Widely Tunable 1.55-μm Detuned Dual-Mode Laser Diode for Compact Continuous-Wave THz Emitter

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We report the use of a widely tunable detuned dual-mode laser diode (DML) as a compact and portable continuous-wave THz emitter. The wavelength difference between the two lasing modes of this DML can be tuned from 2.4 nm to 9.3 nm by using integrated microheaters. The power difference between these modes is less than 1 dB, and the side-mode suppression ratio is greater than 30 dB over the entire tuning range.

Keywords: Distributed feedback lasers, wavelength tunable laser, dual-wavelength, photomixing, terahertz.

I. Introduction

Terahertz technology has attracted considerable attention for filling the frequency gap between millimeter and infrared waves. It has enabled new applications of photonics in fields such as biomedicine, agriculture, security, and short-range wireless communications [1], [2]. Thus far, a combination of a photomixer and an optical beat source has exhibited the greatest potential as a portable and widely tunable continuous-wave (CW) THz emitter [3]. A high-frequency optical beat is typically generated using two independent solid laser sources operating at different wavelengths [4]. Although this setup has its own merits in that it is capable of high-power laser irradiation and exhibits high tunability, a dual-mode laser diode (DML) is preferred as a beating source in a single-chip THz emitter comprising a waveguide photomixer [5]. Moreover, a multisection laser diode (LD) structure that simultaneously exhibits two lasing modes is advantageous owing to its compactness, stability, and ability to generate THz radiation at a stable operating frequency due to the common-mode noise rejection effect [6]. Various optical beat sources exhibiting an LD structure have been proposed. First, a dual-wavelength external cavity laser was reported [7] with a mechanical moving part for tuning the operating wavelength. Second, dual-mode operation was achieved by using a frequency-selective structure or two transverse modes [8], [9]; however, the tuning range was limited. Finally, typical wavelength-tunable LDs with a distributed Bragg reflector were proposed for THz applications [10].

We previously reported a dual-mode distributed feedback (DFB) LD with a limited tuning range of 600 GHz [11]. In this letter, we report a widely tunable detuned DML having improved device characteristics. This novel, multisection LD can potentially be used as a compact optical beat source having a wide and continuous tuning range of over 1 THz with a high side-mode suppression ratio (SMSR) of over 30 dB.

II. Device Structure and Fabrication

A detuned DML consists of two DFB sections and one phase section, as shown in Fig. 1. The length of each DFB section is 300 μm, while the length of the phase section is 50 μm. An all-active waveguide structure is adopted to prevent butt coupling or selective area growth. This simplifies the fabrication procedure and stabilizes the device operation characteristics by eliminating the internal reflections that occur at the interface

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Manuscript received Nov. 9, 2010; revised Mar. 24, 2011; accepted May 3, 2011.

This work was partially supported by the Joint Research Project of ISTK, and the Public Welfare & Safety research program through the NRF funded by the Ministry of Education and Technology (20100020822), Korea.

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http://dx.doi.org/10.4218/etrij.11.0210.0429

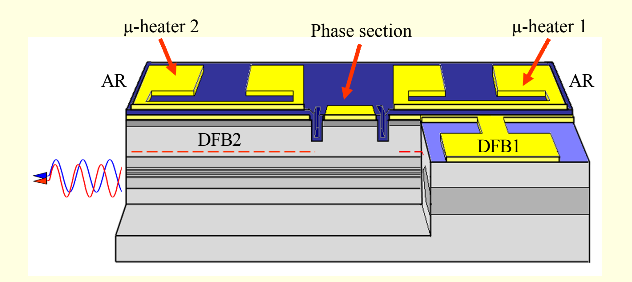

Fig. 1. Device structure of detuned DML consisting of two DFB sections and one phase section. Microheaters are integrated for wavelength tuning. Threshold current of single DFB section is 8 mA.

between a passive and an active waveguide. The active layers are composed of six strain-compensated InGaAsP multiquantum wells (MQWs). The first-order loss-coupled grating with a 240-nm period in the DFB sections is formed using an absorptive layer of InGaAs by electron beam lithography and reactive ion etching. The coupling coefficient κ extracted from the fitting process for single DFB LD with cavity length of 400 μm is 2.08-0.46j cm^{-1}. The grating pitch of each DFB LD is precisely controlled to provide a 5-nm offset between the two lasing modes. This is favorable for increasing the tuning range of the beating frequency.

