Analysis of optical THz-signals from mode-locked semiconductor laser by using a semiconductor optical amplifier-based detection scheme

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***Abstract*— An all-optical approach based on nonlinear interactions inside a semiconductor optical amplifier for measuring the THz beat-tone of a passively mode-locked laser is proposed. This novel approach can be applied to beat-tones in the range from GHz to few THz.**

I. Introduction

DETECTION and accurate measurement of the radio frequency or THz spectrum emitted by narrow- and broad-band light sources have been achieved through a number of techniques.[1-2] In the former case, a typical approach is to convert its temporal intensity into an electrical current using a fast photo-detection and then perform the related analysis using electronics. The main constraint is the limitation imposed by the bandwidth of the photo-detector. In the later case, detection and characterization of broad-band light sources (either pulsed or continuous wave) in the sub-THz regime and beyond is usually achieved by employing bolometers, Golay cells or pyroelectric detectors. On the other hand, two-color and multimode mode-locked lasers have proven to be a feasible approach for generating THz-signals in semiconductor devices.[3-6] Such a THz-emission has been directly detected by using spectroscopic schemes with a bolometer,[3-4] frequency resolved optical gating (FROG) system,[4] and indirectly by a uni-travelling carrier photodiode (UTC-PD) and electrical spectrum analyzer (ESA),[6] which again involves the necessity of large detection setups. Since the THz-signal thus generated is modulating the laser dynamics at a frequency given by its free spectral range, it is feasible to indirectly characterize such an emission by analyzing the THz beat-tone signal measured at the output of the mode-locked laser under investigation. Therefore, in this work we propose an all-optical heterodyne approach based on nonlinear interactions inside a semiconductor optical amplifier (SOA) for measuring both the frequency and linewidth of the THz beat-tone from a multi-mode light source. The source under test is a passively mode-locked Fabry-Pérot (FP) semiconductor laser. Due to the mature manufacturing technology of SOAs, the proposed scheme represents a low cost and room temperature operation approach for analyzing THz beat-tones from mode-locked semiconductor lasers. Moreover, owing to the fast inter- and intra-band carrier dynamics of the utilized SOA, it can be applied to assess light sources with intermodal separation in the range from GHz to several THz.

The experimental setup is shown in Fig. 1. Besides the device under test (DUT), whose spectrum is shown on Fig. 2, two tunable external cavity lasers (ECL-1 and ECL-2) are injected into a multi-quantum well SOA and its output is both measured through an optical spectrum analyzer (OSA) and collected through a 60 GHz photo-detector (PD). The intermediate frequency (IF) signal impinging on the PD is measured with an ESA. Owing to the four-wave mixing mechanism, the SOA under the ECLs injection firstly operates as a local oscillator whose frequency Δf_{ECL} is set by the difference $c|1/\lambda_{ECL1}-1/\lambda_{ECL2}|$ between their corresponding wavelengths, where c is the speed of light in vacuum. Secondly, the SOA is performing alike as an optical frequency mixer whose inputs are the self-modulated spectrum of the DUT and the two ECLs. There exist multiple beating processes inside the SOA between the input beams and their corresponding conjugated and engendered signals. A beating process of particular interest takes place between two adjacent conjugated signals, such as those depicted in the inset of Fig. 3. In this case, they produce a modulation on the SOA active region at an intermediate frequency given by $\Delta f_{IF} = |\Delta f_{DUT} - \Delta f_{ECL}|$, where the frequency Δf_{DUT} of the beat-tone signal associated with the DUT is the unknown variable to be determined. Notice that even though the beating frequencies Δf_{ECL} and Δf_{DUT} can be in the range of several GHz to few THz, its difference can be considerably smaller by properly setting the ECLs wavelengths. Thus, it is feasible to measure such an IF signal (and therefore the beat-tone signal associated to the mode-locking laser) at the output of the SOA in the electrical domain through a photo-detector and ESA.

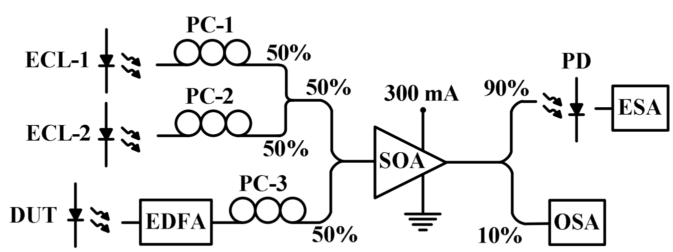

Fig. 1: Experimental setup utilized for analyzing the THz beat-tone signal.

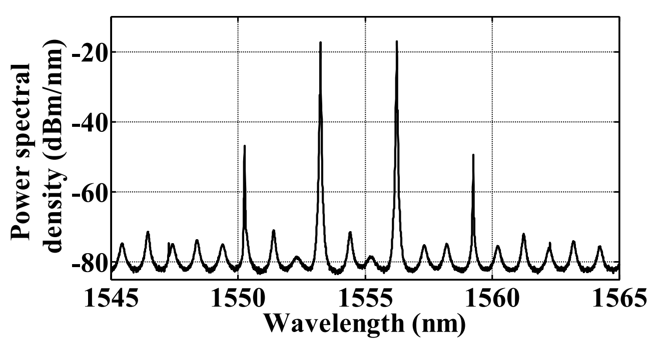

Fig. 2: Collected spectrum at the output of the DUT when it is biased at 88.5 mA and temperature controlled at 25°C.

