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ABSTRACT

In this paper, a 2x1 mini-array VCSEL is studied as a source of CW THz radiation. The frequency of the signal can be tuned by current up to 9.5 mA, at which the laser features optical beatings up to 300 GHz, which are converted to corresponding THz frequencies by photomixing. The influences of the laser current on the optical spectrum of the laser, and thus on the THz signal are also investigated. With its simpleness, compactness and extremely low cost, the mini-array VCSEL has the potential to replace other laser sources to promote CW THz applications in industry.

Keywords: coupled-cavity VCSEL, mini-array VCSEL, THz generation

1. INTRODUCTION

A photonics-based continuous wave (CW) THz setup usually implements two distributed-feedback (DFB) lasers with tunable emission wavelengths to generate the optical beating frequency in the THz range [1]. Recently dual-mode laser diodes have been demonstrated to further reduce the cost and size of the whole setup [2]. Among them are Y-shaped monolithic lasers with either two DFB or two distributed Bragg reflector (DBR) branches [3]. Yet these laser diodes are sophisticated to design and fabricate, thus have a cost which is still too high for industrial applications.

Vertical-cavity surface-emitting lasers (VCSELs), on the other hand, are very compact laser diodes, and have extremely low power consumption and cost. For these reasons they have recently been exploited in THz applications [4]. Especially, multi-cavity VCSELs provide a narrow spectrum yet high optical power [5,6], which is favorable for THz generation. Among them are VCSEL mini-arrays realized with diverse adjacent cavities, allowing photon-photon resonances (PPR) with a frequency range of 50 to 100 GHz [7].

This paper presents the novel idea to use a coupled-cavity VCSEL mini-array as the laser source for THz generation. With a single contact supplied by one current source in the milliampere range, this VCSEL chip can generate THz signals in the range of 50-300 GHz with a standard homodyne THz setup. Further details can also be found in another paper [8].

2. EXPERIMENTAL SETUP

The 2x1 coupled-cavity mini-array VCSEL

The laser diode used in this work is a top-emitting GaAs-based mini-array VCSEL (VI Systems) with 850 nm emission wavelength. It is based on an anti-guiding half-lambda epitaxial design [9] and has a single oxide-confined-aperture placed in the first node position of the optical field. A shared contact is used for both cavities, as is depicted in Figure 1(a). Since the two cavities have only a 7-µm center-to-center distance and a 3-µm diameter for each, strong optical leakage-induced interaction between the coupled cavities happens, allowing for coherent lasing of both cavities [6]. The two cavities can operate in either single- or multimode regime depending on the current. These modes interact with each other, resulting in intense beating frequencies in the THz range.

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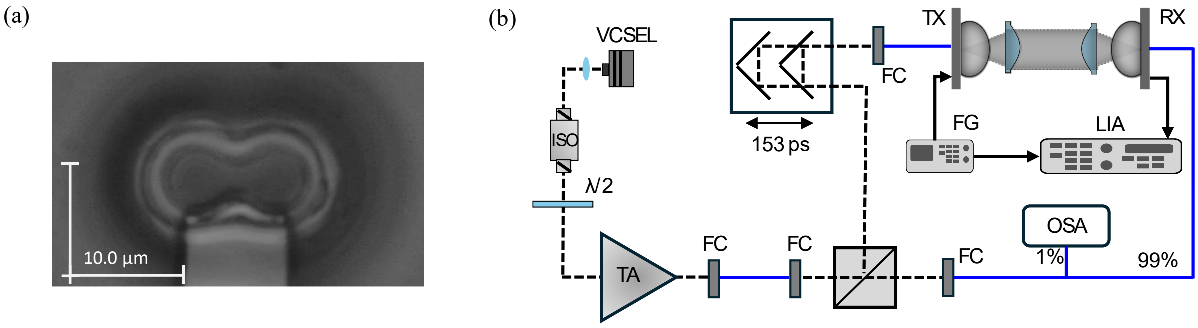

Figure 1. (a): The oxide-confined aperture shape of the 2x1 mini-array VCSEL taken with an optical microscope. (b): Experimental Setup for THz generation. ISO: optical isolator, λ/2: half waveplate, TA: tapered amplifier, FC: fiber coupler, OSA: optical spectrum analyzer, TX: THz emitter, RX: THz receiver, FG: function generator, LIA: lock-in amplifier. Dashed black lines: laser beam in free space; Solid blue lines: laser beam confined in polarization-maintaining fibers; Solid black lines: electrical connection. Not plotted are the current controllers for the VCSEL, the TA and the delay stage.

