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Modeling of nonlinear polarization rotation in tensile-strained semiconductor optical amplifiers using Mueller matrices and carrier density induced refractive index change calculations

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ABSTRACT

A model of nonlinear polarization rotation in a tensile-strained bulk SOA is presented. The model uses a wideband steady-state SOA model to determine the SOA carrier density and the polarization dependent gain. The carrier density distribution is used to determine the phase difference between the TE and TM components of an amplified CW probe signal in the presence of a counter-propagating pump. The active waveguide polarization dependent effective index difference is determined using the Marcatili method and the carrier induced refractive index changes are calculated using a detailed material band structure model. The SOA Mueller matrix, which is modeled as the product of an diattenuator and phase shifter, is used to predict the Stokes vector of the amplified signal. This allows a simple comparison with experiment as the Stokes vector can be easily measured using a polarization analyzer. The model is used to predict the polarization rotation of a probe signal induced by a counter-propagating pump. The model can be used to aid in the design of all-optical signal processing functions such as wavelength conversion and optical logic that use SOA polarization rotation effects.

1. Introduction

There has been considerable progress in the exploitation of optical nonlinearities in semiconductor optical amplifiers (SOAs). Much attention has been paid to carrier density induced nonlinearities, which lead to nonlinear polarization rotation (NPR) in SOAs. NPR is a mixture of cross-phase and cross-gain-modulation effects which cause a rotation of an amplified probe light polarization in the presence of a pump light [1–3]. NPR shows great potential for applications in optical networks for use as wavelength converters and all-optical logic [4,5]. The tensile-strained bulk SOA has attracted much interest due to its relative ease of fabrication and commercial devices are now available [6,7]. Such SOAs introduce tensile strain in the active region to achieve different TE and TM material gain coefficients. This difference is used to compensate for the unequal TE and TM confinement factors in order to equalize the TE and TM gains. Our previous work on modeling SOA NPR used a Mueller matrix model and a relatively simple model for prediction of the amplified signal and spontaneous emission and carrier density, which used many adjustable parameters to give good matching between the model and experiment [1,8]. In [1,8] the SOA material gain was modeled by a simple polynomial model and the additive spontaneous emission by a spontaneous emission factor. The refractive index differential with respect to carrier density was assumed to be constant and independent of wavelength. The effect of carrier density changes on the phase difference between the probe TE and TM components was modeled using a simple effective index model, which only incorporates the SOA active region waveguide structure through the use of the optical confinement factors. In [3] spontaneous emission is neglected and the TE–TM phase difference calculation does not use detailed calculations of the effective index dependence on carrier density and is in essence a spatially independent model. In [4] spontaneous emission is neglected and TE–TM phase differences are calculated using constant linewidth enhancement factors. In this paper the limitations of these models are overcome by modeling NPR through consideration of the band structure of the active region material and the active waveguide polarization, carrier density and wavelength dependent effective index, thereby reducing the number of fitting parameters. We use a combination of a detailed wideband SOA steady-state model [7], carrier density induced refractive index change calculations [9], SOA waveguide TE/TM effective index calculations based on the Marcatili method and the Muller matrix model [8] to accurately predict the polarization rotation of a CW probe signal in the presence of a CW counter-propagating pump signal. Because the model considers fully the detailed physics of the material band structure, the SOA waveguide characteristics, the spatial distributions of the amplified signals and spontaneous emission and the evolution of the light polarization

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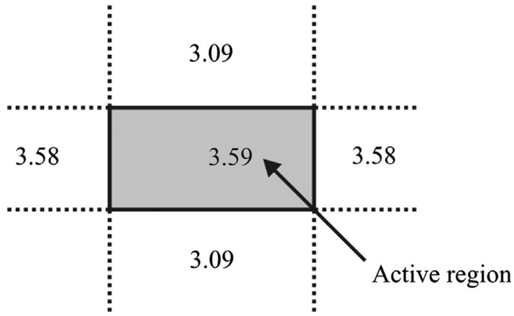

Fig. 1. Tensile-strained bulk SOA waveguide cross-section index profile.

state, it can be used in the design and optimization of all-optical signal processing functions such as wavelength conversion and optical logic that use SOA polarization rotation effects.

2. Mueller matrix model

The SOA modeled in this paper is a tensile-strained SOA (from Kamelian) [6,7], with an active waveguide refractive index profile shown in Fig. 1. The device structure consists of a central 840 μm long active region waveguide having a width of 1.1 μm a thickness of 0.1 μm and two end tapers of 80 μm length with an end width of 0.5 μm.