II. RESULTS

In our experimental demonstration depicted in Fig. 3, two groups of spectral components at the SOA output are identified. The first one corresponds to the injection of the two ECLs whose wavelengths λ_{ECL1} and λ_{ECL2} are set at 1576.82 and 1579.95 nm, respectively. Owing to their nonlinear beating inside the SOA, two main sidebands are generated, giving rise to intra-band carrier-heating dynamic at $\Delta f_{ECL} \approx$ 376.91 GHz. The second group corresponds to the injection and nonlinear amplification of the DUT, where its main components and sidebands are enhanced, giving rise to intra-band carrier-heating dynamic at $\Delta f_{DUT} \approx 371.1$ GHz. These two modulations are shown in the inset of Fig. 3. As it has been mentioned in previous paragraphs, not only such modulations are generated but also their difference $|\Delta f_{DUT} - \Delta f_{ECL}|$. Therefore, by measuring the RF spectrum at the SOA output in the electrical domain, the modulation frequency of the mode-locked laser under investigation is determined. As depicted in Fig. 4, an electrical spectrum centered at $\Delta f_{IF} \approx$ 6.3 GHz is obtained, allowing the determination of the beat-tone Δf_{DUT} associated with the mode-locked laser.

A relevant aspect concerns the resolution of the beat-tone frequency measurement. Whilst the measurement of the IF basically relies on the resolution of the ESA (set to 1 kHz), the accuracy of Δf_{DUT} depends on both the OSA resolution (set to 10 pm, corresponding to ~1.2 GHz) and the detuning accuracy of the ECLs (~5 pm in the utilized lasers). Therefore the retrieved beat-tone frequency is properly expressed as (371.1± 1.2) GHz.

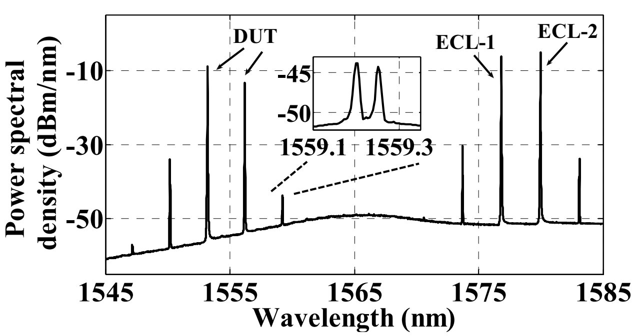

Fig. 3: Measurement of optical spectrum at the SOA output.

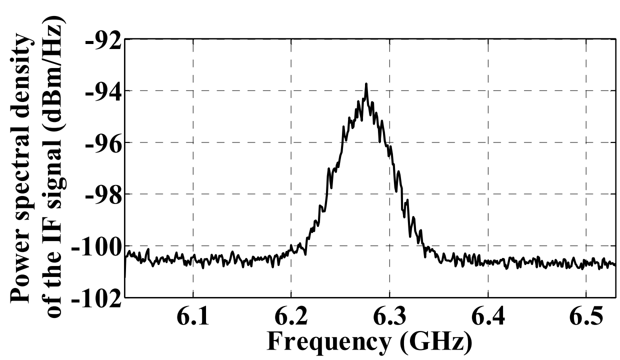

Fig. 4: Measurement of the intermediate frequency in the electrical domain.

Regarding the linewidth of the retrieved beat-tone signal, it is important noticing that the IF depicted in Fig. 4 exhibits a full-width at half maximum (FWHM) of ~34.315 MHz when fitted to a Lorentzian line-shape. In this case, it should be considered that: i) the FWHM of each ECLs is in the order of 100 kHz, therefore its contribution to the linewidth of the IF signal is less than 0.3 %, and ii) each of the two main spectral components of the mode-locked laser exhibit an optical FWHM linewidth of 20 MHz when biased at 88.5 mA and temperature controlled at 25°C. Therefore, the linewidth of such an IF signal is mainly dominated by that of the beat-tone associated with the DUT and thus it is properly expressed as (34.315 ± 0.001) MHz. Both frequency and linewidth of the THz beat-tone signal are in very good agreement with direct measurements already accomplished by spectroscopic schemes with a bolometer and FROG system,[4] and also indirectly by a UTC-PD and ESA.[6] Notice that the dynamic range of the IF signal depicted in Fig. 4 is over 6 dB, and it can be improved by tuning the two ECLs closer to the DUT modes. However this will generate more side-bands which might affect the measurement of such an intermediate frequency.

In conclusion, an experimental setup operating at room temperature for resolving THz beat-tone signals from multimode mode-locked FP semiconductor lasers has been presented. The key feature of this technique is the use of an SOA operating as a local oscillator and optical frequency mixer. The resolution of the retrieved frequency and accuracy of the linewidth associated with the beat-tone signals are comparable with those obtained from interferometric approaches. However, our method thus described overcomes them due to the low running cost, room temperature operation and practicality of the experimental setup.

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