THz generation setup

The experimental setup is depicted in Figure 1 (b). It is a standard coherent detection setup by photomixing with two photoconductive antennae (PCAs) as THz emitter and receiver, respectively. The laser beam from the mini-array VCSEL chip is polarization-adjusted by a half-waveplate, and then amplified to above 200 mW by a tapered amplifier (TA), which is a semiconductor optical amplifier (SOA) with a tapered section for light amplification in addition to the ridge waveguide. With a coupling ratio of nearly 30%, we obtain 60 mW fiber coupled light for THz measurements. The beam is then directed to a free-spaced setup, in which it is split into two arms. One arm is sent to the movable delay stage, of which 23 mm distance (153 ps delay) was used for a suitable measurements time as well as a good resolution for performing FFT. Another arm is split by a fiber coupler with 99:1 ratio to the receiver PCA and the OSA, respectively. Finally, the PM-fiber-coupled log-spiral PCAs receive approx. 16 mW optical power. The distance between the THz emitter and receiver is set to a specific value so that the optical path lengths of the two arms are equal at the middle of the moveable delay, to achieve maximum signal from the coherent detection. The bias voltage of 8 V at 1.234 kHz is used at the TX, while the RX is connected to a transimpedance amplifier and then to a lock-in amplifier with the same frequency set as the TX voltage. The laser diode controller, the delay-stage controller, the OSA and the LIA are remote-controlled with MATLAB.

3. EXPERIMENTAL RESULTS

Figure 2 shows the results at two current supply conditions: 4.9 mA and 9.5 mA, respectively. At 4.9 mA, two clear peaks can be seen in the optical spectrum in Figure 2 (a), which, correspond to the coherent supermodes from both cavities. With a detuning of 100 GHz (0.24 nm), the laser generates THz optical signals by photomixing with exactly 100 GHz frequency, as can be seen from performing Fourier transform (FFT) of the measured THz trace (Figure 2(b)). For 9.5 mA, higher order modes from the two cavities (Figure 2(c)) are excited because of the higher current density in the oxide layer boundaries. After taking THz measurements and performing FFT to the THz traces, one can see that the frequencies of the two peaks in the frequency spectrum (Figure 2(d)) correspond to the differences between the highest peak and the next two peaks in the optical spectrum, respectively.

Moreover, a steady tuning of the laser current from 2.5 mA to 9.5 mA in 0.2 mA steps has been performed, to demonstrate how the peaks in the optical spectra as well as the generated THz frequencies evolve with current. To enhance the signal, four replicate measurements have been carried out for each current. Figure 3 shows the averaged plots of laser spectra and the FFT of the THz traces, in which the averaged noise level was subtracted in the frequency domain. As can be seen the overall THz frequency was tuned from 50 GHz to 300 GHz.

It is worth mentioning that the optical beating from the two initial modes from the two cavities acts as a dominant THz-frequency contributor over the whole current range, while a reduced amplitude up from 7.9 mA current can be observed due to the upcoming higher order modes. Provided with a lower current range, e.g. between 3 mA and 7.7 mA, this laser has a relatively clean spectrum with two current-tunable wavelength peaks, just as dual-mode laser diodes. Therefore, they have the potential to be used for THz measurements, such as FMCW radar or spectroscopy applications.

