Optical phase conjugation technique using four-wave mixing in semiconductor optical amplifier

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A semiconductor-optical-amplifier-based technique to generate the conjugate of an optical signal is presented. The original probe signal and its conjugate appear at opposite ends of the semiconductor optical amplifier, improving, therefore, existing techniques. The basic concept was proposed many years ago but, to the best of our knowledge, has never been experimentally verified. An explanation is given as to why this was not possible, what modifications render the idea practical are explained and experimental results that prove its feasibility are shown.

Introduction: In 1988 Agrawal published a theoretical paper [1] on four-wave mixing that has been widely referenced. In analogy to what is usually done with nonlinear crystals or in resonant two-level media [2], he proposed a bidirectional pumping scheme in a semiconductor optical amplifier (SOA) to achieve optical phase conjugation. There are many applications of optical phase conjugation [3], in particular chromatic dispersion compensation [4]. Agrawal studied and modelled the physics of carrier population oscillations, which underlies the four-wave mixing phenomena that take place in the device [5]. Agrawal predicted the characteristics of the probe and conjugate optical signals and particularly their appearance at opposite ends of the SOA. However, to the best of our knowledge, such behaviour has never been reported.

In [6] the generation of a co-propagating conjugate signal was attributed to the residual facet reflectivity of the SOA. We believe this is not the reason. In fact, since [6] was published the effective facet reflectivities of SOAs have been considerably reduced (by around two orders of magnitude) and still no such behaviour has yet been reported. What is systematically measured are the probe and conjugate waves at both ends of the SOA. These signals can only be separated by optical filtering [7], which makes it difficult to take advantage of the nearly-degenerate regime (small pump-probe frequency detuning). Optical filtering makes the experimental setup very complex if the frequency detuning between the pump and conjugate waves is below the terahertz range [7].

Physical interpretation: The beating between the pump and probe waves is taken into account in [1] as this process is the driving mechanism of population oscillations. However, the fact that the counter-propagating pump signals can create a standing wave inside the cavity was not considered. Such a standing wave results in a periodic longitudinal spatial carrier distribution that leads to an associated periodic refractive index profile (i.e. a Bragg grating). The Bragg grating wavelength peak is automatically tuned (that is to say, the reflectivity takes its highest value) to the pumping wavelength. The reflection bandwidth strongly depends on the amplitude of the refractive index modulation, cavity length and longitudinal optical power distribution and can be very large for long cavities and high refractive index changes [8].

We think that this Bragg grating partially reflects backwards the probe and phase conjugated waves, which explains why their counter propagation inside the SOA has never been reported before. A simple way to avoid this complication is to inject orthogonally counter-propagating pump signals (at the same wavelength). Such pump waves will not interfere to create a Bragg grating in the SOA.

Experimental setup: The experimental setup, shown in Fig. 1, was used to demonstrate the generation of a counter-propagating conjugate wave. The SOA TE and TM modes were identified by measuring the maximum and minimum of the SOA spontaneous emission spectrum after passing through an adjustable linear polariser. A tunable external cavity pump laser (laser 1) is amplified by an EDFA, filtered to reduce its spontaneous emission and split by a 3 dB coupler. One of the coupler outputs is fed to an optical single sideband modulator (OSSBM). Optical single sideband modulation is a simple way to achieve very small pump-probe frequency detuned waves with equal SOP and therefore makes it possible to check the performance of our setup in the nearly degenerate regime (i.e. a frequency detuning which is not very large compared with the inverse of the carrier lifetime) [1]. The modulator losses are high and thus we amplify the pump and probe waves with an EDFA and filter out the out-of-band spontaneous emission. The counter-propagating pump and the co-propagating pump and probe waves are aligned to the SOA TE and TM orthogonal modes using adjustable linear polarisers. Two polarisation controllers (PC1 and PC2) are used to couple the input light along the low loss linear SOP to avoid high losses in the linear polarisers. The optical circulators at both SOA ends are used to inject and extract the input and output waves, respectively. Polarisation-maintaining fibres have been used systematically. The SOA input powers are controlled by two optical attenuators (VOA1 and VOA2).

