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Semiconductor optical amplifier-based heterodyning detection for resolving optical terahertz beat-tone signals from passively mode-locked semiconductor lasers

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An all-optical heterodyne approach based on a room-temperature controlled semiconductor optical amplifier (SOA) for measuring the frequency and linewidth of the terahertz beat-tone signal from a passively mode-locked laser is proposed. Under the injection of two external cavity lasers, the SOA acts as a local oscillator at their detuning frequency and also as an optical frequency mixer whose inputs are the self-modulated spectrum of the device under test and the two laser beams. Frequency and linewidth of the intermediate frequency signal (and therefore, the beat-tone signal) are resolved by using a photodiode and an electrical spectrum analyzer. © *2010 American Institute of Physics*. [doi:10.1063/1.3481674]

Detection and accurate measurements of the radio frequency (rf) or terahertz (THz) spectra emitted by narrow- and broad-band light sources have been achieved through a number of techniques. In the case of narrow-band light sources, a typical approach for measuring the rf spectrum is to convert its temporal intensity into an electrical current using a fast photodetector and then to carry out the related analysis using electronics. In this approach, however, the major constraint is imposed by the bandwidth of the photodetector and the rf electronics, typically limited to 60 GHz. Detection and characterization of broad-band light sources (either pulsed or continuous wave) in the sub-THz regime and beyond is usually achieved by using bolometers, Golay cells and pyroelectric detectors.[1,2] It has also been proposed to analyze the rf spectrum of light sources by means of optical techniques such as nonlinear interactions in highly nonlinear fibers[3] and cross-phase modulation in nonlinear waveguides.[4] In spite of the great achievements accomplished in the majority of the mentioned schemes in terms of frequency resolution (in the order of GHz) and bandwidth (from 100 GHz to few THz), their main difficulties are the necessity of large experimental setups and the cost of the utilized components.

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.[5–8] Such a THz-emission has been directly detected by using spectroscopic schemes with a bolometer[5,6] and frequency resolved optical gating (FROG) systems,[6] and indirectly by a uni-traveling carrier photodiode (UTC-PD) and electrical spectrum analyzer (ESA),[8] 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 multimode light source. The source under test is a passively mode-locked Fabry-Pérot (FP) semiconductor laser whose potential as THz-emitter has been previously demonstrated.[6–8] 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 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. All components are operating at room temperature. The device under test (DUT) is a 350 μm long, InAlGaAs multiquantum well FP laser[6–8] mounted in a standard T0 can. Its 2 μm wide ridge waveguide secures a single mode spatial output, which is characterized by a threshold current $I_{th}=19$ mA. As shown in Fig. 2, when the laser is biased at 88.5 mA and temperature controlled at 25 °C, two longitudinal modes at $\lambda_1 \simeq 1553.22$ nm and $\lambda_2 \simeq 1556.21$ nm dominate the laser emission spectrum. They are accompanied by lateral modes resulting from four-wave-mixing (FWM), indicating strong nonlinear interactions of optical fields inside the laser cavity. The optical side-bands suppression with respect to the two main modes is larger than 30 dB, suggesting that their direct contribution to the beating signal Ω_1 at the difference between λ_1 and λ_2 is negligible. The optical linewidths of the

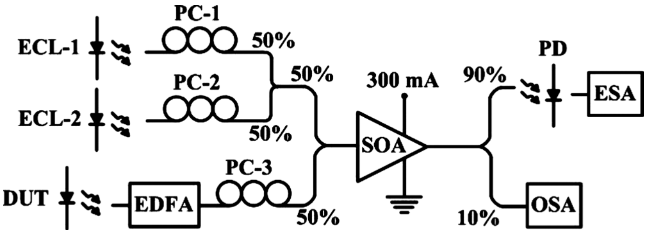

FIG. 1. Experimental setup.

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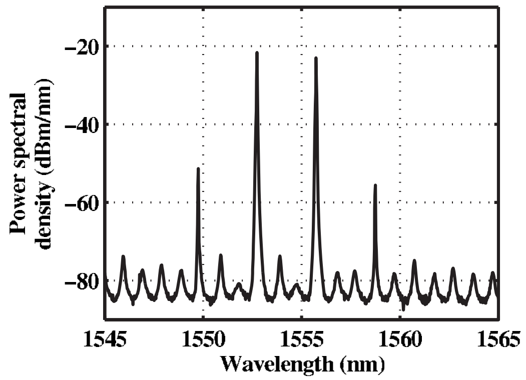

FIG. 2. Power spectral density collected at the output of the DUT. Intracavity beating at $\Omega_1 \simeq 371.1$ GHz between its two main modes gives rise to two side-bands at 1550.2 and 1559.2 nm.