For a given bias current and input pump signal power, the steady-state characteristics of the SOA, including the carrier density spatial distribution, can be determined using the steady-state model [7]. A low-power probe input will experience a phase shift $\Delta\phi$ between its TE and TM components given by

$$\Delta\phi = \frac{2\pi}{\lambda_{probe}} \int_0^L \left[N_{eff,TE}(z) - N_{eff,TM}(z)\right] dz \tag{1}$$

λ_{probe} is the probe wavelength, L the SOA length and $N_{eff,TE/TM}$ are spatially dependent TE and TM effective indices, given by

$$N_{eff,TE/TM}(z) = N_{eff,TE/TM,0}(z) + \frac{dN_{eff,TE/TM}(z)}{dN_1} \Delta N_{1,TE/TM}(n(z)) \tag{2}$$

$N_{eff,TE/TM,0}(z)$ are the effective indices with no injected carriers and were determined using the Marcatili method for rectangular dielectric waveguides [10]. N_1 is the active region refractive index. $\Delta N_{1,TE/TM}$ is the carrier density (n) induced change in N_1 caused by bandfilling and free-carrier absorption, which was determined using the techniques in [9].

The polarization rotation properties of the SOA can be represented by a Mueller matrix $M = M_{dia}M_{ret}$, where M_{dia} is the Mueller matrix of a diattenuator (as the TE and TM components of the probe experience different gains) and M_{ret} is the Mueller matrix of a retarder (phase shifter) [8], given by

$$M_{dia} = \frac{1}{2}\begin{pmatrix} G_{TE}+G_{TM} & G_{TE}-G_{TM} & 0 & 0 \\ G_{TE}-G_{TM} & G_{TE}+G_{TM} & 0 & 0 \\ 0 & 0 & 2\sqrt{G_{TE}G_{TM}} & 0 \\ 0 & 0 & 0 & 2\sqrt{G_{TE}G_{TM}} \end{pmatrix} \tag{3}$$

$$M_{ret} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\Delta\phi & \sin\Delta\phi \\ 0 & 0 & -\sin\Delta\phi & \cos\Delta\phi \end{pmatrix} \tag{4}$$

G_{TE} and G_{TM} are the single-pass modal gains, which were determined using the steady-state model [7]. The Stokes vector of a light signal has four components S_0, S_1, S_2 and S_3, which quantify the total light intensity (normalized to 1), the amount of horizontal or vertical polarization, the amount of linear +45° or −45° polarization and the amount of right or left circular polarization respectively. The Stokes vector of the output probe is given by $\vec{S} = M\vec{S}_i$, where $\vec{S}_i$ is the Stokes vector of the input probe. The ellipticity angle of the output probe is given by

$$\varepsilon = 0.5\tan^{-1}\left(S_3/\sqrt{S_1^2+S_2^2}\right) \tag{5}$$

An ellipticity angle of zero or infinity corresponds to linear polarization and an ellipticity angle of 1 corresponds to circular polarization and is a useful way of visualizing the polarization state of light.

3. Simulations and experiment

All applications of polarization rotation in SOAs use a changing pump power to change the polarization state of the probe, so it is of interest to model the effect on the polarization state of the input probe signal as the pump power is changed. This can be done by using the steady-state model [7], which includes spontaneous emission, to determine the SOA carrier density distribution. The steady-state model [7] is used to determine the active region material absorption spectrum, which is used in the calculation of the TE–TM refractive index difference [9] and hence the TE–TM phase difference using (1) and the SOA Mueller matrix using (3,4). An experiment, shown in Fig. 2, was carried out in which a probe signal at a wavelength of 1545.6 nm and power of −8 dBm was injected into the SOA operating at a bias current of 200 mA. The counter-propagating pump wavelength was 1555.6 nm and its power was varied from −8 to 6 dBm. The counter-propagation mode of operation avoids the difficulty of separating the amplified pump and probe signals that would occur in the co-propagation mode of operation. Polarization maintaining fiber was used as much as possible in the experiment; however the fiber coupled SOA used conventional single mode fiber, which had to be taped down to keep the input probe signal polarization from drifting. The Stokes vector of the input and output probe signal was measured using a polarization analyzer (Agilent 8509C). The Stokes vector of the input probe signal was (1, 0.73, −0.46, 0.13) having a degree of polarization of 87%. The probe input Stokes vector was also used to determine the proportion of the input probe signal power coupled to the SOA TE and TM modes. This is important as the difference between the TE and TM mode gains can be significant as the pump power is increased as shown in Fig. 3. This difference increases the significance of the diattenuator component of the SOA Mueller matrix.

Fig. 4 shows comparisons between the experimental and simulated probe output ellipticity angle as the pump power was varied for two cases of the input probe Stokes vector. The magnitude and general shape of the ellipticity angle trajectories as predicted by the model are in good agreement with the experiment, especially since the model uses no adjustable parameters. The experiment was quite sensitive primarily because of the SOA is coupled using non-polarization maintaining fiber. The

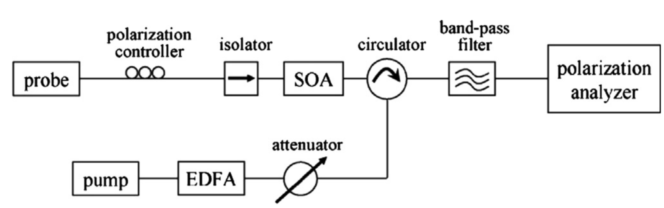

Fig. 2. Experimental setup to measure polarization rotation of a probe signal caused by a counter-propagating pump. The band-pass filter is used to reduce the amplifier output spontaneous emission.