All-optical half-adder based on photonic mode junction

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Abstract: We investigate the operation of all-optical multi-junction half-adder built upon photonic mode-orthogonal hetero-structures. Controlling the dielectric potential of multi-junctions ($\psi_e - \Psi_{eo} - \psi_o$), the flow of photons from $\Psi_{eo}$ region can be abruptly manipulated to $\psi_e$ or $\psi_o$ region in self-induced manner. With exceptional performance metrics, all-optical logic operations for half-adder are successfully derived with the bi-level dynamic mode-conversion across the junction.

1. Introduction
Junction structures, which provide drastic and systematic changes in the electrical potential [1] or spin orientations [2] across a boundary, have enabled highly advanced and non-reciprocal manipulation of electron transport for nonlinear electronic devices. To incorporate the equivalent advantage of the junction into the photonics, in previous work, we focused our attention to the wave nature of photons to realize the ‘photonic mode junction’ [3]. Through the photonic junction structure, exceptional performance metrics was obtained for nonreciprocal device with the breaking of time-reversal symmetry in the photon propagation [3]. Symmetry breaking of the photonic junction is the key property of the isolation between connected device components, which is crucial for all-optical signal processing [4]. Considering the isolation property and modular design scheme of the junction structure, here we investigate the design of the multi-junction half-adder, which is the core building block for the Arithmetic Logic Unit. Different with previous works in the photonic domain [5,6], multi-junction half-adder is composed in monolithic manner, with signal isolation and exceptional performance of 50Gbps speed and sub-W operation power in photonic crystal platforms. Trade-off relation between signal quality and performance figures (operation speed and threshold power) is also studied which is determined by the strength of optical bistability in self-induced nonlinear mode conversion.

2. Design Strategy and Results

Fig. 1. Multi-junction realization of monolithic half-adder; (a) coupling to S (XOR) port with a single logic input ($I_A$ or $I_B$) power below the threshold, (b) coupling to C (AND) port under two input signals ($I_A$ and $I_B$) above the threshold, (c-e) DC Response curve of the multi-junction half-adder for different operating frequency of (c) 193.06THz, (d) 193.11THz, and (e) 193.16THz (blue: AND ($O_c$) port, red: XOR ($O_s$) port).
As shown in Fig. 1a and 1b, the suggested all-optical half-adder based on the $\psi_e - \Psi_{ea} - \psi_o$ multi-junction structure is constructed with 1) the high-$Q$ diatomic nonlinear resonator $\Psi_{ea}$ sandwiched in-between 2) $\psi_e$ (even) and $\psi_o$ (odd) couplers. Setting the power of the incident logical signal $(I_A$ or $I_B$) for $\Psi_{ea}$ resonator slightly below the threshold of mode conversion, coupling only to the XOR output port ($O_2$; supporting $\psi_e$) is enabled for a single input source $I_A$ ($\psi_e - \Psi_e \rightarrow 1$, $\Psi_e - \psi_o \rightarrow 0$; Fig. 1a), meanwhile above the threshold with both two input signals ($I_A \cdot I_B$), the AND operation to the $O_C$ port is activated with the self-induced nonlinear conversion of the mode in the center resonator ($\psi_e - \Psi_e \rightarrow 0$, $\Psi_e - \psi_o \rightarrow 1$; Fig. 1b). On account of the self-induced optical nonlinearity for optical bias, it is essential to consider the optical bistability in the design of multi-junction structure for monolithic half-adder. In the resonance structures such as the di-atomic resonator for multi-junction $\Psi_{ea}$ region, the optical bistability, supporting the steep power response curve but aggravating the response speed by hysteresis effect, can be adjusted with the detuning of operating frequency. Fig. 1c-e shows the power response curve of the multi-junction structure with different detuned frequencies (193.06THz, 193.11THz and 193.16THz for Fig. 1c-e). As can be seen, power range required for mode conversion is much wider for weakly-tuned operating frequency, which gives the serious error for XOR output at the state conversion from (A=0, B=0) to (A=1, B=1). This effect can be overcome by applying strongly-detuned operating frequency, yet involves increasing operating power and degraded device speed by hysteresis effect. In the end, it is necessary to select appropriate operating point for multi-junction structure by considering demanded performance metrics (device speed and power consumption).

Fig. 2 show the AND, XOR operation and their optical eye for the multi-junction monolithic half-adder at 193.06THz operation frequency (Fig. 1c), for the input of two PRBS (Pseudorandom binary sequence) NRZ (non-return-to-zero) signals at 50Gbps. As can be seen, all-optical logic operations of AND / XOR gates are successfully obtained with sub-W operation power, and the performance metric can be improved with the sacrifice of the signal quality by utilizing frequency detuning (Fig. 1d,e). Worth to note, under the arrangement of the multi-junction in three-level $\psi_2 - \Psi_{1/2,3} - \psi_3$ structure, for example with Tri-atom molecule states ($T_0$, $T_-$ and $T^+$, in Fig.1a), the same functionality with full input-to-output isolation could be easily achieved.

The present application examples operating in passive mode without external control, and providing highly nonlinear characteristics with an ultra-low threshold, we anticipate various future applications beyond those demonstrated in this paper.

3. References