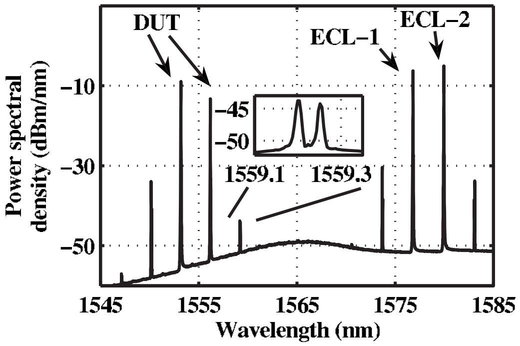

FIG. 3. Optical spectrum measured at the SOA output. In the inset is depicted the modulation components at Ω_1 and Ω_2.

two main modes are in the order of several MHz, which should lead to a linewidth of the sub-THz signal of the same order. Furthermore, based on previous measurements,[6–8] this device has demonstrated a modulation of 372 GHz approximately.

Besides the device under test, two tunable and continuous-wave external cavity lasers (ECL-1 and ECL-2) are injected into an SOA through a 3 dB optical coupler. Both ECLs exhibit an optical linewidth around 100 kHz and can be tuned from 1400 to 1700 nm. The commercially available SOA is an InP multi-quantum-well structure operated at 300 mA and temperature controlled at 19 °C. Its polarization dependant modal gain is 1 dB and its gain peak is around 1555 nm. An erbium doped fiber amplifier (EDFA) is used in order to increase the DUT output power. Polarization controllers PC-1, PC-2, and PC-3 allow the polarization of the injected beams to be aligned to the transverse electric eigenaxis of the SOA waveguide. The output of the SOA is both measured through an optical spectrum analyzer (OSA) set at 10 pm resolution and collected through a 60 GHz photodetector (PD). The intermediate frequency (IF) signal of our interest impinging on the PD is measured with an ESA set at 1 kHz radio bandwidth resolution.

The aim of the experiment is to use the SOA as an optical frequency mixer whose inputs are the self-modulated spectrum of the device under test on one hand, and the two ECLs on the other hand. In this case, the frequency Ω_1 of the beat-tone signal associated with the DUT is the unknown variable to be determined. The SOA under the ECLs injection operates as a local oscillator whose frequency Ω_2 is set by the difference $|c/\lambda_{\mathrm{ECL-1}} - c/\lambda_{\mathrm{ECL-2}}|$ between their corresponding wavelengths, where c is the speed of light in vacuum. Such an oscillation is sustained by the FWM phenomenon occurring in the SOA active waveguide and is associated with the modulation of its complex refractive index produced by the beating of the two ECLs. Thus, the SOA is considered as an optical mixer and also as a local oscillator at a tunable frequency Ω_2. It is worth noticing that even though the beating frequencies Ω_1 and Ω_2 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 $\Omega = |\Omega_1 - \Omega_2|$ at the output of the SOA in the electrical domain through a photodetector and ESA. Therefore, the beat-tone Ω_1 associated with the mode-locked laser can be determined through the measurement in the electrical domain of the IF signal oscillating at Ω. This is accomplished provided that both ECL wavelengths can be tuned with a sufficient precision and that they are far enough from the DUT wavelengths, thus avoiding the addition of unwanted IF components.

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 and nonlinear amplification of the DUT, where its main components and sidebands are enhanced, giving rise to intraband carrier-heating dynamic at $\Omega_1 = |c/\lambda_1 - c/\lambda_2| \simeq 371.1$ GHz. The second group corresponds to the injection of the two ECLs whose wavelengths $\lambda_{\mathrm{ECL-1}}$ and $\lambda_{\mathrm{ECL-2}}$ are set at 1576.82 nm and 1579.954 nm, respectively. Owing to their nonlinear beating inside the SOA, two main sidebands at $(\lambda_{\mathrm{ECL-1}} - c/\Omega_2)$ and $(\lambda_{\mathrm{ECL-2}} + c/\Omega_2)$ are generated. In this case, the ECLs detuning frequency gives rise to intra-band carrier-heating dynamic at $\Omega_2 \simeq 377.39$ GHz. These two modulations are shown in the inset of Fig. 3, where the engendered signal at 1559.2 nm generated by the FWM beating of the DUT main spectral components is accompanied by a spectral component at 1559.25 nm, which is generated by the ECLs beating. The important point is that such modulations inside the SOA are not only at the frequencies Ω_1 and Ω_2, but also at their difference $|\Omega_1 - \Omega_2|$. 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 $\Omega \simeq 6.29$ GHz is obtained, allowing the determination of the beat-tone Ω_1 associated with the mode-

