Vertical-External-Cavity Surface-Emitting Laser for THz Generation

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Abstract— We demonstrate the stable operation of a dual-frequency vertical-external-cavity surface-emitting laser for THz generation. The two-frequency operation is based on the passive stabilization of two Laguerre-Gauss modes. An operation with a frequency difference between the two modes has been demonstrated up to 450 GHz.

I. INTRODUCTION

COHERENT, tunable and compact continuous-wave Terahertz (THz) sources are required for many applications, especially those involving spectroscopy. Photo-mixing techniques offer precious advantages such as wideband tunability and high-modulation bandwidth at room temperature. A straightforward solution consists in exciting a photo-mixer with two lasers emitting at different frequencies to generate a THz beat note. Different kinds of efficient photomixers have been developed (some even commercialized) in the last decade, such as ErAs:GaAs inter-digitated photomixer [1], uni-traveling-carrier photo-diode (UTC-PD) [2], ion-irradiated In₀.₅Ga₀.₅As inter-digitated photo-mixers [3], or using difference-frequency generation (DFG) [4]. However, coherent and tunable THz emission is usually based on either complex and/or expensive systems for optical-beating generation. We propose a breakthrough solution to generate dual-frequency high-power coherent and continuously-tunable laser emission, in a robust and integrated device exploiting III-V semiconductor nanotechnologies, for THz generation.

Photo-mixing based on two uncorrelated lasers have been demonstrated, e.g. using UTC-PDs [5,6] or DFG [4]. Unfortunately, using such uncorrelated sources leads to a deteriorated coherency of the terahertz radiation, therefore a stable dual-frequency laser is required in order to cancel-out technical perturbations. Many kinds of designs have been already proposed for terahertz dual-frequency lasers; however, only a few of them offer interesting performances mainly due to difficulties in managing laser dynamics. Many attempts to reach compact, stable, continuously-tunable, coherent and powerful bi-frequency lasers have been already proposed for terahertz generation, but none of them meet fully the requirements for applications such as terahertz generation. Well-known multimode operation can be observed in monolithic semiconductor edge-emitting diodes that rely on complex non-linear process, like spatial hole burning and four-wave-mixing. Mode competition becomes sufficiently small to allow for multimode operation, but usually in a quite unstable coupled state with complex dynamics (partition fluctuations), i.e. with no robustness, without tunability and with limited coherence (highly-divergent elliptical beam, linewidth of tens of MHz, parasitic frequencies) [7]. External-cavities diode laser using spectral filter(s) can allow bi-frequency stability, but to the detriment of output power, cavity complexity, alignment sensitivity/robustness, beam quality, and coherence as the laser tends to operate two sets of longitudinal modes rather than two modes [8]. Another technique used to reduce mode coupling consists in a separation of laser beams within the cavity. Such a two-axis cavity can be obtained for example by polarization separation [9] and shows interesting results in terms of tunability and coherence. However, tunability occurs by steps, output power is limited to few milliwatts, cavity is complex with intra-cavity movable elements, almost impossible to integrate on a single device, and coherence is degraded. More recently, a Brillouin-based dual-frequency laser was demonstrated [10] but continuous-tunability and compactness remain insufficient. Finally, one can control the power of the two laser lines of a crystal by tilting one of the cavity mirrors [11], allowing high output power but no tunability.

Among these possible laser designs, Vertical-external-Cavity Surface-Emitting Lasers (VeCSEL) are very promising solutions for dual-frequency lasers as they are inherently compact, wavelength flexible, widely tunable, powerful and highly coherent (spectrally, spatially and in terms of polarization) along with a class-A dynamics regime [12]. Dual-frequency laser operation based on the coexistence of two longitudinal modes has been demonstrated for THz generation in a VeCSEL [13], but such a design does not allow for simultaneous operation of both laser lines. Here, we demonstrate the realization of a novel dual-frequency highly-coherent laser based on the stabilization of two transverse modes in a single-axis cavity VeCSEL.

II. DUAL-FREQUENCY VECSSEL DESIGN AND OPERATION

Our aim is to design and realize a robust and agile VeCSEL-based continuously-tunable highly-coherent bi-frequency optical source, exploiting mature integrated III-V technologies and external concave-type optical cavity without the need for intracavity spectral filters. Output powers up to 100 mW are expected along with optical linewidth of few kHz and continuous tunability from 100 GHz to 2 THz. Integrated metallic mask within the VeCSEL can be used to select the existence of any single Laguerre-Gauss (LG) mode [14] by adding spatially-dependent losses. In this work, we will discuss how to select two transverse modes and assure a stable simultaneous operation of the two transverse modes. The VeCSEL can operate on a robust dual-frequency light state characterized by two transverse LG modes.

We demonstrate such a dual-frequency operation for a diode-pumped GaAs-based quantum-wells VeCSEL. As shown in Fig. 1, we observe a dual-frequency operation of the laser, with a frequency difference between the two modes of 162 GHz. Frequency differences up to 450 GHz have been measured using other designs. The laser is operating at room temperature at a wavelength around 1 μm. Each mode linewidth is the apparatus function of the high-resolution
optical spectrometer we used. The inset of Fig. 1 shows the far-field intensity map of the laser that clearly shows that both two modes coexist. These two modes were selected thanks to the integrated metallic mask.

Figure 2 shows the output power of the laser as a function of the pump power. We clearly observe the threshold of the first mode around 150 mW of pump power, and the threshold of the second mode around 250 mW, as confirmed by a simultaneous observation of the far-field intensity map. As expected, we observe a change in the laser efficiency (slope of the output power shown in Fig. 1) as the second mode appears.

We believe that both transverse modes coexist and operate on a single longitudinal mode, thanks to a careful characterization using Fabry-Perot spectrum analyzer, and high-bandwidth spectrometers (30 kHz using a Zoom spectra from Resolution Spectra Systems).

Finally, one can wonder how to couple the two orthogonal transverse modes in order to excite a photo-mixer. We show that the spatial coupling of the two orthogonal modes is possible by injecting the laser beam in a single-mode optical fiber with a theoretical beat efficiency that can exceed 20% with an adequate offset of the fiber center relatively to the beam center.

This dual-frequency III-V semiconductor laser design can be extended to any wavelength, like at 1.5μm using InP based structures.

III. SUMMARY

Stable operation of a dual-frequency operation of a VeCSEL based on the coexistence of two transverse modes within a single-axis cavity as been demonstrated, thus allowing for coherent THz generation, for example using nonlinear crystals or uni-travelling-carrier photodiodes. Further work consists in the study of the tunability of the laser, along with THz generation.

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REFERENCES