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THz emission driven by a dual-transverse-modes laser

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Abstract

The state of the art and the perspectives of THz emission driven by a dual-frequency laser that operates simultaneously on two transverse modes around 1064 nm are presented. The reported THz performances in terms of tunability (50–700-GHz), coherence (150-kHz for 3-ms acquisition time), and power (1 μW at 260 GHz) are presented while using a uni-travelling-carrier photodiode for photo-mixing. Novel photo-mixers specifically designed to match the transverse modes of the laser are discussed in terms of transverse beam characteristics and power.

1 Introduction

Coherent, tunable and compact continuous-wave Terahertz (THz) sources are required for many applications, such as bio-medical sensing and imaging, communications, or security. A large variety of solutions exists for THz emission, from optics to electronics, but existing solutions are often cumbersome or limited in terms of output power, tunability and/or modulation bandwidth. At the upper band of the THz spectrum (far-infrared side), sources are usually pulsed and/or require low-temperature operation, e.g. for quantum-cascade lasers [1] or P-germanium laser [2]. At the lower band of the THz spectrum, electronic-based sources usually operate easily at room temperature in a continuous-wave operation, but at a fixed frequency of emission, e.g. for Gunn, impact avalanche transit time or resonant-tunneling diodes. Frequency-multiplied sources offer enhanced tunability, but do not provide simultaneously sufficient output power and high modulation bandwidth, compactness, or affordability. 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 photo-mixers have been developed in the last decade, such as ErAs:GaAs inter-digitated photo-mixer [3], uni-traveling-carrier photo-diode (UTC-PD) [4], ion-irradiated InGaAs inter-digitated photo-mixers [5]. However, coherent and tunable THz emission is usually based on either complex and/or expensive systems for optical-beating generation.

2 State of the art of dual-frequency lasers

Photo-mixing based on two uncorrelated lasers have been demonstrated, e.g. using difference-frequency generation [6], UTC-PDs [7, 8]. Unfortunately, using such uncorrelated sources leads to a deteriorated coherence of the terahertz radiation, therefore a stable dual-frequency laser is required in order to cancel-out technical perturbations. Many attempts to reach compact, stable, continuously-tunable, coherent and powerful dual-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 (SHB) and four-wave-mixing (FWM). 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) [9]. 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 [10]. 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 [11] and shows interesting results in terms of tunability and coherence. However, output optical 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 [12] 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 [13], 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 [14]. Dual-frequency operation has been already demonstrated using a VeCSEL by stabilization of two polarization modes [15] with the advantage of a 1550-nm emission wavelength, but the beat frequency was limited to few GHz, and most importantly the laser was operated on two different optical axis for the two polarization modes, along with moveable intracavity elements such as an etalon filter, thus reducing the possible laser integration, robustness and stability. Dual-frequency laser operation based on the coexistence of two longitudinal modes has been demonstrated for THz generation in a VeCSEL [16], but such a design does not allow for simultaneous operation of both laser lines. None of the state-of-the-art methods offering an inherently robust, compact/integrated and flexible solution for cw, coherent and tunable beat signals in the GHz–THz range, we recently proposed a novel dual-frequency highly-coherent laser based on the stabilization of two transverse modes in a single-axis cavity VeCSEL [17], and proved the simultaneous operation of the two modes.

3 Dual-frequency laser based on transverse modes operation

The dual-frequency VeCSEL based on the coexistence of two transverse modes is attractive as it is free of moveable intra-cavity element, thus assuring a very robust operation, but is also free of etalon spectral filter that is limiting for tunability. As detailed in [16], the principle consists in the stabilization of two Laguerre-Gauss (LG) transverse modes within the plano-concave cavity of an optically-pumped VeCSEL, thanks to an adequate pumping diameter (gain selection) along with a specifically-designed absorbing mask (loss absorption). Figure 1 shows an illustration of the laser structure and a photograph of the absorbing mask. Typical performances of the dual-frequency laser are presented in Fig. 2. One can observe that the transverse beam is composed of the superposition of the LG_00 and LG_{02} transverse modes with similar output power as shown in the power characterization. As detailed in [18], the pump-induced radial thermal gradient in the VeCSEL structure leads to a differential frequency shift for the transverse modes, that can be controlled by the pump power, as shown on the optical spectrum presented in Fig. 2. Using the LG_{00}/&LG_{03} mode couples instead of the LG_{00}&LG_{02} couple allows for a broader beat-frequency tunability, thanks to the lower confinement of the LG_{03} mode, if compared to the LG_{02}, with possible tunability of 50 to 700 GHz by 15-GHz steps (cavity free-spectral range) as reported in Ref. [18].

