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Experimental verification of the existence of optically induced carrier pulsations in SOAs

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ABSTRACT

Experimental investigation of the role of interband effects in four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is reported. Carrier density pulsations (CDP) in SOAs, caused by optical wave beating, are measured in the RF domain. This gives strong experimental confirmation of the link between CDP and wave mixing, as usually assumed in theory of FWM in SOAs. The dependence of CDP amplitude on bias current and optical power is also established.

1. Introduction

FWM is a well-known nonlinear effect, which can produce new optical waves when at least two distinguishable optical beams of the same polarization are input into the SOA. Many theories of FWM in SOAs have been published; see for example [1–3]. Almost every theory of FWM assumes two types of processes mediating wave mixing: interband and intraband processes. Interband processes (CDP) involve carrier transitions between the valence and conduction bands and their response time is limited to about 200 ps by the carrier injection rate. Intraband effects, like spectral hole burning (SHB) and carrier heating (CH) are caused by the modulation of the occupation probability within a band and have much lower strength and much shorter characteristic times (below 1 ps).

Although there has been extensive study of SOAs in the optical domain, little experimental work has been done in the electrical domain. CDP, if present, should result in a measurable electrical current. Direct electrical measurement of CDP in semiconductor lasers has only been reported once [4] and there are no such reports concerning SOAs. While four-wave mixing has been performed in both semiconductor lasers and travelling-wave SOAs, nearly all current work has focused on wave mixing in SOAs [5]. Although the operational characteristics of semiconductor lasers and amplifiers are different, CDP and the resulting wave mixing are due to the same physical processes as the material physics is the same. However, the carrier density in lasers is usually clamped to its threshold value so that the depth of modulation is shallower than in SOAs where large excursions of the carrier density are not uncommon. Additionally, the presence of optical feedback in lasers complicates the carrier dynamics, which manifests itself for example as relaxation oscillations. A deeper understanding of the physical processes is therefore more straightforwardly obtainable with SOAs. The SOA also makes it possible to investigate different experimental configurations. For example, the issue of pump co- or counter-propagation with the probe is ambiguous in lasers due to the strong reflections and can therefore be only meaningfully investigated using a travelling-wave SOA. There is also work reporting detection of the terahertz radiation due to FWM in SOAs [6]. At the same time, in most theories of FWM in SOAs, the existence and form of the CDP are assumed and phenomenologically introduced [1–3]. As CDP have been predicted to be the strongest effect mediating wave mixing for small detunings, an experimental verification of this assumption is important. If further motivation for the investigation is required it should be noted that numerical models are becoming increasingly concerned with the details of CDP and how optical fields interact in functional photonic devices. Measurements like the ones in this paper provide important input for theoreticians to produce robust and more sophisticated models for future functional photonic devices. Here, successful detection of the CDP in the RF domain is reported. The measurements confirm that the center frequency of the CDP is determined by the optical

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beat frequency and the CDP spectrum corresponds to the convolution of the two beating optical spectra.

2. Experimental setup

The experimental setup is shown in Fig. 1. Two diode lasers LD1 and LD2 are temperature fine tuned so that the detuning between them is less than 3 GHz (primarily limited due the bandwidth of the SOA electrical connection; the specific value then arising from choice of an appropriate RF spectrum analyzer (RFSA)). An optical spectrum analyzer (OSA) was used to monitor the detuning and to help with coarse tuning. The lasers used in the experiment were standard telecommunications lasers, both at a nominal wavelength of 1547.02 nm. Optical isolators (ISO) were inserted to ensure a stable lasing frequency and to suppress any back reflections. The SOA was a commercial InGaAs based multi-quantum well amplifier from CIP [7]. It was temperature stabilized using a thermoelectric cooler (TEC). A DC bias current was input to the SOA using a BiasT to uncouple it from the RF path. Similarly, the RF spectrum was measured at the RF port of the BiasT by the RFSA. RF shielding isolated the SOA and BiasT from any external electromagnetic interference. Polarization controllers (PC) were used to set the polarization states of the interacting waves.

Before measuring the CDP spectrum, the reference beating spectrum between the two lasers was measured by heterodyning them on a fast photodetector. The detector used was a standard telecommunications 10 Gb/s receiver. Fig. 2 shows the heterodyne spectrum. The 3-dB bandwidth of the spectrum was about 40 MHz, which suggests that the laser linewidths were about 20 MHz, assuming they were identical. The spectral shape was approximately Lorentzian as expected.

