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All-optical multicasting NOT and NOR logic gates using gain modulation in an FP-LD

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Abstract: We demonstrate all-optical NOT and NOR logic gates at 10 Gb/s based on gain modulation of a transverse electric (TE) polarized light in a Fabry-Perot laser diode (FP-LD). An FP-LD shows a gain for a TE-polarized injected probe beam. The gain can be modulated by injection of a pump beam. Using the gain-modulation characteristic, we implemented all-optical NOT and NOR logic gates. We investigate double channel out performances as an example of the multicasting function of the gates. We measured around 1.5 dB power penalty at a bit-error-rate of 10^{-9} and observed over 12 dB extinction ratio in each of the gate operation.

Keywords: All-optical logic gate, multicasting, Fabry-Perot laser diode, gain modulation, injection locking

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

All-optical logic gates (AOLGs) have attracted considerable interest in optical signal processing systems. All-optical signal processing is essential for high-capacity core networks to avoid bottleneck-like opto-electronic conversion. For the past years, digital optical devices have been anticipated as key components for realization of all-optical signal processing and all-optical computing. The AOLGs are the basic elements for the digital optical devices. Many researches for the AOLGs have been intensively conducted [1, 2, 3]. Various functions such as optical packet detection, optical regeneration, time demultiplexing and so on, are implemented by the AOLGs [4, 5]. For the realization of AOLGs, interferrometric arrangements have been widely used and they offer speed advantages and Boolean logic capabilities. These arrangements consist, in general, of two separate optical paths where the phase of an optical field may be independently controlled in a nonlinear optical medium by optical means. Early research efforts used an optical fiber as the nonlinear material exploiting the ultra-fast Kerr nonlinearity. However, the fiber nonlinearity is rather weak, requiring a long length fiber, making the devices difficult to be integrated and their switching energies high. Fast phase variations can also be obtained by using a semiconductor optical amplifier (SOA). SOA based interferrometric gates are attractive due to their compactness and potential of the low switching energy. However, they still suffer from the fabrication complexity and sensitivity of a phase change due to environmental effects such as temperature variation, mechanical vibration etc. Moreover, SOA based AOLGs require multiple units of interferrometric gates to be cascaded [1, 2] resulting in increased design and fabrication complexities as well as increased number of control signs for each gate.

In this paper, we demonstrate all-optical NOT and NOR logic gates at 10 Gb/s based on gain modulation of a transverse electric (TE) polarized light in a Fabry-Perot laser diode (FP-LD). We experimentally investigated the performances of NOT and NOR logic gates. As an example of multicasting function of the gates, we investigate the double channel out performances of the gates. The AOLGs using FP-LD is very simple structure, cost-effective and supports high speed operation along with multicasting function with high ER and low power penalty.

2 Operation Principle

A significant characteristic of an FP-LD is that if the TE-polarized light of any laser beam with the power over a certain threshold is injected slightly longer wavelength side of any longitudinal mode of the FP-LD, the corresponding mode is locked by the injected beam and the beam experiences a power gain, while all other side modes of the FP-LD are suppressed. These phenomena are called as injection-locking. If another TE-polarized beam with the higher power and wavelength detuning is injected against any other mode of the FP-LD, the FP-LD is locked by the second beam. At this moment, the first beam experiences reduction of its gain by releasing the locking

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state while the second beam experiences a power gain. The gain variation of the first beam by the second beam is gain modulation [6]. For gain modulation, the power of the modulated first beam should be lower and the detuning wavelength should be shorter than those of the second beam. In this paper, the first and second beams are a probe and a pump, also, output and input of an AOLG, respectively.

