Optimising Four-Wave Mixing in Ultralong SOAs

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***Abstract*—The numerical modelling of four-wave mixing in ultralong semiconductor optical amplifiers (UL-SOAs) is discussed. Inside the UL-SOA, complex wave mixing interactions take place so that time-domain modelling is an important requirement for the simulation model. We validate our simulations by comparison with measurements and show that the confinement factor is a crucial parameter for the device optimisation with regard to the generation of broad FWM combs.**

I. Introduction

Recent investigations have shown that ultralong semiconductor optical amplifiers (UL-SOAs) have a tremendous four-wave mixing (FWM) efficiency. For this reason applications as a short pulse source or as a WDM channel source are possible [1], [2]. In order to optimise these applications, important informations for a redesign can be obtained from simulations.

In this article, the requirements for modelling FWM in UL-SOAs are discussed. Moreover, using a proper simulation model, the confinement factor could be identified as an important design parameter in order to obtain broad FWM spectra from UL-SOAs.

II. Properties and Simulation of UL-SOAs

The purpose of UL-SOAs is to benefit from the fast intraband effects. In the first part of an UL-SOA, the signals are amplified and deeply saturate the second part. In the saturated section mainly the fast intraband effects interact with the signals. When injecting two co-polarised CW-signals with a wavelength spacing $\Delta\lambda$, dynamic gain and index gratings develop due to the beating as seen in Fig. 1. These beatings cause four-wave mixing between the CW signals also for large spacings due to the small intraband time constants. ¿From this description, it is clear that a time-domain model has to be used in order to correctly represent the UL-SOA dynamics. The simulation model used for this article is based on [3], [4]. The main idea is to use a second-order finite-impulse response (FIR) filter to model the wavelength dependence of the gain in each SOA segment. In order to apply the model on UL-SOAs, the filter coefficients are adaptively fitted to a cubic gain model. Moreover, further nonlinear effects like free carrier absorption (FCA) and two-photon absorption (TPA) were implemented with rate equations in order to automatically incorporate the bandwidths of the effects [5], [6]. Another advantage of a time-domain model is that it can be used in communication system simulations with PRBS signals [7].

III. Four-Wave Mixing in UL-SOAs

In Fig. 2, a comparison between simulated and measured FWM spectra for an 8-mm-long SOA is shown. The agreement is very good confirming our simulation model. The spectra developed due to the injection of two co-polarised CW-signals with $\Delta\lambda$=0.2 nm for different absolute wavelengths. The broad FWM combs result from a cascaded interaction of neighbour FWM products indicating the tremendous FWM efficiency in the UL-SOA. The shape of the spectra is asymmetric due to the Bogatov-like effect [8] that is caused due to the superposition of FWM contributions due to the gain and the index gratings.

For use as short-pulse source or WDM channel source, the FWM combs should be as broad as possible. Because the intraband effects that mediate the FWM depend on the photon density within the active region, the confinement factor describing the transverse mode confinement to the active

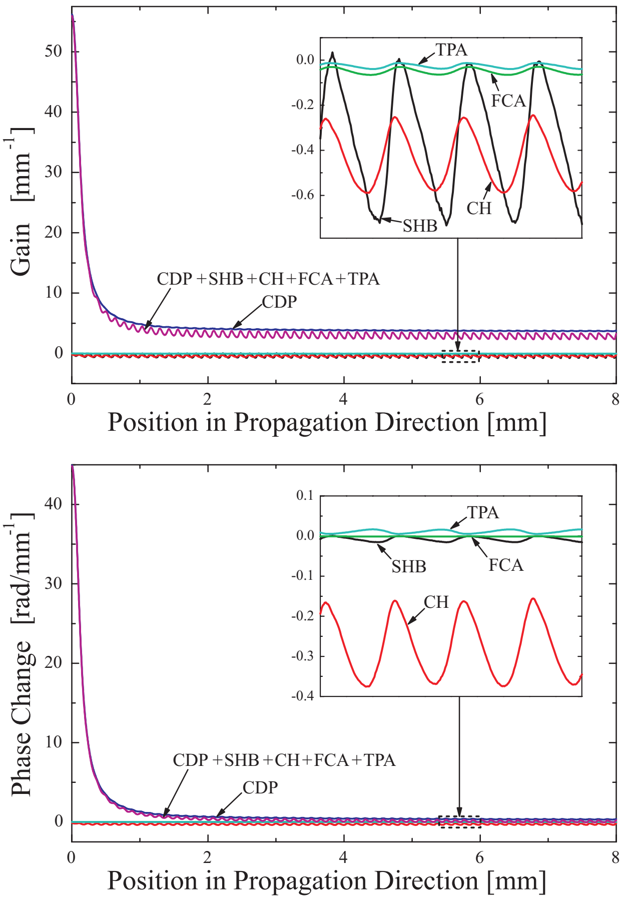

Fig. 1: Dynamic gratings in an UL-SOA along the propagation direction due to the beating of two coplarised signals with a wavelength spacing of 5 nm (CDP - Carrier Density Pulsation, CH - Carrier Heating, SHB - Spectral Hole Burning, FCA - Free Carrier Absorbtion, TPA - Two Photon Absobtion); the pulsation frequency is the difference frequency of the two input signals (a) dynamic gain grating, b) dynamic index grating)

