Laterally-Coupled Dual-Grating Distributed Feedback Lasers for Generating Mode-Beat Terahertz Signals

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Abstract: We present a laterally-coupled AlGaInAs/InP DFB laser emitting two longitudinal modes simultaneously within the same cavity and integrated with EAM. A stable 0.82 THz beating signal was observed over a wide range of bias parameters.

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THz radiation is of increasing importance for a variety of new applications, such as medical imaging, remote sensing, and THz communications [1-2]. One of the techniques used to generate optical THz signals is by photomixing beams from two different distributed feedback (DFB) lasers [3, 4] or alternatively using lasers in an extended cavity configuration [5]. Dual mode lasers (DMLs) utilising integrated distributed Bragg reflector (DBR) or DFB laser cavities have also been used [6, 7]. A DML source, capable of uncooled operation and with a simple device structure is strongly desired. Among the various reported DML configurations, simultaneous emission of two longitudinal modes within the same cavity is very appealing because such a device is compact, can be manufactured at low cost and is straightforward to package, while generating a stable beat frequency that is relatively immune to thermal effects and has a high spectral quality.

Here we report, for the first time, a 1.56 μm DML with two longitudinal modes lasing simultaneously within the same cavity separated by 0.82 THz. Because both modes are affected by much the same electrical, thermal and mechanical fluctuations, the device has a high level of common-mode-noise rejection [3]. The frequency difference between the modes is determined essentially by each side of the laterally-coupled grating structure, and, crucially, not by the ambient temperature or injection current. An additional resonator, containing an electroabsorption modulator (EAM) in which four-wave mixing (FWM) takes place, locks the phase of the two optical signals. The results presented in this paper suggest that our device could be used as a practical compact, stable, solid-state laser source for generating THz radiation using a photoconductive antenna [3] or nonlinear optical crystal [8].

The epitaxial structure and fabrication process used for the device are similar to those described in [9]. A schematic of the fabricated device along with its dimensions is shown in Fig. 1(a). The device comprises an EAM section (30 μm), a DFB section (600 μm) with AR coating (<0.05%) on the output facet and with an electrical isolation slot (20 μm) between the EAM and DFB. The ridge waveguide is 2.5 μm wide and 1.92 μm high. The EAM section, with an HR coating (92%) on its facet, and the DFB gratings form a cavity that is resonant at both of the DFB wavelengths. This cavity is used to enhance coupling between the two longitudinal modes, to improve phase locking and stabilize the mode beating frequency through the mechanism of FWM in the EAM [10]. The gratings are of first-order with a 50% duty cycle and formed by etching 0.6 μm recesses into the sidewalls of the waveguide, as shown in Fig. 1(b). The periods of the gratings on each side of the ridge are 244 nm (Λ_1) and 245 nm (Λ_2), which select Bragg wavelengths of λ_1 (1561.60 nm) and λ_2 (1568.3 nm) respectively. The separation of the wavelengths is 6.70 nm, and the corresponding beating frequency is 820 GHz. Quarter wavelength shifts were inserted at the middle of the DFB laser gratings to ensure each line oscillated in a single longitudinal mode (see Fig. 1(b)).

A beating signal was observed when the DFB section was forward biased and the EAM section was either left floating or had

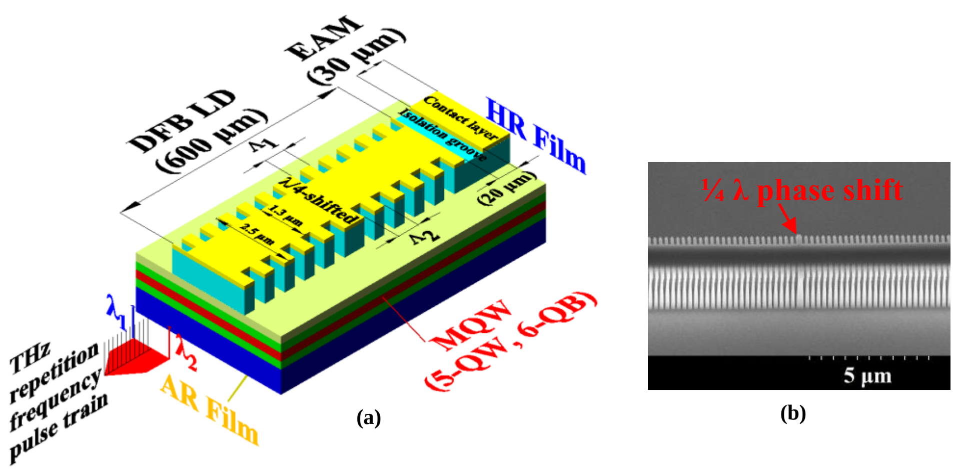

Fig. 1. (a) Schematic of the device, (b) SEM picture of the first-order 50% duty cycle sidewall gratings with a 0.6 μm recess and λ/4 shift.

a reverse bias applied. Stable beating over a wide range of electrical drive parameters is also a key feature of this laser, with stable THz mode beating observed for -1.0 V $\leq V_{EAM} \leq$ -0.3 V and 60 mA $\leq I_{DFB} \leq$ 110 mA. For -0.3 V $< V_{EAM} \leq$ 0 V and -2.0 V $\leq V_{EAM} <$ -1.0 V, the beating signal was less clear, and coherence was poor for $V_{EAM} <$ -2.0 V. These results confirmed the importance of FWM in the EAM section – in the bias range -1.0 V $\leq V_{EAM} \leq$ -0.3 V, increasingly strong mixing took place, similarly to [10]. As the bias voltage was made more negative than -1.5 V, the absorption of the EAM was so large and the cavity Q so low, the HR was effectively isolated from the DFB section, the modes were no longer locked and the FWM peaks were no longer visible in the optical spectrum, as discussed in more detail below.

