Low-power thermo-optic switching using photonic crystal Fano structure with p-i-n junction

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ABSTRACT

We report the use of Fano resonances as compact optical switches by exploiting their sharp asymmetric lineshape together with thermo-optic effects. This enables low footprint and efficient on chip integrated systems. The device consists of a photonic crystal (PhC) membrane with a waveguide side-coupled to a nanocavity surrounded by a p-i-n junction. We demonstrate the thermal tuning of an asymmetric Fano resonances with low power requirements and a response time of 16.1µs. Their high extinction ratio and close spectral separation between maximum and minimum of transmission makes Fano resonances suitable candidates for such optical switching.

Keywords: Fano resonances, photonic crystal, p-i-n junction, optical switching

1. INTRODUCTION

With the always increasing demand on optical interconnects, there is a real motivation to move from bulky discrete components to on-chip devices. Not only is the footprint of the different elements greatly reduced, but also their energy consumption, which in turn leads to a possible densification of the devices [1]. Photonic crystals are widely used structures for such a purpose. Able to guide light as well as squeeze it in very small modal volumes by high quality factor (Q) nanocavities, it has led to many new possible phenomena, one of them being Fano resonances in nanophotonic [2, 3].

Photonic crystal Fano resonance structures have already been shown to be promising for various optical operations, such as light emission [4], wavelength conversion [5], non-reciprocal operation [6], optical time domain demultiplexing [7], pulse carving [8] and signal reshaping [9]. In this work, we investigate the use of Fano structures as thermo-optic switches.

2. PHOTONIC CRYSTAL FANO STRUCTURES

The platform chosen to fabricate such devices is the indium phosphide on silicon hybrid system. As it allows the embedding of active medium [10], it is a good choice for all-on-chip systems. The details of device fabrication are discussed in [5]. The p-i-n junction is built prior to membranization using zinc diffusion in metalorganic vapour phase epitaxy (MOVPE) chamber for the p-side with a concentration of about 10^{17}cm^{-3} and germanium diffusion through the metal contact for the n-side [11].

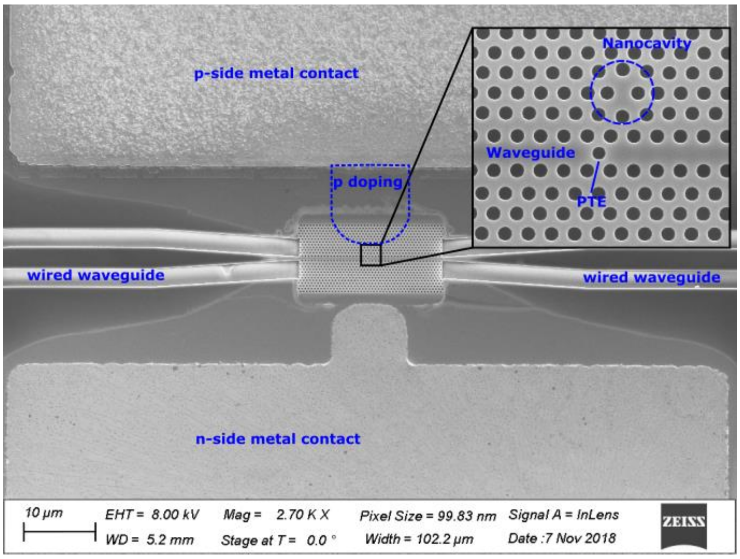

Figure 1: SEM image of a photonic crystal Fano resonance membrane surrounded by the metal contacts. The light is coupled to the structure by butt-coupled wire waveguides. The dashed delimited area corresponds to the p-doping region in the photonic crystal. Inset: zoom on the fine structure of the photonic crystal. It shows a line defect waveguide side coupled to an H0 nanocavity. An additional air hole is added in the waveguide to act as partially transmitting element (PTE).

The scanning electron microscope (SEM) image in Figure 1 shows the structure of a Fano device with p-i-n junction. The photonic crystal, at the centre, is surrounded by the p-doped (top) and the n-doped (bottom) contacts. The p-doping slightly extends in the photonic crystal in a similar shape as the n-side metallic contact and is delimited by the dashed line in Figure 1. Two wire waveguides are butt-coupled to the photonic crystal for light transmission. The probing beam is coupled to and from the wire waveguides with an optical fiber using grating couplers. The inset of Figure 1 is a closer view of the photonic crystal. The line-defect waveguide is side coupled to an H0 cavity, where the surrounding air holes were slightly displaced away from the center. The interference between the discrete mode of the cavity and the continuum of waveguide modes generates a Fano resonance. An air-hole is added in the waveguide as a partially transmitting element (PTE) to get a blue-parity asymmetric Fano resonance [12].

