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Intersubband All-Optical Logic Gate in InGaAs/AlAsSb Quantum Wells

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Abstract
A monolithically integrated all-optical OR/XOR logic gate is experimentally demonstrated with a Michelson interferometer (MI) gating device in InGaAs/AlAsSb coupled double quantum wells. The logical operation is based on the cross-phase modulation associated with intersubband transition, and is successfully realized at 10 Gb/s. A higher bit rate is also possible due to the intrinsic ultrafast nonlinear response.

1. Introduction

Ultrafast all-optical signal processing devices play a key role for future communications networks, where an important aspect is all-optical logical operation, such as OR/exclusive OR (XOR) gate. Logic gate is indispensable in encoding and decoding schemes, and can be used in many occasions such as half adder, parity checking, and pseudo-random bit sequence (PRBS) generators, etc. All-optical logical operation for binary phase shift keying (BPSK) signal has been successfully demonstrated in a number of platforms, and most are based on the four-wave mixing, while utilizing an idler at a different wavelength, increasing the complexity of the experimental system. Alternative platforms are of significant interest for a different operation mechanism without any change of the system bandwidth capacity.

InGaAs/AlAsSb coupled double quantum wells (CDQWs) are a good candidate owing to its distinctive nonlinear cross-phase modulation (XPM) mechanism with only a few picoseconds relaxation time, which is free from the patterning effect beyond 100-Gb/s operation [1]. For such CDQWs, with the intersubband transition (ISBT) caused by the transverse magnetic (TM) pump light, XPM can be induced to the transverse electric (TE) probe light, which excites interband transition and is immune to ISBT absorption [2]. It has been used for all-optical signal processing experiments such as demultiplexing [3], wavelength conversion, and non-return-to-zero (NRZ) to return-to-zero (RZ) format conversion. This ISBT-induced XPM has already been applied in many monolithically integrated high-speed all-optical switch devices [4–6], which could be used for delivering real-time video signals of a 172-Gb/s optical time division multiplexed (OTDM) system [7]. We can further expand its signal processing application scopes and realize an all-optical logical operation. The BPSK signal can be converted from RZ ON-OFF keying (OOK) format by an ISBT wire waveguide, and we can use two BPSK signals to interfere with each other for realizing a desired logical operation. In the following, an all-optical XOR/OR operation is achieved with a monolithic Michelson interferometer (MI) gating device.

2. ISBT Logical Operation

To proof our concept, a monolithic MI gating switch was fabricated and the schematic illustration is shown in Fig. 1. The wafer was phosphorus ion implanted and underwent rapid thermal annealing at 760 ºC for 3 min to reduce the propagation loss to around 2 dB/mm, with the XPM efficiency of 0.71 rad/pJ for a 1-mm-long straight waveguide with both facets anti-reflection coated [8]. The gating device consists of a multi-mode interference (MMI) 3-dB coupler with a total length of 1 mm. The left facet was anti-reflection coated for the input/output of TE probe signal, whereas that on the right was half-reflection coated for both TM pump light input and TE probe signal reflection. The reflected TE signals from two arms on the right of the MMI coupler can interfere with each other as an MI configuration. After fabrication of the photonic integrated circuit, the sample was planarized by BCB polymer and a resistive heater (80-nm-thick Ti and 10-nm-thick Au) was then attached to one arm for a static phase bias control.

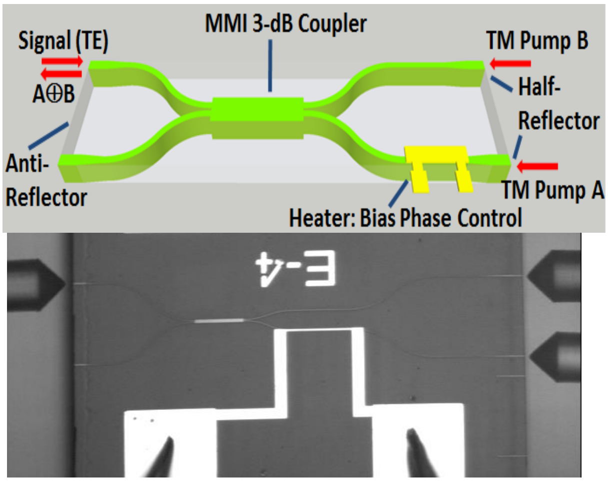

Fig. 1. Schematic diagram of an ISBT-MI logic gate with the bottom microscope image for the fabricated chip under test.

A 10-Gb/s RZ OOK data signal at 1559 nm is first generated and separated into two data branches through a 3-dB coupler, and marked as route A and B. An optical delay line ($\Delta\tau$) adjusts the relative time delay between the two data streams (here 21 bits data delay in the experiment). Variable optical attenuators (VOAs) are placed on both data branches for adjusting the input pump intensity, which are kept at TM polarization by a polarization controller. Due to the half-reflection coating, an average pump power of 44 mW is needed to induce a π phase modulation. The cw probe (TE polarized) is centered at 1545 nm with an incident power of 15 mW. We use the same waveguide port for both probe signal input and output, and a tunable optical band pass filter and low-noise erbium-doped optical fiber amplifier are used to extract the desired logic output.