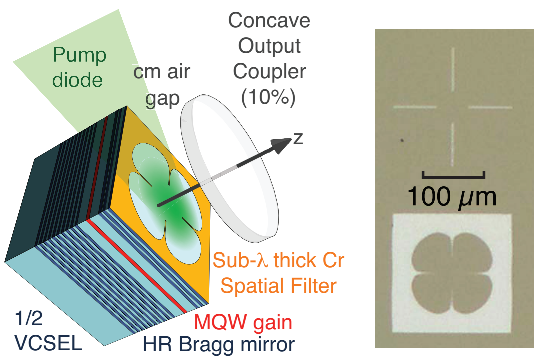

Figure 1. Dual-frequency VeCSEL structure. Left: illustration of the laser structure. Right: Photograph of two possible Cr mask realized for the selection of the LG_{00} and LG_{02} modes.

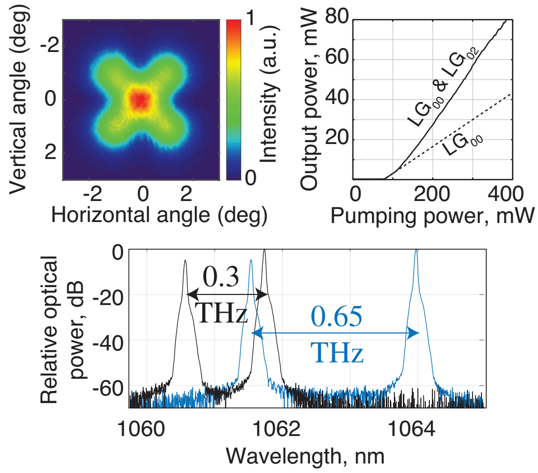

Figure 2. Optical characterization of the dual-frequency laser. Top left: Far-field beam intensity. Top right: Output power as a function of the pump power, the dash line is the extrapolation of the output power of the fundamental mode. Bottom: Output spectrum for pumping rates of 1.7 (0.3-THz beat note) and 2.7 (0.65-THz beat note).

4 State of the art of THz emission driven by the dual-frequency VeCSEL based on dual transverse modes operation

The demonstration of THz emission has been realized by coupling part of the two modes within a single-mode fiber as shown in Fig. 3, in order to project the two LG orthogonal modes on a single mode (LP_{00} fiber mode) and allow for emission at the beat frequency. A pigtailed UTC photodiode was used for photo-mixing of the two frequency and generate a THz signal at the beat frequency. The THz signal was collimated then focused on a heterodyne receiver that allow the observation of the calibrated THz spectrum on a spectrum analyzer.

As shown in Fig. 4, a highly-coherent THz signal was observed, thanks to the technical-noise correlation between the two transverse modes. A linewidth of 150-kHz was measured for a 3-ms acquisition time around 260 GHz, which is lower than the optical linewidth. As reported in Ref. [18], the frequency noise of the THz signal is actually about four orders of magnitude lower than the optical one. Fig. 4 also shows the possible tunability of the THz signal,

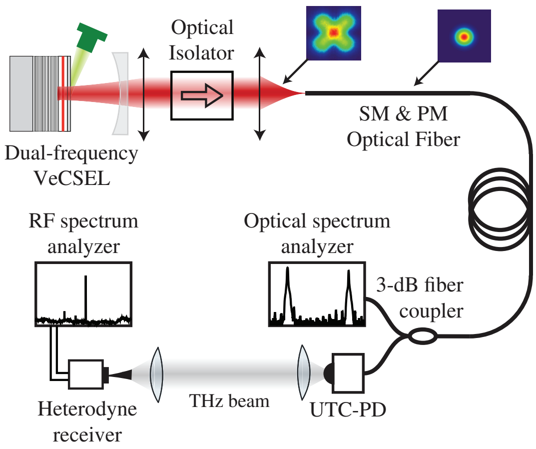

Figure 3. Experimental setup for emission of a THz signal driven by the dual-frequency laser that operates on two transverse modes.

driven by the pump power. The possible frequency ranges from 50 GHz to 700 GHz, but THz signal was only characterized using the two available heterodyne mixer heads operating at frequency of 75–110 GHz and 220–3252 GHz. Finally, a key metric for THz sources is the output power, that is here around 1 μW. Such an output power is limited by the UTC photodiode maximum input optical power. At low frequencies, the integrated bow-tie antenna of the UTC photodiode is two small thus reducing the output power (due to a smaller antenna gain), additionally the laser output power is smaller at small beat frequencies. At higher beat frequencies, the laser output power is larger, but the cut-off of the photodiode limits the output THz power.