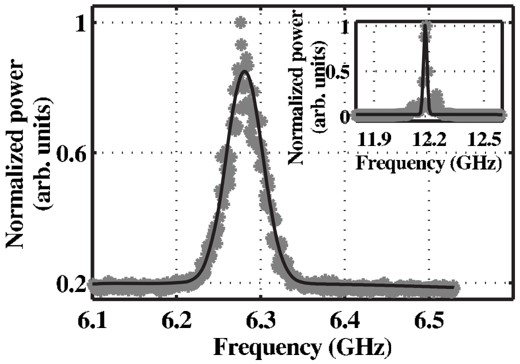

FIG. 4. Output of the SOA measured in the electrical domain depicting the intermediate frequency signal associated with the 371.1 GHz beat-tone from the mode-locked laser under investigation. In the inset is depicted the intermediate frequency of a 909.5 GHz beat-tone signal. Experimental measurements are shown in (∗) and Lorentzian fitting in continuous line.

locked laser. Notice that the beating frequency Ω, which in our experiment has been measured by setting $\Omega_2 > \Omega_1$, could also have been obtained from the same ECLs detuning frequency but satisfying the relation $\Omega_2 < \Omega_1$. In such a case, the retrieved beat-tone frequency Ω_1 is incorrect. However, this ambiguity has been ruled out by analyzing the trend in Ω while increasing and decreasing the ECLs detuning frequency. Another relevant aspect concerns the resolution of the beat-tone frequency measurement. While the measurement of the IF basically relies on the resolution of the ESA (set to 1 kHz in our case), the accuracy of Ω_1 depends on both the OSA resolution (set to 10 pm in our case, 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 $\Omega_1 \simeq 371.1 \pm 1.2$ GHz.

It is important noticing that the IF signal depicted in Fig. 4 exhibits a full- width at half maximum (FWHM) of ~34.315 MHz when fitted to a Lorentzian lineshape. In this case, the following should be considered: (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. A measured beat-tone linewidth (~34.315 MHz) smaller than that of the two optical modes altogether (~40 MHz), is indeed a signature of the mode-locking mechanism taking place inside the laser under investigation. Moreover, the resolution of the FWHM measurement is determined by the ESA radio bandwidth (in our case, set at 1 kHz), while the minimum resolved linewidth by our experimental setup is determined by that of the utilized ECLs. Therefore, the retrieved FWHM is properly expressed as 34.315 ± 0.001 MHz. As summarized in Table I, 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,[6] and also indirectly by a UTC-PD and ESA.[8]

Using the same experimental setup, another passively mode-locked FP semiconductor laser similar to the analyzed DUT but featuring main modes separated by ~7.4 nm has been tested. As depicted in the inset of Fig. 4, an electrical spectrum at ~12.126 GHz with a FWHM of 12.25 ± 0.001 MHz is measured after setting the ECLs at 1572.74 and 1580.18 nm. This results in a beat-tone signal of 909.5 ± 1.2 GHz for such a passively mode-locked laser.

TABLE I. Comparison of the different analyzed schemes for detecting THz-signals and THz beat-tones. Reported data for FROG and bolometer schemes are after Ref. 6, while UTC-PD is after Ref. 8.

Scheme	Frequency (GHz)	Linewidth (MHz)
FROG	373 ± 3.6	Not achievable
Bolometer	350 ± 1.8	Not achievable
UTC-PD	371.89 ± 0.001	16.89 ± 0.12
SOA-based	371.1 ± 1.2	34.315 ± 0.001

In conclusion, an experimental setup operating at room temperature for resolving THz beat-tone signals at ~372 and ~909 GHz from mode-locked FP semiconductor lasers has been presented. The key feature of this technique is the use of an SOA operating as an optical frequency mixer and local oscillator. 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 overcome them due to the low running cost, room temperature operation and practicality of the experimental setup.

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