By using the gain modulation, we can make an all-optical NOT gate because the output probe beam and the input pump beam have inverse relation. As shown in Fig. 1 (a), in absence of the input pump, the output probe is logically HIGH (dash) and in presence of the input pump, the output probe is logically LOW (solid line). This is NOT function. We can also implement

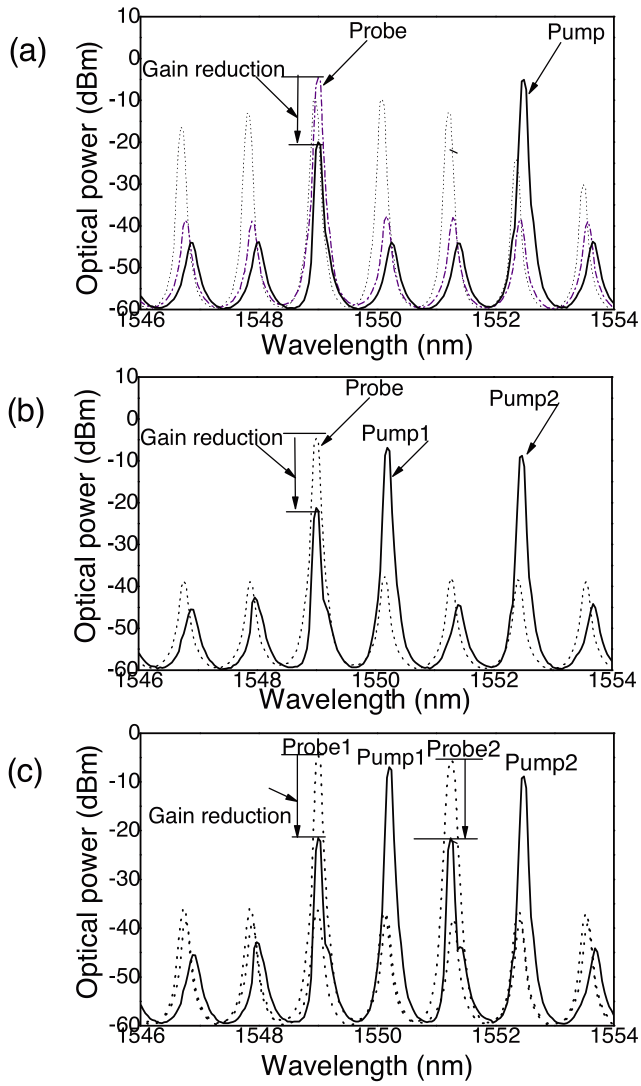

Fig. 1. Measured optical power spectra of output of each gate. (a) NOT gate; without pump (dash line), with pump injection (solid line), no injection (dots). (b) NOR gate; without pumps (dots), with pumps (solid line). (c) Multicasting operation of the NOR gate; without pump (dots), with pump (solid line).

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an all-optical NOR gate using the inverting characteristic. In the NOR gate, a logical HIGH output results when both the inputs (pump1 and pump2) to the gate are logically LOW (dots) and when any one or both the inputs are logically HIGH, LOW output (solid line) results as shown in Fig. 1 (b).

The AOLG based on the gain modulation of the injection-locked FP-LD is simpler than the interferrometric gate and requires low operation power. Another advantage of the gain modulation technique is that it can be applied to multiple probes simultaneously. In other words, it supports a multicasting function, sending any gated output to many destinations simultaneously. If two probes are incorporated in two different modes of the FP-LD, then the AOLG results a same pattern of the output probe beams. Fig. 1 (c) shows the multicasting function of the NOR AOLG. Pump1 and pump2 are the gate inputs. Simultaneous output can be cast by filtering probe1 (1549.04 nm) and probe2 (1551.28 nm) in the output terminals of the NOR AOLG.

3 Experimental setup and results

Fig. 2 (a) shows the experimental setup and results for the NOT and NOR gates for single channel output. Fig. 3 (a) shows the experimental setup and results for double channel output, i.e., the multicasting function. In the multicasting setup, two probes were used. To generate data signal, pump1 and pump2 beams were modulated by two external optical modulators fed by a 10 Gb/s predetermined $2^{31}-1$ pseudo random binary sequence pattern from the pattern generator. The wavelength of pump1 and pump2 were 1550.24 nm and 1552.52 nm, respectively. The probes wavelengths were 1549.04 nm for probe1 and 1551.28 nm for probe2, respectively. The wavelength of probe1 in Fig. 3 (a) is same with that of probe in Fig. 2 (a). The detuning of pump beam was 0.14 nm each, and the detuning of probe beam was 0.08 nm each. The pump and probe power before gate operations were −4 dBm and −7 dBm each, respectively. In this experiment, an FP-LD with a nominal lasing wavelength around 1550.2 nm and longitudinal mode spacing of about 1.2 nm was used for the AOLG functions. The FP-LD was biased at 8 mA (threshold current 4 mA) and the package temperature of the FP-LD was 19°C.