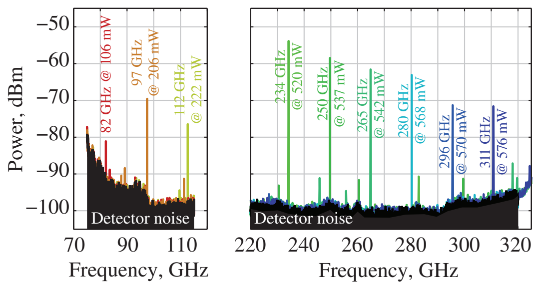

Figure 4. THz spectra for various pump power showing coherent and tunable THz emission within the available heterodyne receiver ranges (75–110 GHz and 220–325 GHz).

5 Towards a higher-power THz emitter

Future perspectives consist to develop a novel THz source that remains coherent and tunable, with industrial perspectives in terms of robustness, compactness and cost, if compared to the cumbersome THz sources that are presently available, but with a higher output power. To this end, we propose to take advantage of the transverse beam structure at the laser output. As shown in Fig. 5, despite the orthogonality of the laser transverse mode, there are multiple limited area where THz emission is possible. In the previously-

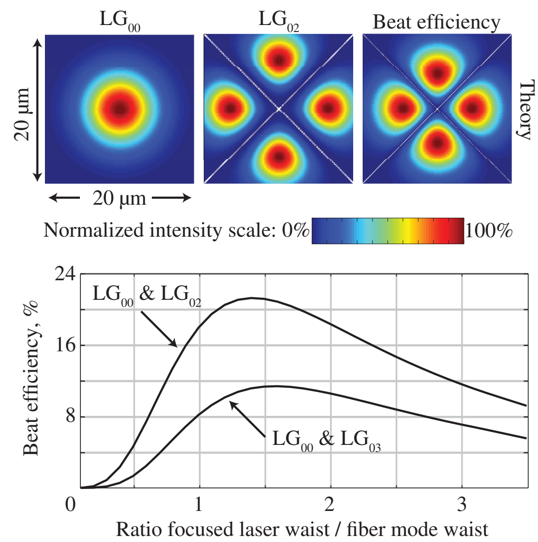

Figure 5. Beat Efficiency of THz emission. Top: intensity maps of the coupled power within the single-mode optical fiber, as a function of the fiber transverse position relatively to the optical axis, for the LG_{00} mode and the LG_{02} mode. The normalized beat efficiency map corresponds to the resulting beat power between the two transverse modes. Bottom: Maximum beat efficiency for the LG_{00}& LG_{02} or LG_{00}& LG_{03} modes as a function of the matching between the laser and the fiber beam waists.

described experiment, the optical fiber was aligned with one of the four possible lobes of the beat-efficiency map, thus offering only 21% of the available THz power (see bottom plot of Fig. 5) if compared to the ideal case where transverse modes would be colinear. Therefore, one possible solution to increase the output power is to use the four possible lobes of the beat efficiency map to reach possibly 84% of power efficiency, that correspond to a transverse spatial multiplexing of the photo-mixers. Such a multiplexing would be readily possible thanks to the high transverse coherence of the laser beam, that ensures a stable phase relationship between the different lobes, if compared to the excitation by four uncorrelated laser, thus offering a highly-coherent THz beam. However, the different lobes of the high-ordre LG modes being alternatively out-of-phase, the THz beam would present a specific transverse intensity profile unless optical or THz phase is corrected. The output THz power at the photo-mixer output being usually limited by the photo-mixer itself, the total output power would be then multiplied by the number of photo-mixers, thus encouraging to use higher-order LG modes, such as LG_{03} or LG_{04}.

Additionally, more-efficient photo-mixers at 1064 nm would be required. The UTC photodiode bandgap being designed for an optical excitation at 1550-nm, the quantum efficiency is reduced by the ratio of wavelengths. Also, as cw operation is concerned, plasmonic antenna photomixers [19] could improve significantly the possible THz output power.

6 Summary

We presented a review of the state-of-the-art performances of the dual-frequency VeCSEL based on the coexistence of two transverse modes, revealing an excellent candidate for photo-mixing-based THz source due to its broad beat-frequency tunability along with spatial and spectral coherence. Tunable and coherent THz emission has been actually demonstrated but with a limited THz power. Therefore, novel solutions to improve such a power have been proposed, taking avantage of the transverse coherence and transverse spatial profile of this dual-frequency laser to improve the output power. This works opens the path to original 2D antenna multiplexing designs that could lead to a high power, coherent, tunable and compact THz source.

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