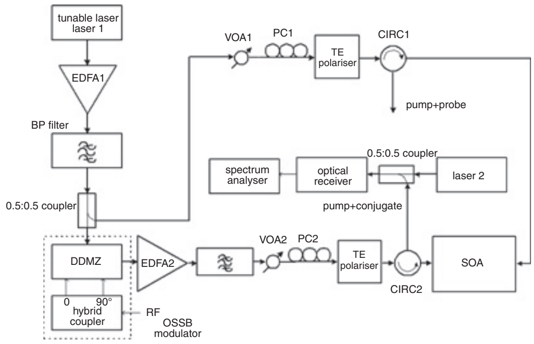

Fig. 1 *SOA-based optical phase conjugating system*

Pump and probe waves are injected through CIRC2 and only pump wave is injected through CIRC1

Because of the small pump-probe frequency difference, the output conjugate signal is not easy to measure. To achieve an effective optical frequency resolution of the order of 100 MHz, the output pump plus conjugate wave was mixed with a highly coherent laser (laser 2) the emission frequency of which is detuned from the pumping laser by 4 GHz using a highly linear photodiode. The receiver input optical power was kept low to avoid photodiode nonlinearities.

In our experiments the SOA is driven by low currents (from 25 to 30 mA) and the pump power takes values in the −3 to 4 dBm range (4 dBm was the maximum available pump power). At these pump powers, larger bias currents seem to make the four-wave mixing effects become too intense. Harmonic waves at frequency detuning values that are integer multiples of the modulating frequency are detected. Also an additional conjugate signal co-propagating with the probe appears.

The bias current had to be increased slightly inside the 25 to 30 mA range for increasing pump powers in the −3 to 4 dBm range. We think that this is because higher input optical powers deplete more the carrier population. To have a significant carrier concentration that can oscillate, the pumping current must therefore be increased to compensate for the higher carrier depletion.

The orthogonality of the counter-propagating pump waves had to be very precise. A large misalignment between the pumping waves made the probe and the conjugate waves appear at the two ends of the SOA. A relatively small orthogonality misalignment can lead to the generation of an unstable sporadic probe wave that propagates in the same direction as the conjugate signal.

The optical single sideband modulator operation conditions were also rather stringent. A sideband suppression ratio of less than 25 dB induced a bidirectional propagation of both the probe and conjugate waves. In our experiments, the modulation index has always been set equal to one (pump and probe signals had equal powers).

Results: Fig. 2 shows the pump and conjugate signals for a modulation frequency equal to 500 MHz as measured on a spectrum analyser. The bias current was 27 mA and the pump power at each input was 0 dBm. The SOA output wave probe and conjugate powers were −7 and −27 dBm, respectively, yielding a low conversion efficiency of $\eta = 0.2\%$. The efficiency is defined as $\eta = P^{out}_{conj}/P^{in}_{probe} \times 100$.

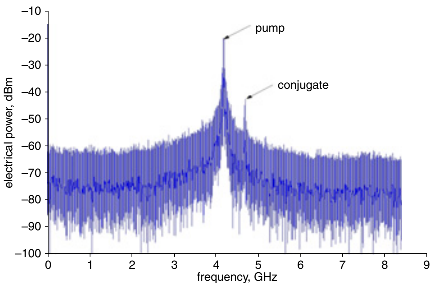

Fig. 2 *Measured spectrum at optical receiver output for 500 MHz modulation frequency*

Horizontal co-ordinate represents frequency detuning between laser 2 and pump and conjugate waves. This frequency is measured in gagahertz. Vertical co-ordinate represents measured electrical power measured in dBm

We repeated this measurement for modulation frequencies ranging from 0.5 to 3.5 GHz with 0.5 GHz steps. The conjugate signal power (relative to its power at 500 MHz) is shown in Fig. 3. The frequency response is not flat, as predicted in [1].

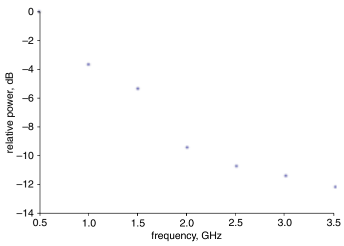

Fig. 3 *Conjugate wave relative powers measured in dB*

Reference power is −27 dBm. Modulation frequencies are 0.5, 1, 1.5, 2, 2.5, 3 and 3.5 GHz
Operation conditions are same as in Fig. 1

Conclusion: We have shown experimentally that, in strong contrast to existing techniques, SOA-based optical conjugation schemes are not necessarily restricted to the highly non-degenerate four-wave mixing regime, because the probe and conjugate waves can propagate in opposite directions inside the SOA, as proposed in [1].

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One or more of the Figures in this Letter are available in colour online.

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