3.1 NOT and NOR AOLGs

In case of the NOT gate, single pump and single probe were used. When two pumps were active, the circuit operated as the NOR gate. Fig. 2 shows the basic logic module that can show dual functions of NOT and NOR by switching the pump LD2 and shows input and output characteristics. When the pump LD2 is inactive, the module is a NOT gate and when it is active, the module is a NOR gate. Observing the valleys in Fig. 2 (d) and peaks in Fig. 2 (e), we can recognize that only when the two inputs are logically LOW, the gate output is logically HIGH. This is NOR gate. The clear eyes in Fig. 2 (g) show successful gate operations at 10 Gb/s. We observed over 12 dB extinction ratio (ER) for the gate operations of both NOT and NOR gates. The power penalty was around 1.5 dB for both NOT and NOR

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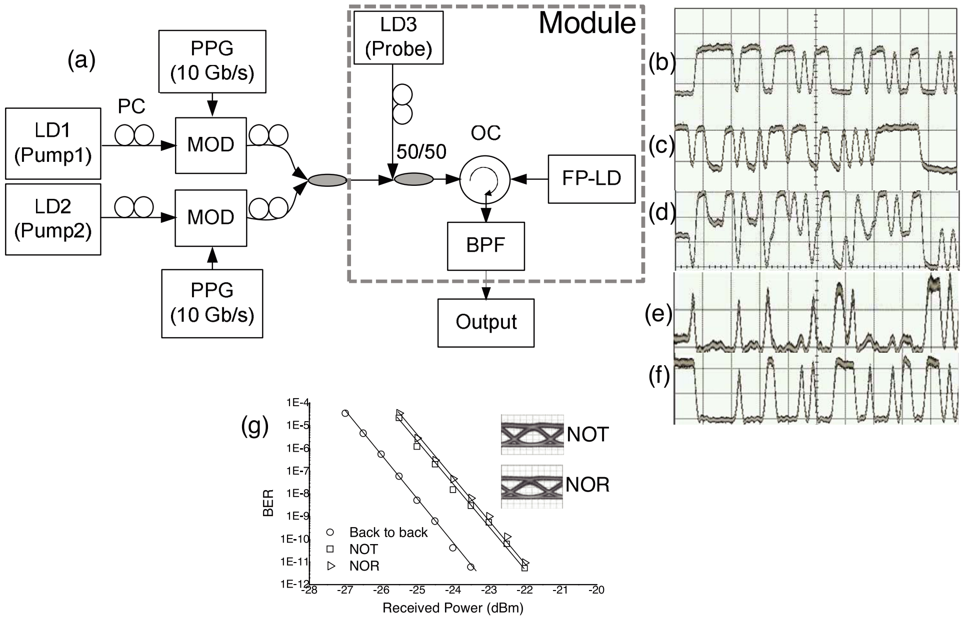

Fig. 2. (a) Experimental setup. (b)–(i) results for the NOT and NOR AOLGs; (b), (c) two inputs, (d) sum of two inputs, (e) NOR gate output, (f) NOT output for input (b), (g) BER results and eye diagrams. LD: laser diode, MOD: modulator, PC: polarization controller, PPG: pulse pattern generator, OC: optical circulator, BPF: optical band pass filter.

operations at the bit-error-rate (BER) of 10^{-9}. No BER floor was observed up to BER values of 10^{-12}, which proves the excellent performance of the logic module.

