Function-lock strategy in OR/NOR optical logic gates based on cross-polarization modulation effect in semiconductor optical amplifier

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We have studied a function-lock strategy for all-optical logic gate (AOLG) utilizing the cross-polarization modulation (CPM) effect in a semiconductor optical amplifier (SOA). By monitoring the power of logic light, the strategy realized controllable methods to capture OR and NOR functions and switch between them. The strategy has been successfully applied in experiment with 10-Gb/s not-return-to-zero (NRZ) signals, which has a high success-rate above 95% and ensures the high extinction ratio of result light above 11.4 dB. Every step in the strategy has definite numeric evaluation, which provides the potential of automatic implementation.

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All-optical logic gate (AOLG) is one of the crucial components in future optical networks, which is the base of all-optical routing and package switching[1,2]. AOLG utilizing cross-polarization modulation (CPM) effect in the semiconductor optical amplifier (SOA) has several advantages: compact structure, low energy consumption, no synchronization, and diverse functions[3−7]. In optical logic operation, OR and NOR functions can be realized with a same structure[4]. As the functions can only be available at specific working points, which are sensitive to several parameters and difficult to capture, a definite and controllable method to lock system to the working points is very necessary in practical applications. However, recent research for the optical logic gates is mainly focused on the function capability of a certain setup, and the function-lock progress is not mentioned or just by manual attempts. In this paper, a function-lock strategy with optimized system setup is raised up to meet the requirements, which has a potential of automatic implementation by computer, and it should be a significant complement to existing research.

The experiment setup in this paper is described in Fig. 1. A continuous-wave (CW) probe light fed into the SOA is controlled for polarization state by a polarization controlling module (PCM) and the output of the SOA is sent to a polarizer through a circulator. Two lights at other wavelengths, modulated as 10-Gb/s not-return-to-zero (NRZ) signals with different time delays, are coupled and injected into the SOA to saturate it and introduce additional birefringence. Transverse-electric (TE) and transverse-magnetic (TM) modes of the probe light experience different phase shifts in the SOA, and interfere at the polarizer to convert the phase difference into amplitude variation[8,9]. Due to the saturation effect in SOA and nonlinear conversion at polarizer, the phase shifts remain almost the same when two signals are one plus zero and one plus one, and with different setup of probe light's polarization, it produces function OR or NOR.

As a control strategy, the function-lock strategy has three elements: monitor variables, control variables and adjusting method.

The average power of result light P_{r} is selected as the monitor variable. In traditional experiments, the waveform of result light is always monitored, which is too complicated and costly, and it must be judged by humans, which causes much uncertainty. Comparably, P_{r} is convenient to monitor by just adding a power meter, and the numeric analysis of its dynamic characteristic can represent the system working point.

Control variables include the working currents of probe laser diode (LD) I_{LD} and SOA I_{SOA}, the power of signal light P_{s}, and polarization of every light. Instead of three polarization controllers (PCs) in traditional setup, only one PC is used here so that the controlling complexity is reduced greatly. By utilizing a SOA with low polarization dependent gain (PDG), the PC for signal light is not

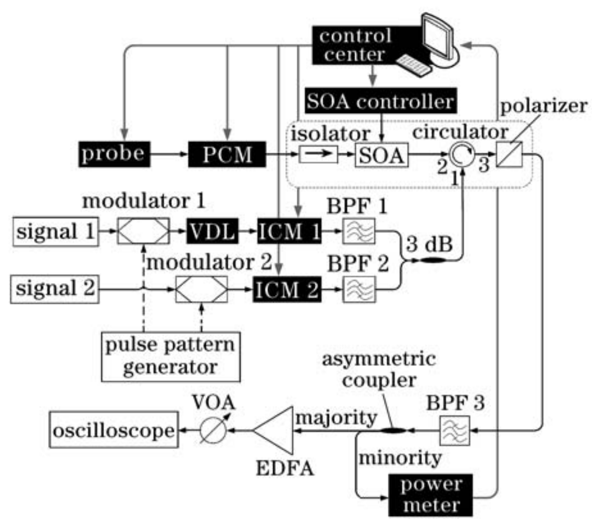

Fig. 1. Experiment setup of CPM OR/NOR AOLG. EDFA: erbium-doped fiber amplifier; VOA: variable optical attenuator; BPF: band-pass filter; VDL: variable delay line; ICM: intensity control module.