The difference between the gain peak wavelength and lasing wavelength is also optimized to increase the thermal tuning range. The gain peak is set to 1,543 nm considering the full-width half maximum of photoluminescence. A microheater (μ-heater) is integrated into each DFB section for thermal wavelength tuning. Detailed procedures for device fabrication are described elsewhere [11].

III. Experimental Results and Discussion

Thermal wavelength tuning of DFB LDs is beneficial in CW THz applications because it ensures that the spectral linewidth is maintained and that the phase section is not required for continuous tuning [12]. Hence, thermal wavelength tuning is generally employed in commercially available CW THz emitters that consist of two independent DFB LDs. However, an independent and efficient mode-tuning method should be adopted for each DFB LD in the DML. Further, it is advantageous to use a μ-heater because it is easy to fabricate and provides independent thermal tuning via local heating.

Although μ-heaters can be easily fabricated on a large scale, their tuning range is limited by the optical gain shift and thermal crosstalk between the two DFB LD sections. To increase the thermal tuning range, we carefully control the optical gain peak of the MQWs by considering the full-width-half-maximum of the photoluminescence of the MQWs at a fixed DFB-operating wavelength.

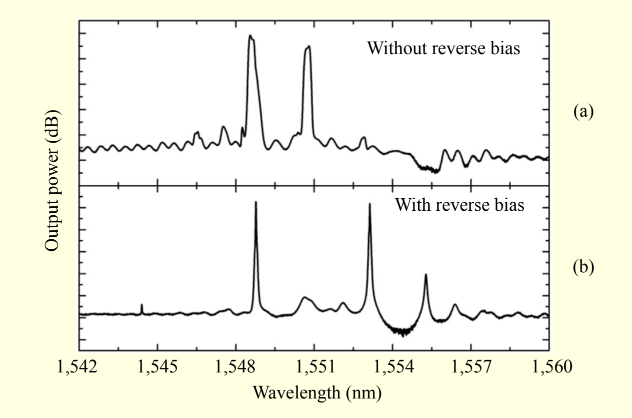

Fig. 2. Output spectra of detuned DML (a) without reverse bias and (b) with reverse bias in the phase section ($V = -0.3$ V).

The operation of the phase section in our waveguide structure depends on the bias condition. Under forward bias, the phase section controls the interaction between the two DFB sections by changing the optical phase [13]. Under reverse bias, the phase section serves as a controllable optical loss medium. Figure 2 shows the output spectra of the detuned DML with and without reverse bias in the phase section. When the two DFBs operate simultaneously, a compound-cavity mode is activated [14]. Because of the increased optical interaction under a forward bias condition, this compound-cavity mode cannot be suppressed. However, the phase section acts as a saturable absorber under reverse bias (see Fig. 2(b)) thus increasing the optical loss and successfully suppressing the compound-cavity mode by reducing the round-trip optical gain. This indicates that the all-active structure and phase section under reverse bias provide important means for controlling the compound-cavity mode.

Figure 3 shows the wavelength tuning characteristics of the detuned DML. The initial state is represented by $P_1=0$ and $P_2=0$. Here, P_1 and P_2 denote the dissipated power in μ-heaters 1 and 2, respectively. To suppress the operation of the compound-cavity mode, a reverse bias of –0.3 V is applied to the phase section. When the current in the μ-heater of DFB1 is increased, the difference between the two lasing modes decreases. However, the optical interaction between the two DFB sections increases because of the overlapping of the two stop bands. Hence, the compound-cavity mode is reactivated. Although the compound-cavity mode can be suppressed by applying a higher reverse bias voltage to the phase section, the optical power balance between the two lasing modes is disturbed because of an excessive optical loss in the phase section. Thus, we obtain a minimum wavelength difference of 2.4 nm at a μ-heater power of 0.21 W.