3.2 Multicasting operation of the AOLGs

Fig. 3 shows the multicasting operation of the NOT and NOR AOLGs. We incorporated two probe beams in two modes of the FP-LD for the multicasting operation. The clear eyes in Fig. 3 verify the good performance of multicasting operation of the NOT and NOR AOLGs. The ER was over 12 dB in each of the gated output. The power penalties at a BER of 10^{-9} were 1.5 dB for both NOT outputs and less than 2 dB for both NOR outputs. The investigated results of the logic module guaranty to increase the number of inputs and the number of outputs channels. It is mentioned that the FP-LD has a wide range of lasing modes; hence, by incorporating more pumps/probes, it can be implemented the multi-inputs as well as multicasting AOLGs.

4 Conclusion

We demonstrate AOLGs with NOT and NOR functions using gain modulation in the injection-locked FP-LD. Gating and multicasting functions of the AOLGs at 10 Gb/s were experimentally performed. We observed ERs over 12 dB and power penalties around 1.5 dB for every outputs excluding multi-

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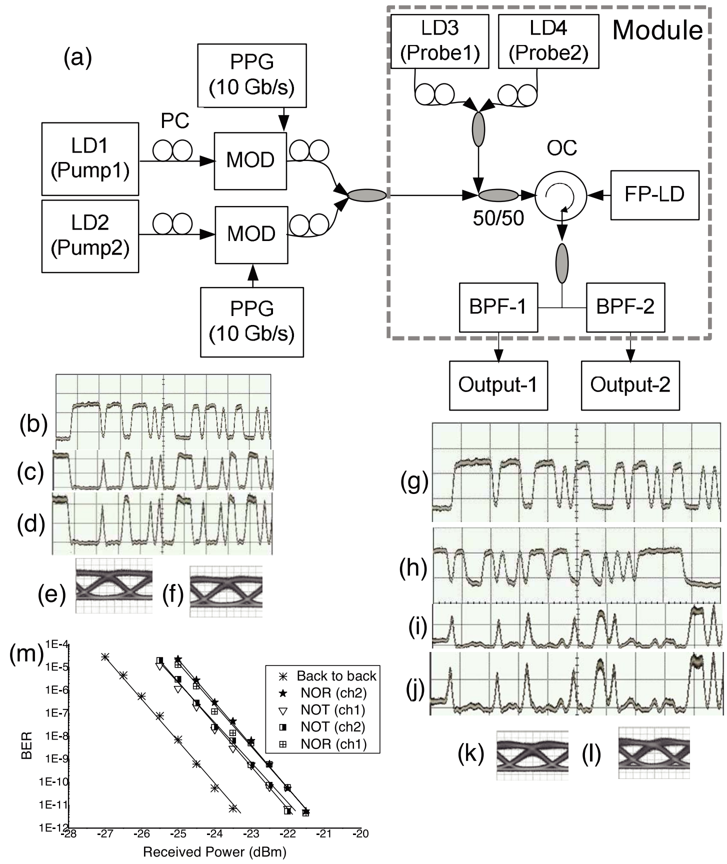

Fig. 3. (a) Experimental setup and (b)–(m) results for multicasting operation. (b) input of the NOT gate. (c), (d) waveforms and (e), (f) eye diagrams of two multicasting outputs of the NOT gate. (g), (h) two inputs of the NOR gate. (i), (j) waveforms and (k), (l) eye diagrams of two multicasting outputs of the NOR gate, and (m) BER results. LD: laser diode, MOD: modulator, PC: polarization controller, PPG: pulse pattern generator, OC: optical circulator, BPF: optical band pass filter.

casting NOR operation of the NOR gate. For multicasting NOR operation, the power penalty was less than 2 dB. According to our observation, it can be noted that by controlling the polarization state of all the channels precisely it is possible to increase the ER and to reduce the penalty more. The High ERs and low power penalties prove that this logic gates perform well. The results ensure to increase the number of inputs and output channels as well as operate at higher speed. The NOR gate is the universal gate, so all other gates can be implemented by the combination of the NOR and NOT gates. This scheme can be used in optical signal processing as it is simple, cost-effective and supports high speed operation.

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