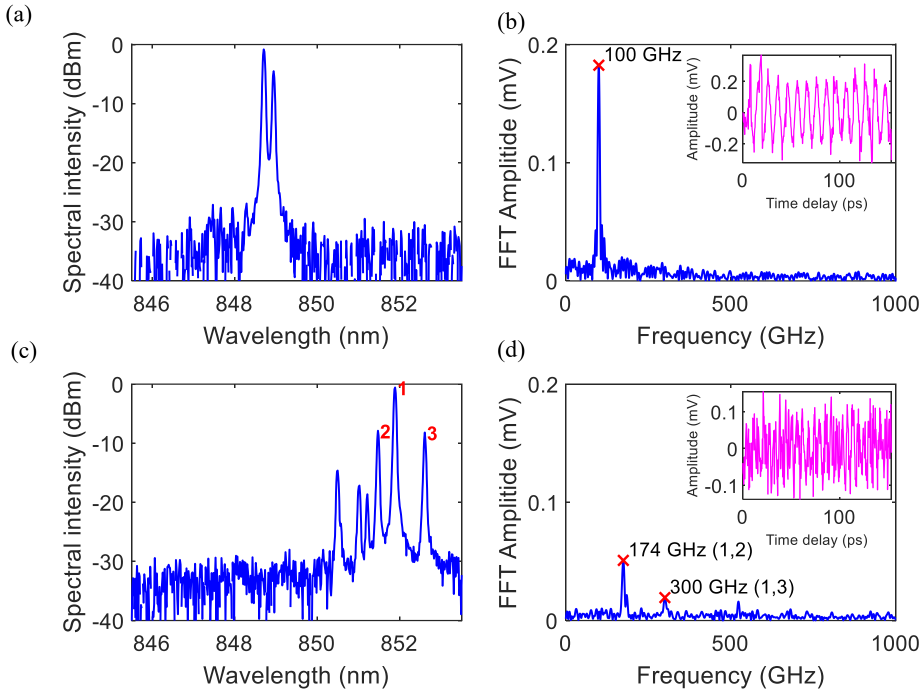

Figure 2. The emission spectrum of the laser and the corresponding THz frequencies obtained from the FFT of the measured traces. (a)(b): With 4.9 mA current, (c)(d): With 9.5 mA current. Insets in (b) and (d): THz traces obtained from the lock-in detection.

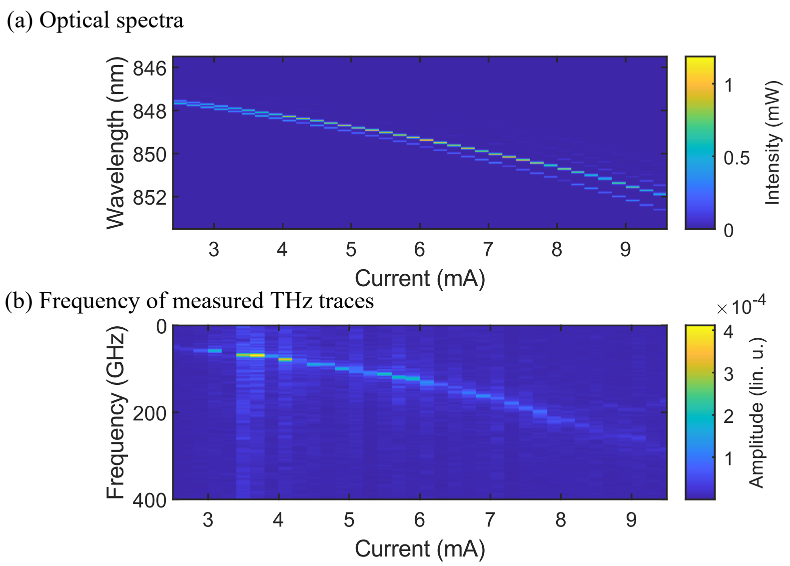

Figure 3. Laser current tuning with 0.2 mA step and the corresponding optical spectra and THz measurements, respectively. (a) Optical spectra of the laser over different currents. (b) THz frequencies at each current by performing FFT to the measured THz traces.

4. CONCLUSION

A coupled-cavity mini-array VCSEL is reported in this work as a new laser source for coherent CW THz systems. The optical beating between the modes of the two cavities provides THz frequencies up to 300 GHz. With a moderate current supply, this laser diode provides an intense optical beat for THz generation, which can also be continuously tuned via current. Fulfilling requirements for THz applications such as FMCW radar or spectroscopy, this mini-array VCSEL is the simplest and most cost-effective laser source ever for CW THz systems. Further investigation and design of such mini-array VCSELs make them an easily accessible alternative for THz applications in industry and research areas.

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