On the other hand, the wavelength difference can be

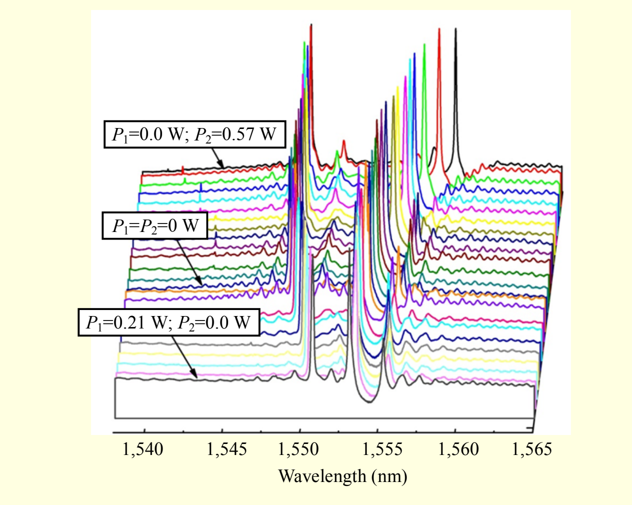

Fig. 3. Wavelength tuning characteristics of detuned DML. P_1=P_2=0 W represents initial operating condition without any input power to μ-heaters. Wavelength difference can be tuned from 2.4 nm (0.3 THz) to 9.3 nm (1.15 THz). Operation current of each DFB LDs ranges from 16 mA to 30 mA depending on power balance condition.

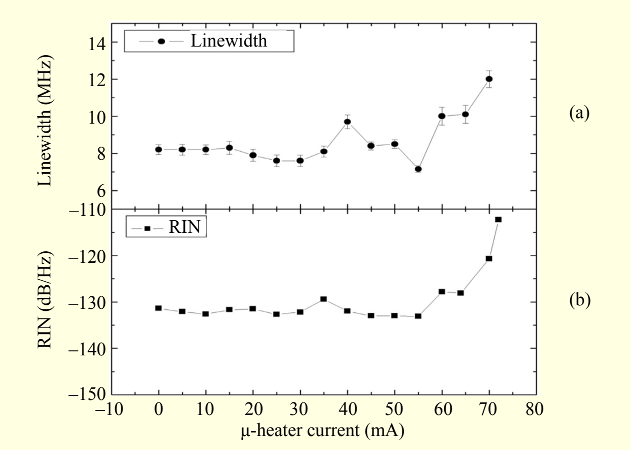

Fig. 4. (a) Optical linewidth and (b) relative intensity noise of lasing mode from DFB2 in dual-mode operation.

increased from 5 nm to 9.3 nm by changing the current in the μ-heater of DFB2. In this case, the compound-cavity mode does not seriously affect mode tuning. However, as the gain peak is thermally shifted, the power balance is disturbed when the μ-heater power exceeds 0.57 W.

The thermal crosstalk between the two DFB LDs prevents independent thermal tuning and hence limits the tuning range of the optical beat frequency. By enhancing the thermal contact between the detuned DML and the submount, we can virtually eliminate the thermal crosstalk, as shown in Fig. 3. Consequently, the wavelength difference can be continuously tuned from 2.4 nm (0.3 THz) to 9.3 nm (1.15 THz). The SMSR is maintained above 30 dB over the entire tuning range.

Because of the operation of the compound-cavity mode at a high operating current, the output power of the detuned DML is not sufficiently high for direct CW THz generation. This limitation can be overcome using a semiconductor optical amplifier with high saturation output power, which can easily be integrated into an all-active structure.