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necessary, and the function of the PC for output light of SOA can be carried by the PC for probe light, so the two PCs can be removed. The PC for probe light is replaced by a PCM with polarization stabilization ability and the PCM includes a voltage-controlled PC, whose effect on polarization is similar to SOA's, which can provide a direct adjusting function. All the variables have numeric values, so every step of the adjusting method can be evaluated numerically, which is the base of automatic implementation.

According to the characteristic of CPM effect, the strategy will approach the OR function from initial status first, and then switch between the two functions. The adjusting method is divided into four stages.

Stage 1: set the bias current of active devices, including probe laser and SOA. According to the theoretical analysis of SOA, higher working current makes shorter saturation recovery time[10], but more instability. The initial current of SOA $I_{\mathrm{i,SOA}}$ is set as

$$I_{\mathrm{i,SOA}} = 0.75 I_{\mathrm{m,SOA}} + 0.25 I_{\mathrm{t,SOA}} \tag{1}$$

as a tradeoff, where $I_{\mathrm{m,SOA}}$ is the maximum permitted current, and $I_{\mathrm{t,SOA}}$ is the threshold value.

The initial current of probe laser $I_{\mathrm{i,LD}}$ is set as

$$I_{\mathrm{i,LD}} = I_{\mathrm{t,LD}} + 2(I_{\mathrm{sa,LD}} - I_{\mathrm{t,LD}}) \tag{2}$$

to make deep saturation in SOA, where $I_{\mathrm{t,LD}}$ is the threshold current, and $I_{\mathrm{sa,LD}}$ is the minimum current for saturation.

Stage 2: set the polarization bias. According to theoretical and experimental analysis[11,12] for CPM effect, as OR function, the polarization of output light from SOA during symbol "0" should be orthogonal to the direction of polarizer. The polarization state during "0" is also the state without signal lights; so this stage is to reduce P_{r} to its minimum by adjusting three channels of PC. Considering hysteresis effects of piezoelectricity ceramics in PC, the adjusting process must be single-direction and real-time judged. P_{r} is monitored during stages $2-4$. A sample curve is shown in Fig. 2, and the gray or white sections in part of stage 2 stand for the three channels of PC.

Stage 3: make saturation by the signal lights. After setting up the polarization state, P_{s} should be increased to the minimum value of saturation to make the function and avoid damage to SOA. The two signal lights are ensured to have the same intensity during the process by help of intensity control modules (ICMs). A sample curve of P_{r} versus P_{s} is shown in Fig. 3, which has four periods: below threshold, linear, single saturated, and double saturated. Current period during adjustment is judged by the slope of the curve. The aim point is double saturation period, which is judged as

$$\frac{\Delta P_{\mathrm{r}}}{\Delta P_{\mathrm{s}}} < \frac{1}{N}\frac{P_{\mathrm{r}} - P_{\mathrm{t,r}}}{P_{\mathrm{s}} - P_{\mathrm{t,s}}}, \tag{3}$$

where ΔP_{s} is the increasing step of P_{s}, ΔP_{r} is the increased value of P_{r}, $(P_{\mathrm{t,s}}, P_{\mathrm{t,r}})$ is the threshold point of the curve, N is an experience constant such as 10.

Stage 4: switch between functions. The main difference of working points between OR and NOR functions is the azimuth angle of probe light's polarization, as shown in Fig. 4. This angle is mainly determined by a main channel of PC, which is measured during the initial stage. For common signals such as pseudo random binary sequence (PRBS), the symbols "1" and "0" have the same amount, and P_{r} for OR and NOR is also equal. So in this stage, firstly P_{r} is decreased by adjusting the voltage of PC, until reaching its minimum (the switching point), and then increased through the same adjusting direction to $P_{\mathrm{r,OR}}$ (P_{r} of OR function), which is the working point of NOR function. A sample adjusting curve and the waveforms are also shown in Fig. 4. Actually, this situation means the output polarization of symbol "1" is orthogonal to the polarizer.

