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An optical threshold function based on polarization rotation in a single semiconductor optical amplifier

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Abstract: Optical threshold functions are a basic building block for all-optical signal processing, and this paper investigates a threshold function design reliant on a single active element. An optical threshold function based on nonlinear polarization rotation in a single semiconductor optical amplifier is proposed. It functions due to an induced modification of the birefringence of a semiconductor optical amplifier caused by an externally injected optical control signal. It is shown that switching from both the TE to the TM mode and vice versa is possible. The measured results are supported by simulation results based on the SOA rate equations.

OCIS codes: (190.0190) Nonlinear optics; (070.4340) Nonlinear optical signal processing.

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1. Introduction

Optical threshold functions are a basic building block for optical signal processing as they provide an all-optical way of implementing simple decisions in various applications. In [1] an optical threshold function is described where a laser diode was subjected to external feedback and light injection. This setup suffered from instability due to a free space optics implementation and frequency dependence. In [2] a fiber optic approach based on coupled ring lasers is introduced. The threshold function can be extended to form an arbiter using a laser neural network, used for all-optical buffering in [3]. One disadvantage of this coupled ring laser design is that it uses two active elements, semiconductor optical amplifiers (SOAs), hence increasing the footprint of the setup and its power consumption. Another limitation is that the injected optical power must be sufficient (e.g. 8.2dBm as described in [3]) to suppress one lasing mode before the other can start lasing.

In this paper we demonstrate a novel threshold function that relies on a single SOA, and switching between the two states requires smaller optical powers, resulting in application flexibility. The threshold function uses the principle of nonlinear polarization rotation in an SOA that results from the device birefringence due to the difference between the amplifier TE and TM mode effective indices [4]. The advantage of using this effect in an SOA is that a small index difference can cause a large relative phase shift. TE and TM modes show different gain response because they couple to different hole reservoirs [5]. As the optical power in the SOA increases, the saturation-induced phase difference alters the intensity of the light that is output from the SOA.

2. Operating principle

When an optical signal propagates through a semiconductor optical amplifier, the TE and TM components propagate independently, although the two modes are indirectly coupled through the carriers in the SOA. As in [5] we use that the TE and TM polarizations couple the electrons in the conduction band with two distinct reservoirs of holes.
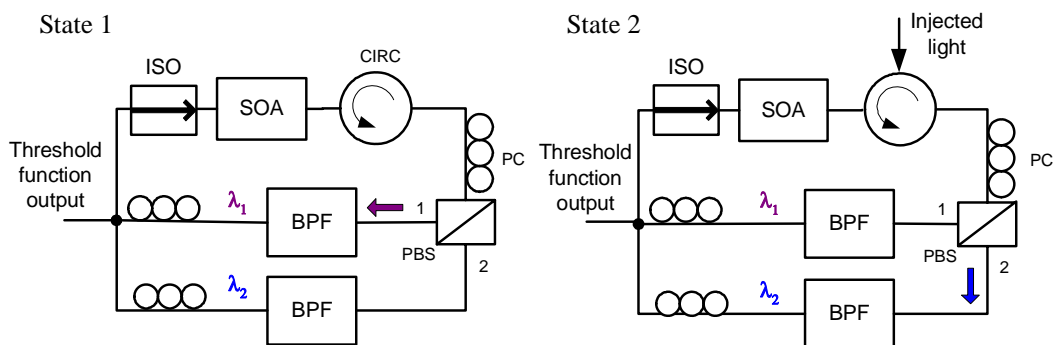

Fig. 1 Experimental setup of the threshold function. PC: polarization controller, SOA: semiconductor optical amplifier, CIRC: circulator, BPF: band pass filter, PBS: polarization beam splitter, ISO: isolator.