For the MI gating performance, the signal output intensity $I=I_0*\cos^2((\Delta\phi+\phi_A-\phi_B)/2)$, where I_0 is the maximum output intensity, $\Delta\phi$ is the applied bias phase by the attached heater, ϕ_A and ϕ_B are route A and B pump pulse induced phase shift, respectively. The XOR operation works at a destructive interference condition of the MI gate with a static zero signal output ($\Delta\phi=\pi$) [9]. Both pump A and B have the same power by adjusting the VOAs for $\phi_A=\phi_B=\pi$. As shown in Table I, when no pump pulse or both pulses arrive, the output signal intensity is zero (logic "0"). When there is only one pump pulse applied, the output intensity is I_0 (logic "1"). For the OR operation, a different working condition is adopted with $\Delta\phi=5\pi/4$, $\phi_A=7\pi/6$, and $\phi_B=5\pi/6$. As presented in Table II, with only one pulse or both pulses arrived, the output intensity is $0.629*I_0$ (logic "1"). If there is no data pulse, the output intensity is $0.146*I_0$ (logic "0"). This indicates that the OR operation can be realized but with a reduced signal extinction ratio.

Table I Truth Table for XOR Operation ($\Delta\phi=\pi$).

Pump A (Phase)	Pump B (Phase)	XOR Output (Intensity)
"0" (0)	"0" (0)	"0" (0)
"0" (0)	"1" (π)	"1" (I_0)
"1" (π)	"0" (0)	"1" (I_0)
"1" (π)	"1" (π)	"0" (0)

Table II Truth Table for OR Operation ($\Delta\phi=5\pi/4$).

Pump A (Phase)	Pump B (Phase)	OR Output (Intensity)
"0" (0)	"0" (0)	"0" ($0.146*I_0$)
"0" (0)	"1" ($5\pi/6$)	"1" ($0.629*I_0$)
"1" ($7\pi/6$)	"0" (0)	"1" ($0.629*I_0$)
"1" ($7\pi/6$)	"1" ($5\pi/6$)	"1" ($0.629*I_0$)

Figure 2 presents the time dependent waveforms of the output probe signal modulated by pump data stream A and B, respectively, along with the XOR/OR logical operation with both data streams applied. The logical relationship as well as the expected data patterns is demonstrated. The high-level pulse corresponds to logic "1" with zero intensity to logic "0". Bottom pulse trace is data "10011 01101 01101 11101" for pump route A and pump route B is data "11111 01000 01110 00100", while the corresponding XOR output data is "01100 00101 00011 11001". By adjusting the heater voltage for a different bias phase ($\Delta\phi=5\pi/4$) and changing the VOA for a varying pump induced phase shift ($\phi_A=7\pi/6$, $\phi_B=5\pi/6$), the OR operation can be realized and the corresponding output data is "11111 01101 01111 11101" (pulse trace at top of Fig. 2). It can be seen that the gate output can accurately reflect the XOR/OR logical operation for two input data signals, but with a different signal extinction ratio.

For the XOR logic function, we also measure the bit error rate (not shown here), and error-free operation can be confirmed. It should be noted that the TE probe light travels through the ISBT waveguide twice in the MI gate with a total propagation loss of about 4 dB, together with an additional 3-dB half-reflection loss at the pump-input port, thus the logic performance of the device is more sensitive to the anti-reflection coating at the waveguide facet for the probe signal input and output.

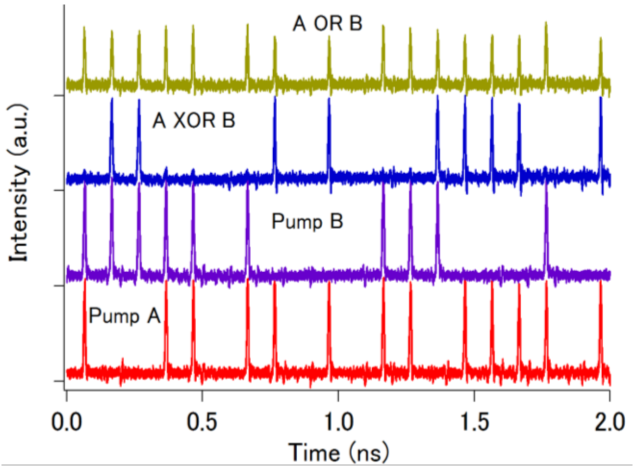

Fig. 2. Pulse traces of the output probe signal modulated by pump data stream A, B, and XOR/OR logic output, respectively.

3. Conclusions

In conclusion, we demonstrate a monolithic all-optical MI logic gate for XOR/OR operation with a 10 Gb/s PRBS data stream. The ISBT-based logic device can work at even higher data bit rates due to the intrinsic ultrafast modulation mechanism. This multi-functional ISBT logic gate has the advantages such as low-cost, reliability, and wide working bandwidth, which would have broad application prospects for signal processing photonic devices.

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Appendix

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