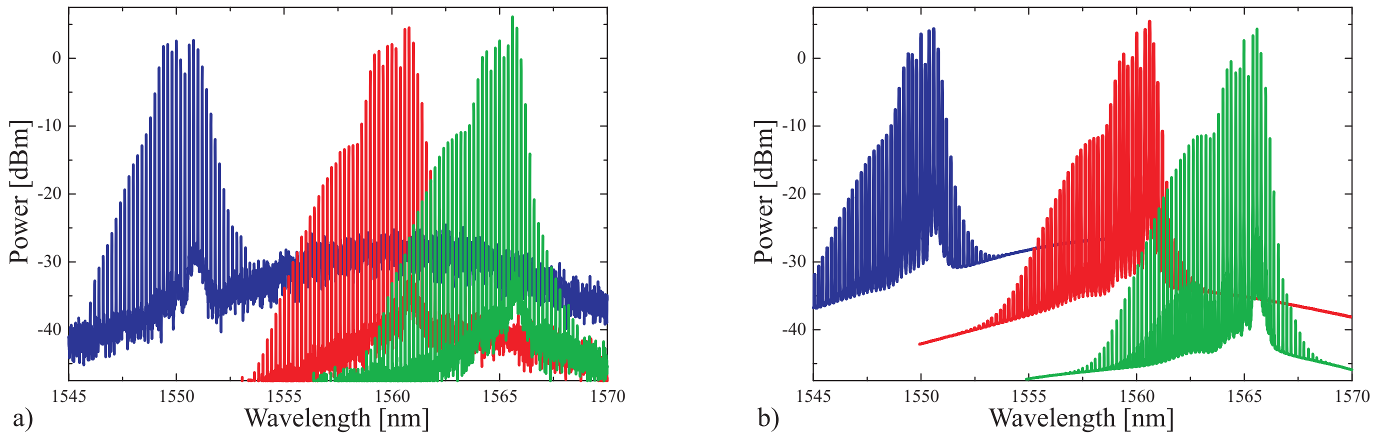

Fig. 2: FWM spectra at the end of an 8 mm-long UL-SOA caused by two injected co-polarised CW signals around 1550 nm, 1560 nm and 1565 nm with $\Delta\lambda$=0.2 nm, P_1=P_2=2 dBm (a) simulations, b) measurements); the FWM products again interact with their neighbour signals so that at the end of the UL-SOA a broad FWM comb can be obtained due to the good FWM efficiency; because of the broad FWM comb the UL-SOA is mainly saturated by FWM products instead of ASE

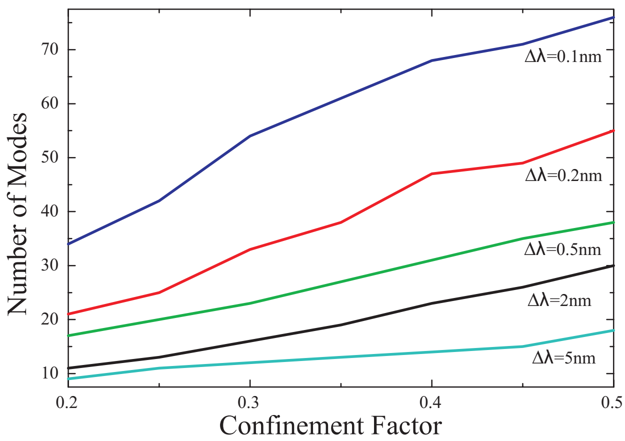

Fig. 3: Dependence of the number of FWM modes at the UL-SOA's output on the wavelength spacing and the confinement factor; P_1=P_2=2 dBm and λ_1=1560 nm

region should impact the strength of the dynamical gain and index gratings and therefore the FWM efficiency.

In Fig. 3, the dependence of the number of FWM modes on the wavelength spacing and the confinement factor are shown. Only the modes with a minimum SNR of 10 dB have been taken into account. As expected, the number of modes increases with the confinement factor showing that it is an important parameter for the device optimisation. For larger wavelength spacing, the number of modes decreases since FWM efficiency decreases.

However, one should note that chromatic dispersion is not included in our model but reduces the FWM efficiency. Since the chromatic dispersion in UL-SOAs is dominated by the material dispersion of the active region, an increasing confinement factor will result in an increased dispersion. For this reason, the results in Fig. 3 may differ for FWM combs with very broad bandwidth if chromatic dispersion is included.

IV. Conclusion

In this paper, the need for time-domain modelling of UL-SOAs was discussed. The validity of our model was confirmed by comparing our simulation results with measurements of broad FWM spectra. These spectra were generated by injecting two CW signals into the UL-SOA. Using the model, we could show that increasing the confinement factor is one way to optimise the device in order to increase the FWM comb's bandwidth.

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