Figure 1 shows the experimental setup that is based on the principle that the TE and TM modes can be treated independently in a coupled ring laser that is built using an SOA. The two ring lasers are coupled through the SOA, so that a single gain element is shared by both lasers. The two laser cavities are then separated through the polarization beam splitter (PBS), and the resulting TE and TM modes pass through band pass filters with different wavelengths to facilitate distinction between the two modes. The two modes are coupled together again with a 2×2 coupler that provides the output of the threshold function as well as completing the ring laser through an isolator.

The system operates as follows. The two coupled ring lasers are separated by the PBS so that one laser works with the TE mode, and the other with the TM mode, as output by the two PBS ports. Optical band pass filters are placed in each cavity and act as wavelength selective elements so that each cavity lases at a different wavelength. Three polarization controllers are placed in the cavities. A misalignment of the input wavelengths to the SOA is required to translate a phase shift into polarization rotation. Thus the polarization controllers are used to ensure that the wavelengths are not coupled into the principal polarization axes of the SOA. The role of the first polarization controller is to align the SOA output light with the PBS and thus to separate the two cavities. The role of the other two polarization controllers is to align the polarization of the SOA input light with the SOA layers. This determines the working point of the system. Based on the theoretical model presented in [5] it is assumed that the working point of the system corresponds to one wavelength propagating completely in the TE mode in the SOA and the other completely in the TM mode.

The system can have two states. In state 1, the cavity operating at wavelength λ_1 (cavity 1) is lasing while the cavity operating at λ_2 (cavity 2) is suppressed. In this case the polarization controllers are aligned such that maximum feedback is achieved for cavity 1 and that the feedback for cavity 2 is very small (although still slightly above threshold). If additional light is injected via the circulator, the control light introduces additional polarization rotation in the SOA, causing the feedback in cavity 1 to reduce and the feedback in cavity 2 to increase. If the power in cavity 1 has dropped sufficiently below threshold, cavity 1 switches off and cavity 2 switches on. This situation remains until injection of the external light has stopped.

3. Nonlinear polarization rotation

The model for the threshold function is based on the SOA model introduced in [5]. This model is based on the fact that purely TE and TM polarized modes propagate independently through the SOA. The modes are indirectly coupled via the carriers. The change in phase, θ, between the TE and the TM modes due to the polarization rotation results in a change in photon numbers associated with the TE and the TM modes. The phase difference is given by:

$$\theta = \phi^{TE} - \phi^{TM} = \frac{1}{2}\left(\frac{\alpha^{TE}\Gamma^{TE}g^{TE}}{v_g^{TE}} - \frac{\alpha^{TM}\Gamma^{TM}g^{TM}}{v_g^{TM}}\right)L \tag{1}$$

Where the linearized gain gTE/TM for each mode is given by:

$$g^{TE} = \frac{\xi^{TE}(2n_x + n_y - N_0)}{1 + \varepsilon(S^{TE} + S_{inj}^{TE})}$$

$$g^{TM} = \frac{\xi^{TM}(2n_y + n_x - N_0)}{1 + \varepsilon(S^{TM} + S_{inj}^{TM})} \tag{2}$$

Where $S_{inj} = S_{inj}^{TE} + S_{inj}^{TM}$ because the injected light consist of both a TE and a TM component, n_x and n_y refer to the hole reservoirs associated with the TE and TM modes respectively, $\xi^{TE/TM}$ are the gain coefficients for each mode, L is the SOA length, $\Gamma^{TE/TM}$ are the confinement factors for both modes and N_0 is the carrier number at transparency. The rate equations for n_x and n_y are given by:

$$\frac{\partial n_x}{\partial t} = -\frac{n_x - \overline{n_x}}{T} - g^{TE}\Gamma^{TE}S^{TE} - g^{TE}\Gamma^{TE}S_{inj}^{TE}$$

$$\frac{\partial n_y}{\partial t} = -\frac{n_y - \overline{n_y}}{T} - g^{TM}\Gamma^{TM}S^{TM} - g^{TM}\Gamma^{TM}S_{inj}^{TM} \tag{3}$$

