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Ultrafast low-energy all-optical switching using a photonic-crystal asymmetric Fano structure

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Abstract—We experimentally demonstrate 20 Gbit/s all-optical switching with low-energy consumption using a simple and ultra-compact InP photonic-crystal structure by employing a well-engineered Fano resonance in combination with broken mirror symmetry.

Keywords—Nonlinear optical devices, Photonic crystals, All-optical devices

I. INTRODUCTION

Ultra-compact photonic structures that perform optical signal processing such as modulation and switching at high-speed with low-energy consumption are essential for enabling integrated photonic chips that can meet the growing demand for information capacity [1], [2]. In cavity-based switches, an applied control signal changes the refractive index of the cavity, thereby shifting the cavity resonance and modulating the transmission of the data signal [3]. The shape of the transmission spectrum is important, since it determines the refractive index shift, and thereby the control energy, required for achieving a certain on-to-off ratio [3]-[5].

As shown in Fig. 1(a), the extended tails of a Lorentzian spectrum imply large switching energies, since the resonance needs to be shifted significantly to properly switch the signal. In contrast, a Fano resonance [6], [7] has an asymmetric spectrum, featuring a large transmission change within a narrow wavelength range, determined by the transition from constructive to destructive interference between the discrete resonance and the continuum, thus enabling low-energy switching. The advantage of a Fano resonance was recently demonstrated using a symmetric photonic-crystal (PhC) structure employing an H1-type cavity [8]. It was also found that the non-monotonous frequency-dependence of the Fano transmission spectrum implies an inherent reduction of patterning effects. In contrast, a Lorentzian spectrum, with its monotonously-varying tails, converts (slow) dynamics of the resonance shift into amplitude modulation, limiting the bitrate due to the long carrier lifetime [9]-[14].

Fig. 2 numerically compares the high-speed performance of a comparable Fano and Lorentzian structure for aperiodic

Fig. 1. (a) Comparison of transmission spectra for structures with Lorentzian and Fano-type resonance. The Q-factors and resonance wavelengths are the same. (b) Transmission spectra for Fano resonance with and without mirror symmetry.

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Fig. 2 numerically compares the high-speed performance of a comparable Fano and Lorentzian structure for aperiodic
pump signals. It is seen that the Fano structure has a considerably larger eye opening than the Lorentzian structure, which is ascribed to the suppression of the slow decay component. We quantify the performance by calculating a quality factor $Q$, from the eye diagram, a measure of the distortion of the eye due to patterning effects. The Fano structure is seen to result in a larger eye opening than the Lorentzian over a wide range of cavity $Q$-factors.

II. DEVICE DESIGN

Here we experimentally demonstrate that by breaking the mirror symmetry of a Fano structure, the switching properties can be further improved. Fig. 3(a) shows the fabricated InP membrane structure. The scale bar corresponds to 1 μm. The structure is made asymmetric with respect to the mid-plane (vertical dashed line) by displacing the BH one lattice constant towards port 1. (b) Example of FDTD-simulated transmission spectrum of the structure showing a Fano resonance.

III. EXPERIMENTAL RESULTS

Next, we experimentally investigate the all-optical switching properties of the structure at 10 and 20 Gbit/s. RZ pump pulses (10 ps) are first generated and then modulated in the OOK format at 10 and 20 Gbit/s with a PRBS with the length of $2^{31}-1$. The modulated pump and a CW signal are coupled into the PhC device through port 1. At the output of the device, i.e. port 2, the combined signal is amplified before the modulated signal is separated from the pump using an optical band-pass filter, and subsequently detected by a receiver. The pump and signal are slightly red-detuned from the Fano resonance maximum and minimum, respectively. Fig. 5(a) shows the measured BER curves for 10 Gbit/s all-optical modulation. The BER decreases as the pump energy increases due to an enhanced switching contrast. Error-free (BER<10⁻⁹) operation is achieved with a coupled pump energy of 60 fJ/bit, which is several times lower than the result obtained using an H1-type cavity with a symmetric configuration [8]. This low energy consumption is mainly ascribed to the asymmetric configuration of the device. Besides, a larger $Q/V$ value of the H0 cavity also acts to reduce the switching energy.
the threshold for employing forward error correction (FEC) schemes. Compared with a traditional Lorentzian structure [11], we find that patterning effects are significantly suppressed and the energy consumption is reduced, enabling modulation rates higher than the carrier relaxation rate. This speed enhancement originates from the regeneration characteristics of the nonlinear transfer function of the Fano resonance. Considering backward operation using the same device, we found the performance to be seriously degraded, i.e., 20 Gbit/s modulation cannot be achieved under the same conditions, proving that the advantage of the asymmetric structure originates from the larger coupling from the waveguide into the nanocavity.

IV. CONCLUSION

We suggest and demonstrate a simple InP PhC asymmetric Fano switch based on an ultrasmall H0 nanocavity. This structure has two distinctive features. First, a Fano resonance is achieved, exhibiting a large on-off contrast between the Fano resonance extrema, which enables large switching contrast, low pump-signal cross-talk and switching at speeds beyond the carrier relaxation rate dictated by the slow carrier recombination. Second, rather than the symmetric configurations usually considered, the structural mirror symmetry is broken, leading to a large coupling coefficient between the input port and cavity, which efficiently lowers the pump energy. These two elements allow the simultaneous achievements of error-free 10 Gbit/s RZ-OOK all-optical modulation with a pump energy as low as 60 fJ/bit. For 20 Gbit/s operation, a BER three orders lower than the FEC limit is obtained. In both cases, long, telecom-grade, PRBS patterns of length $2^{31}-1$ were employed. The advantage relies entirely on optical design improvement and further performance improvements for ultrafast, low-energy on-chip signal-processing for high-density integrated photonic circuits can be expected.

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