In an experiment with 10-Gb/s NRZ signal, we realized the AOLG using the above strategy. The signal wavelengths are 1555.5 and 1560.3 nm respectively, and the probe's is 1548.7 nm. The waveforms of signals and result

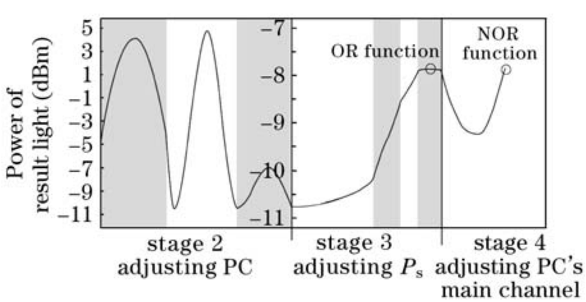

Fig. 2. Principle adjusting curve during stages $2-4$.

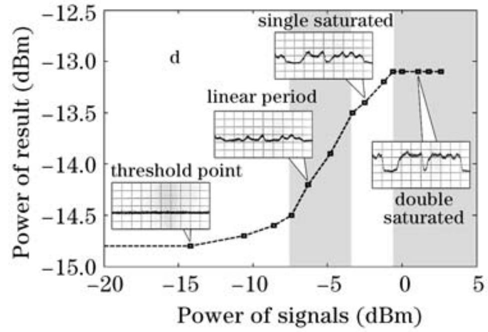

Fig. 3. Sample curve of P_{r} versus P_{s} and waveforms of result light at key points in stage 3.

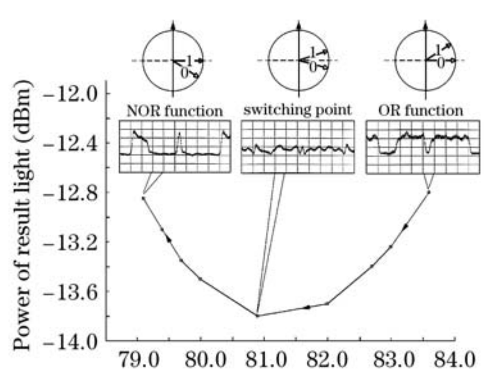

Fig. 4. Sample curve of P_{r} versus voltage of PC's main channel $V_{\mathrm{main,PC}}$ and waveforms of result light at key points in stage 4.

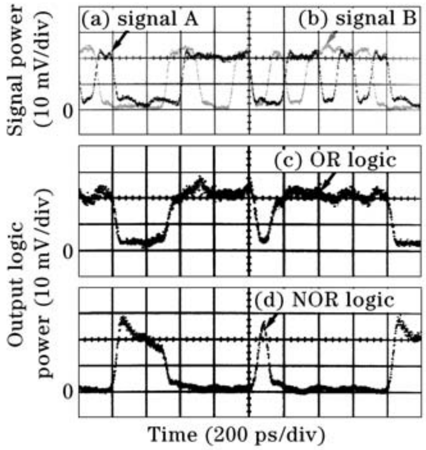

Fig. 5. Waveforms of signal and result lights.

are shown in Fig. 5. Figures 5(a) and (b) show the waveforms of signals A and B, whose extinction ratios (ERs) are 8.87 and 13.23 dB respectively. By performing the approaching method without any information of the result waveform, the function OR and NOR was reached as Figs. 5(c) and (d), and Figs. 3 and 4 show the adjustment process, which is fit for the principle. The ERs of OR and NOR results are 11.41 and 11.49 dB respectively, which is very near to the best results, so the function-lock method is proved to provide a high quality result signal. As all the steps in the strategy have definite numeric judgments, the strategy is expected to have an automatic implementation by computer. The process has been repeated for different devices with the same setup, and the recorded success rate is higher than 95%.

In conclusion, a function-lock strategy with optimized system setup for OR/NOR AOLG based on CPM effect in SOA is raised up to present a controllable method to approach the functions' working points and switch between them. In an experiment with 10-Gb/s NRZ signals, by help of the strategy, the logic functions are reached with high ERs above 11.4 dB, and the success rate is higher than 95%. The strategy has the potential of automatic implementation, and further research is being carried on.

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