown in inset of Fig. 5. The signal-to-noise ratio of the generated CW THz in this frequency range is over 40 dB.

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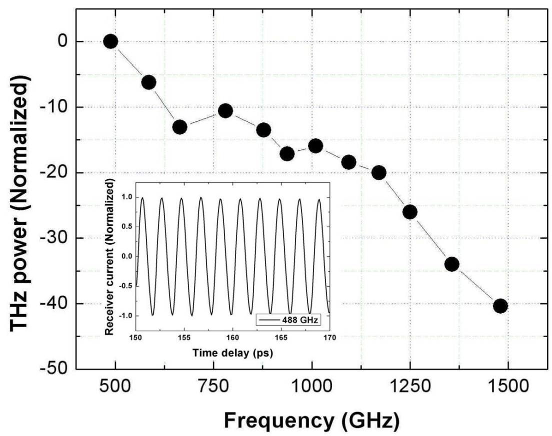

Fig. 5. CW THz spectrum measured with the DFB-DBR dual-mode laser and LTG InGaAs photomixers. Inset shows the CW THz waveform at a frequency of 488 GHz.

Although the tuning range of DFB-DBR exceeds 2.3 THz, the CW THz spectrum is limited by 1.5 THz due to the characteristics of our LTG InGaAs photomixers. The tuning range of CW THz radiation in the low frequency is also limited by the minimum optical beat frequency of the DFB-DBR laser. This limitation can be easily overcome by adjusting the initial operating wavelength of the DBR mode. For example, if the initial optical beat frequency is set to 1.3 THz, the DFB-DBR laser can cover a wide frequency range from 0.2 THz to 2.4 THz. Tuning range of optical beat frequency is determined by the stopband width of the DFB laser and the optical gain bandwidth of the active medium.

5. Summary

We developed a widely tunable dual-mode laser diode with single cavity geometry. By introducing a DBR LD structure to a phase-shifted DFB LD, the tuning range of the optical beat frequency increased while maintaining the spectral characteristics. This novel device showed a wide mode beat frequency tuning range from 0.48 THz to over 2.36 THz. Operating characteristics that were independent of the compound cavity mode were achieved, which enhanced the output power. In addition, the lasing modes had a narrow optical linewidth of below 5.6 MHz. By using the LTG-InGaAs photomixers, we demonstrated CW-THz generation from 488 GHz to 1.5 THz.

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