$\overline{n}_x$ and $\overline{n}_y$ are the respective equilibrium values given by:

$$\overline{n}_x = \frac{\overline{n}f}{1+f}$$

$$\overline{n}_y = \frac{\overline{n}}{1+f} \tag{4}$$

Where

$$\overline{n} = \frac{I}{e}T \tag{5}$$

In Eq. (5), I is the injection current, e is the elementary charge unit and T is the electron-hole recombination time. In the case of an isotropic bulk, the transitions will be symmetric. But for a bulk medium experiencing tensile strain, one of the two modes may be favoured. (Other causes of polarization dependence, such as waveguide asymmetry and anisotropic gain in quantum wells [6], are beyond the scope of this analysis.) The population imbalance factor, f, is used to model this type of asymmetry. Due to tensile strain the mixture of light and heavy holes in the bulk medium [7] can be such that TM transitions are favoured over TE transitions [5]. Finally, the rate-equations for photon numbers of the TE and TM modes are:

$$\frac{\partial S^{TE}}{\partial t} = (\Gamma^{TE} g^{TE} - \alpha_{cav}^{TE} \cos(\theta + \delta^{TE})) S^{TE} \qquad \frac{\partial S^{TM}}{\partial t} = (\Gamma^{TM} g^{TM} - \alpha_{cav}^{TM} \sin(\theta + \delta^{TM})) S^{TM} \qquad (6)$$

Equation (6) includes the loss for both TE and TM components in the cavities of the ring lasers, α_{cav}^{TE} and α_{cav}^{TM}, as well as the phase for both components, δ^{TE} and δ^{TM} (determined by the polarization controllers as shown in Fig. 1).

The photon number $S^{TE/TM}$, and the output optical power from the threshold function, $P^{TE/TM}$, are related through the following equation:

$$S^{TE/TM} = \frac{P^{TE/TM}}{\hbar\omega} \frac{L}{v_g} \qquad (7)$$

Here v_g is the group velocity of the light in the SOA, ω is the frequency of the light and $\hbar$ is Planck's constant (we use $\hbar\omega = 0.8$ eV).

The values for the parameters used in the simulations can be found in Table 1.

Table 1. Parameter Definitions

Symbol	Parameter	Value
α^{TE}, α^{TM}	Phase modulation coefficients	5, 5
Γ^{TE}, Γ^{TM}	Confinement factor	0.2, 0.14
v_g	Group velocity	100 μm/ps
L	SOA length	800μm
ξ^{TE}	TE Gain coefficient	$7.0 \times 10\text{-}9$ ps^{-1}
ξ^{TM}	TM Gain coefficient	$6.4 \times 10\text{-}9$ ps^{-1}
N_0	Optical transition state number	10^8
T	Electron-hole recombination time	500 ps
f	Hole population imbalance factor	0.5
I	Electric current	160 mA
e	Electric charge unit	1.6×10^{-19}C
τ_e	Carrier lifetime	1 ns
$\alpha_{cav}^{TE}, \alpha_{cav}^{TM}$	Cavity losses for the ring laser	0.9
ε	Gain saturation	10^{-7}

3. Experiment and results

In the setup shown in Fig. 1, a commercially available bulk SOA with an 800μm active region was used. The filters used were Fabry-Perot filters with a 3 dB bandwidth of 0.2nm, and they were set to the following wavelengths: $\lambda_1 = 1552.55$ and $\lambda_2 = 1543.55$ nm. In this SOA the gain difference between the two wavelengths used is less than 2dB. At the bias current used, the polarization gain difference is negligible. The band pass filters ensure that the two ring lasers operate at two distinct wavelengths. For the demonstration, the threshold function was set to lase at λ_1. When the external optical signal was injected into the SOA, polarization