3. Experimental results

Firstly, the CDP spectrum was found on the RFSA. It was confirmed that the CDP is caused by the interaction between the input optical beams, as the RF signal disappeared when one of the lasers was switched off. Also, the RF signal was polarization sensitive and could be completely suppressed by adjusting the two PCs to the orthogonal states. The CDP spectrum corresponding to the heterodyne spectrum from Fig. 2 is shown in Fig. 3. The CDP spectrum is similar to the heterodyne spectrum, as expected from the fact that carrier rate equation governing carrier dynamics is linear with carrier concentration (therefore no new components are produced due to electrical nonlinearities). A slight shift in the peak frequency is due to a slow drift of the laser frequencies in time. The narrow frequency lines visible in Fig. 3 are due to the current source and SOA's TEC switching frequencies. According to FWM theory, additional beating is produced between the newly generated conjugate beam and the input beams. The frequency of this beat tone should be twice the frequency of the primary beating. Fig. 4 shows that this new tone can indeed be observed. Markers M1 and M2 indicate the beating spectra. A weak component at the second harmonic of the detuning frequency appeared, which may be due to beating between one of the input waves and the first order FWM product (as predicted by most FWM theories) or due to higher order harmonics in the CDP due to the asymmetry in the stimulated emission rate caused by gain saturation. Although the OSA did not have enough resolution to directly measure the output waves, the existence of new frequencies in the optical spectrum was confirmed by observing the CDP spectrum, which exhibited an additional peak at twice the detuning frequency and dependent on polarization. Further evidence of the presence of new frequencies is given by noting that the bandwidth of the second harmonic is larger than the bandwidth of the primary harmonic by a factor of over 1.5 (as predicted by standard FWM theory). This is consistent with the generation of the second harmonic by the beating between one of the original inputs and a new wave, which is itself already broadened compared to the input waves. Another heterodyning spectrum obtained on a fast photodetector placed (unlike that of Fig. 2) after the SOA was seen to contain the new components. The simultaneous disappearance of the CDP spectrum and the new components in this post-SOA heterodyning spectrum,

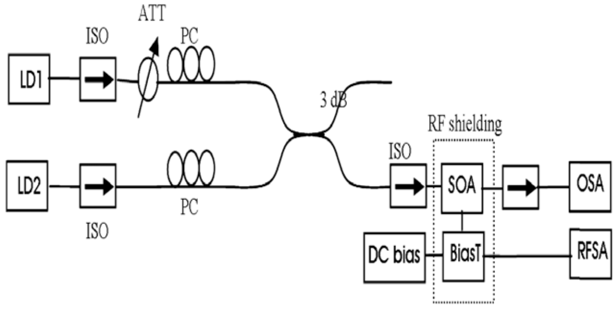

Fig. 1. Experimental setup to measure CDP.

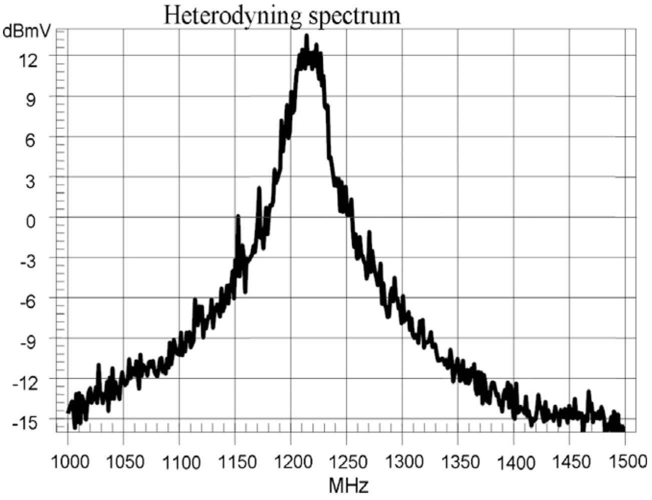

Fig. 2. Electrically detected heterodyne spectrum of LD1 and LD2.

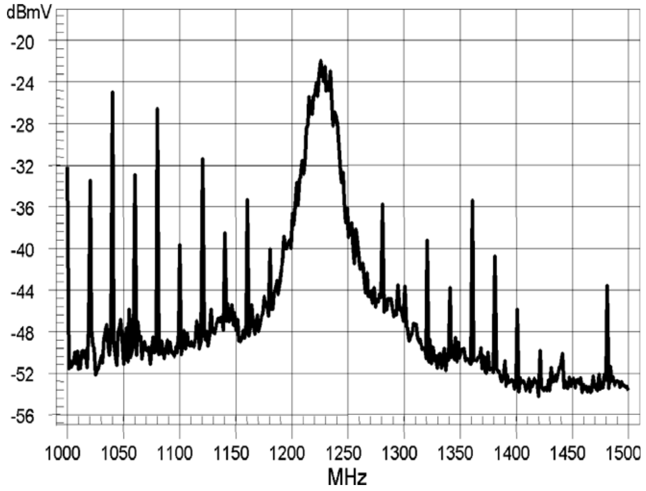

Fig. 3. CDP spectrum observed on the RFSA. Detuning between LD1 and LD2 of 1230 MHz.