Spectral purity is an important factor in THz spectroscopy applications and in the seeding source for low-noise THz amplifiers. The linewidth and relative intensity noise (RIN) are good criteria for determining the spectral purity. A linewidth of a few MHz and an RIN of –130 dB/Hz can easily be achieved for a single DFB LD [15]. However, the spectral purity strongly depends on the mutual interaction between each section in a multisection LD [14]. To determine the spectral purity, we measured the linewidth of the spectrum and RIN during thermal wavelength tuning, as shown in Fig. 4. A delayed self-homodyne method with a time delay of 25 μs was used for the linewidth measurement [16]. Figure 4(a) shows the linewidth of the right side mode (DFB2) as a function of the μ-heater operation current. Each measured mode was selected using a narrow band-pass filter. The linewidth broadens slightly from 8 MHz to 12 MHz with an increase in the μ-heater power. RIN also exhibits a similar behavior, as shown in Fig. 4(b). The measured RIN values are around –131 dB/Hz for a moderate μ-heater power, and these values rapidly increase as the μ-heater power increases.

By comparing the RIN of a commercial DFB LD using the same measurement setup, we found that the signal-amplified spontaneous emission beating noise due to the erbium-doped fiber amplifier, along with the mode partition noise, contributes a noise spectral density of 7 dB/Hz. This implies that the RIN of a detuned DML exceeds –138 dB/Hz. The unstable RIN value at a μ-heater operation current of around 35 mA might be the cause of the compound-cavity modes. However, we believe that this unstable behavior can be prevented by precisely controlling the coupling coefficient of each DFB LD and the reverse bias in the phase section. It should be noted that increases in linewidth and intensity noise are only serious under high μ-heater power. The reason for this spectral purity degradation might be related to the thermal noise and gain peak shift toward the long wavelength side [17].

As an optical beat source of the CW THz emitter, the mode beating efficiency is the most important parameter. The spatial overlap, power balancing, and polarization affect the mode beating efficiency which in turn affects the spectral purity of the generated THz radiation. Figure 5 shows the autocorrelation traces as changing the wavelength difference between two modes. Clear and efficient mode beatings are observed through whole tuning range. It is important that polarization control and other optics are not used for increasing

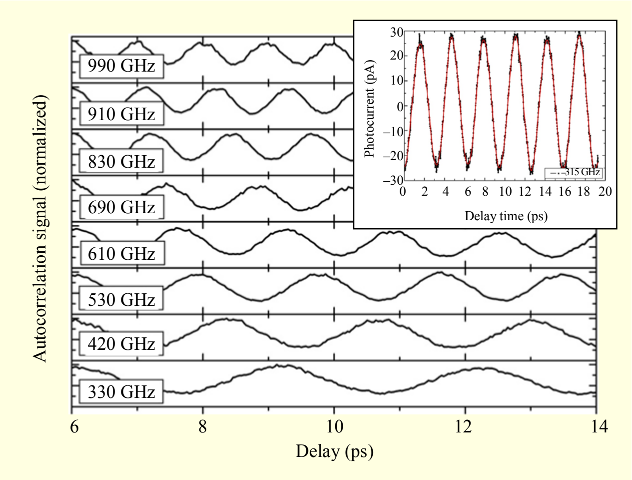

Fig. 5. Autocorrelation traces and generated THz waveform at 315 GHz (inset) of the detuned DML.

the mode beating efficiency in this measurement.

We also successfully demonstrate the THz generation with LTG-InGaAs photomixers integrated with the log-spiral antenna as shown in inset of Fig. 5. A typical homodyne method is used, and clear THz signals are measured from 315 GHz to over 700 GHz. The inset only shows the CW THz signal at 315 GHz. We estimated the THz output power of 10 nW at 315 GHz by comparing our previous results [11]. Terahertz output power and the bandwidth are still limited due to the long carrier lifetime of the LTG-InGaAs photomixers. The detailed experimental procedure for THz generation and the photomixers will be reported elsewhere.

Finally, we believe that the superior physical properties of the detuned DML, such as the wide beat frequency tuning range, high SMSR, sufficiently narrow linewidth, and stable operation, make our detuned DML a key component of portable single-chip THz emitters.

IV. Conclusion

We have successfully realized a widely tunable detuned DML in which microheaters are used for wavelength tuning. The wavelength difference can be tuned from 2.4 nm to 9.3 nm while simultaneously maintaining a high SMSR and narrow linewidth. These results prove that photomixing using the detuned dual-mode DFB LD is very promising for the realization of compact and cost-effective tunable CW THz generators.

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