rotation resulted in a phase change between the TE and the TM modes, causing the transmittance through the PBS in cavity 1 to reduce and in cavity 2 to increase. This results in a reduced carrier number in cavity 1 and an increased carrier number in cavity 2.
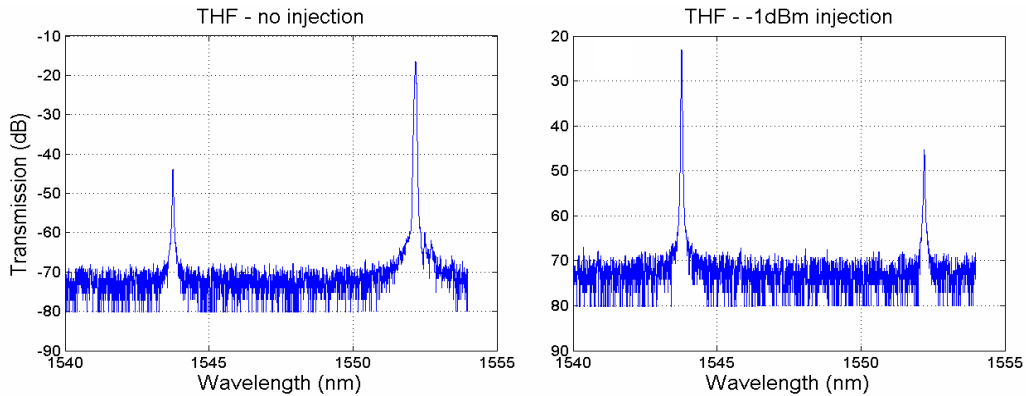

Fig. 2 Spectra of the two states of the threshold function. a) λ_1 = 1552.55nm is dominant until b) -1dBm of external optical power is injected, after which λ_2 = 1543.55nm becomes the dominant wavelength. In each case a contrast ratio of approximately 20dB can be achieved.

The optical spectra are shown in Fig. 2. It is visible that if no external light is injected in the threshold function, cavity 1 dominates over cavity 2. If -1 dBm of external light (λ= 1555.7 nm) is injected into the laser, the system changes state and cavity 2 dominates over cavity 1. The contrast ratio between both states is approximately 20 dB. Figure 2 shows the optical power in both cavities directly before and after switching with a small control signal.
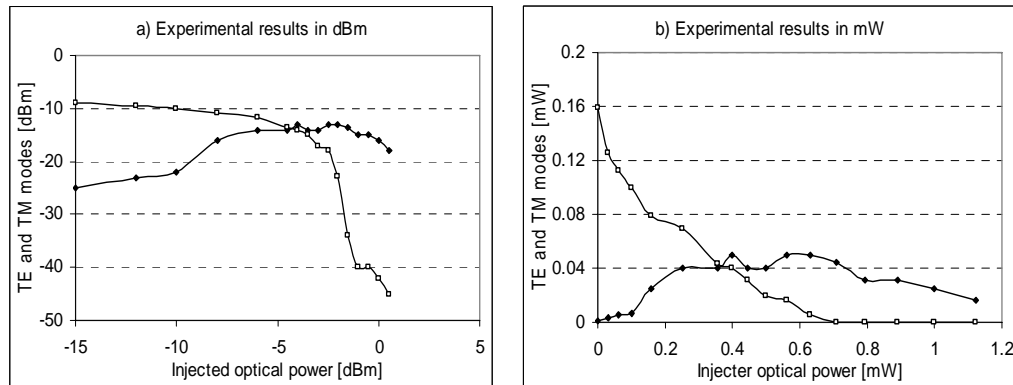

Fig. 3 Measured results shown in dBm and mW. Here switching is shown from the TM mode (open square) to the TE mode (solid diamond), with an extinction ratio between 15 and 20dB. Switching is achieved with an injected optical power of approximately -4dBm.

Figure 3 shows the experimental results where the injected control signal is increased gradually until it results in gain quenching of the two threshold function wavelengths (the exact values in Fig. 2 and Fig. 3 differ as the two figures were produced from different runs of the experiment; the measured values differ due to the polarization dependence of the setup). In Fig. 3 it can be seen that the cavity that is not dominant after switching is suppressed to below lasing threshold due to the gain quenching caused by the increasing injected control signal. The cavity that is not dominant is originally slightly below threshold, and increases with approximately 10dB to just above threshold after the control signal switches the threshold function. This results in an extinction ratio between 15 and 20dB.