Figure 2(a) shows the optical spectra of the DFB laser at an injection current of 100 mA with V_{EAM} = -0.6 V. The measured lasing modes were at wavelengths of 1562.8 (peak P1) and 1569.5 nm (peak P2), corresponding to a difference frequency of 820 GHz, with a side mode suppression ratio (SMSR) >42 dB. The values of P1 and P2 differ because of the gain spectrum of the material. The FWM sidebands at 1556.2 (peak FWM1) and 1576.3 nm (peak FWM2) can be clearly seen. The 15 dB power enhancements of the sidebands above the cavity modes indicate good phase stability between the two main modes [6]. In a practical THz system, the sidebands would not affect photomixing, as their power is, in turn, about 35 dB below the two main lasing modes. The corresponding measured AC trace is shown in Fig. 2(b), which indicates a sinusoidal modulation with some fluctuations in the peak intensity, which are due to the finite resolution of the autocorrelator system and technical noise that stems from the measurement system itself. The average period of the measured emitted pulse train was 1.22 ps, which corresponds to the expected repetition frequency of 820 GHz, and is in agreement with the optical spectrum mode spacing shown in Fig. 2(a). Fig. 2(c) shows the dependence of the FWM output power on applied EAM voltage. As can be seen, FWM1 and FWM2 increased when V_{EAM} was changed from 0 V to -0.6 V, and then reduced when V_{EAM} <-0.6 V. The FWM signals were apparent until the bias on the EAM reached -1.4V, beyond which point no evidence of FWM could be seen in the optical spectrum. FWM1/P1, (the ratio of FWM1 to P1), and FWM2/P2, (the ratio of FWM2 to P2) follow the same trend. Fig. 2(c) confirms the key role that the EAM plays in terms of locking the phases of the two longitudinal modes [10].

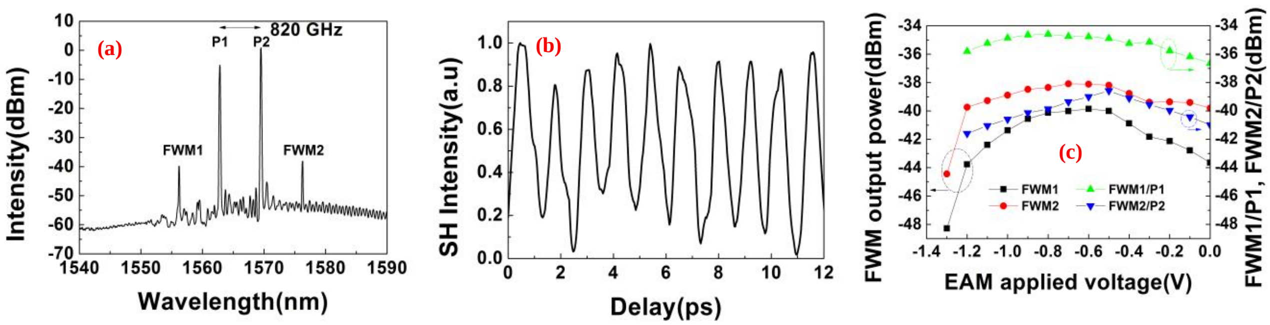

Fig.2.(a)Optical spectrum and (b) measured autocorrelation pulse train for I_{DFB} =100 mA and V_{EAM}= -0.6 V. (c) FWM output power and ratio to the corresponding lasing power vs the EAM applied voltage.

We also measured the beat mode linewidth as a function of I_{DFB} for V_{EAM}= -0.6 V. We note the trend that the beat mode linewidth reduces as I_{DFB} is increased. The narrowest observed linewidth of about 700 kHz was achieved at I_{DFB} = 100 mA. In contrast, a separate measurement of a counterpart single grating DFB laser emitting a single longitudinal mode fabricated in the same wafer has a typical optical linewidth of 3.5 MHz at the same current injection level. This reduction of the linewidth further provides strong evidence that in the beating regime, the two modes are indeed mutually phase-locked.

The far field pattern (FFP) at I_{DFB} = 100 mA and V_{EAM}= -0.6 V from the DML was measured with high resolution (0.9º). The beam is almost circular (34° × 35°) and is indistinguishable to that expected from the fundamental mode of the ridge waveguide, confirming both of the lasing wavelengths are in the fundamental *TE* mode. Moreover, when displacing an optical fiber along the transversal horizontal direction (//) closely approaching the DFB output facet while scanning I_{DFB} and V_{EAM}, the measured optical spectrum is not sensitive to the fiber position.

In conclusion, a laterally-coupled, dual-wavelength DFB laser integrated with a nonlinear FWM cavity has been fabricated and characterized. The device emits two longitudinal modes simultaneously from within the same cavity, separated by 0.82 THz at a wavelength of around 1560 nm. The devices were fabricated using simple first-order sidewall grating technologies, which have the advantages of eliminating crystal regrowth and allowing the AlGaInAs quaternary structure to be used in the QW active section. The surface grating eliminates the need for complex regrowth fabrication steps normally associated with DFB lasers. Due to FWM in the resonant cavity, the device strongly favours operation in the mode-beating regime, with stable mode beating observed over a wide range of bias parameters in terms of drive current to the DFB and bias to the EAM. Compared with other reported DMLs, our laser uses a simple and reproducible fabrication technology and exhibits highly controllable and robust mode-beating operation. These laser diodes are expected to open up many opportunities for future compact THz applications.

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