4. Theoretical analysis

Solving Eq. (1) to (7) using the parameters as described in Table 1 yields results as shown in Fig. 4. Differences between the analytical and measured results are possibly due to the phases in Eq. (6) that are unknown and need to be estimated, loss factors in the experimental setup such as connector and transmission loss to the measurement equipment, and loss and polarization change of the injected light. Errors inherent to the numerical solution of nonlinear equations that have multiple solutions can also play a role. Another factor influencing the measured results is the change in polarization over time, and may be compensated for by using polarization maintaining fiber in the experimental setup.

It was clear from both the experiments and the analysis that the system is very sensitive to any changes in parameters, especially the phase, δ^{TE} and δ^{TM}, as shown in Eq. (6). The results shown in Fig. 4 were obtained using phases $\delta^{TE} = \delta^{TM} = 1.1\pi$ (obtained through trial and error) , taking into account the loss of the injected light before reaching the threshold function, assuming the injected light consists of 90% TE and 10% TM modes, and assuming a cavity loss of 0.9.
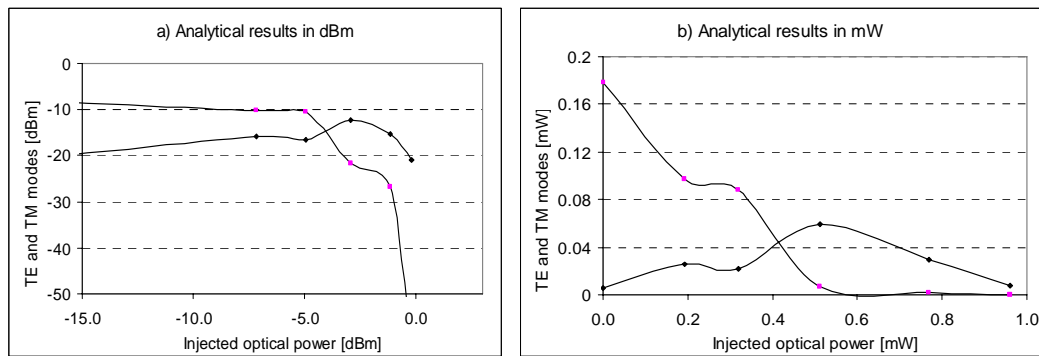

Fig. 4 Analytical results are similar to the measured results shown in Fig. 5.3: switching from TM (pink squares) to TE (black diamonds).

5. Conclusions

In this paper a novel optical threshold function that can be used in optical signal processing has been proposed. It functions due to an induced modification of the birefringence of a semiconductor optical amplifier caused by an externally injected optical control signal. The major advantage of the configuration is that a single active element is used.

An important advantage of implementing an all-optical threshold function using polarization rotation in a SOA is that it does not require a significant rotation to affect a change in output. The reason for this is that the laser threshold curve is very steep which means that a small change in polarization will lead to a large difference in output optical power. The measured contrast ratio between the output states was in the order of 20 dB. It is possible to switch the threshold function with a control signal of less than 0dBm, which is significantly lower than 8dBm, as described for the threshold function used in [5]. As the injected power increases, the two signals in the threshold function are quenched due to the injected light.

The measured results were supported by the simulation results that are based on the SOA rate equations. The model used is based on the fact that the TE and TM components of the light correspond to the two principle axes of the SOA, and that the two modes are indirectly coupled through the carriers. Differences between the measured results and the simulated results are mainly due the change of polarization in the experimental setup over time and the phases of the TE and TM mode photon numbers which are determined by the polarization controllers in the setup shown in Fig. 1 and are estimated in the analysis; these phases are important as the setup is very sensitive to any variations.