The optical characterization of the devices is performed by coupling a tunable light source (TLS) through a polarization controller to the device via grating couplers at an incident angle of 13°. The insertion losses are estimated to a minimal value of -21.6 dB at 1484nm. A variable voltage is applied to the junction by a source-measure unit via direct current (DC) needles. Figure 2 shows two measured asymmetric Fano lineshapes at different applied voltages. A shift of 1.7nm is achieved with a 0.72mW increase of injected electrical power due to the thermal refractive index change [13] in the nanocavity and an extinction ratio of the switching operation close to 30dB is observed as indicated by the green shade in Figure 2.

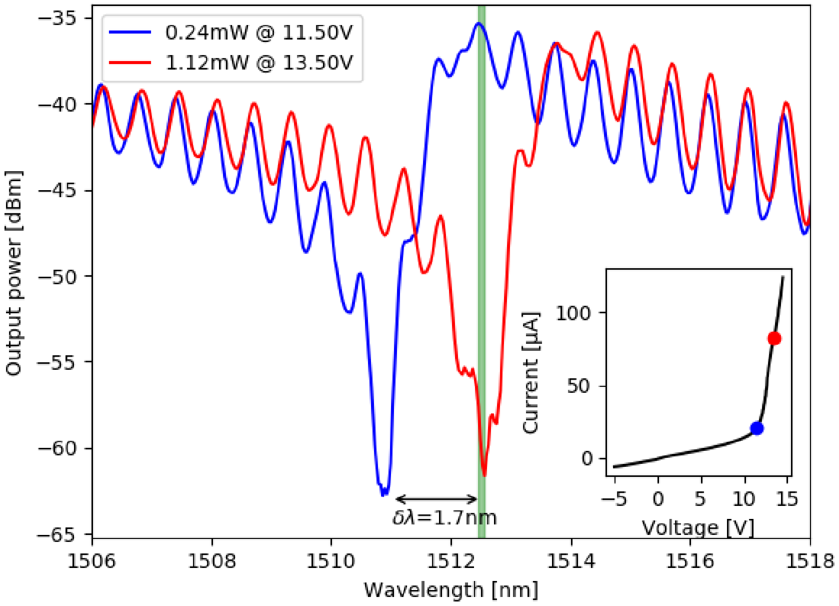

Figure 2: Transmission spectra and static characterization of photonic crystal Fano structures. Spectra at two different applied voltages are shown with their clear Fano resonance peak at 1511.5nm and 1513.2nm. The green shade is the proposed wavelength for the input signal to perform switching with ~30 dB extinction. Inset: voltage-current curve of the same device with 3.2dBm of optical power in the photonic crystal waveguide.

3. THERMO-OPTIC SWITCHING

We use a bias-tee to combine a DC bias voltage with an alternative current (AC) signal generated by an arbitrary waveform generator (AWG). In this case, the TLS is set to a fixed wavelength of 1512.5 nm, aiming for the peak transmission at low voltage, and the output signal is directed to a photodiode. The generated electronic signal is acquired either by an oscilloscope or a radio frequency (RF) spectrum analyser. A switching measurement is performed at lower frequencies, i.e. 10 kHz, to measure the recovery and rise time of the device. This ensures that the device recovers fully between two consecutive input pulses.

Figure 3 shows the conversion from the electrical Figure 3(a) to the optical domain Figure 3(b). An optical beam is coupled in the device at the Fano resonance peak. When the input electrical signal is in the high state, the resonance is red-shifted due to thermo-optic effects, hence the output signal is suppressed. On the other hand, when the electrical signal is in the low state, the transmission is maximal for the input signal. A total recovery time of 9.8µs is calculated with an average consumption power of about 0.7mW at 50% duty cycle, showing a good tradeoff between speed and energy consumption compared to other low-power thermo-optic switches. Faster thermo-optic switches with response time of 2.4 µs have been demonstrated with a higher power consumption of 12.7mW using Mach-Zehnder interferometer on silicon [14]. More energy efficient devices have been realized using silicon waveguide-based switches with power consumption down to 0.49mW [15] and 540 µW [16], however their reported response times of respectively 266 µs and 141 µs are considerably long. Additionally, a

3.78 µm long thermo-optic switching based on silicon coupled photonic crystal microcavities with switching power of 18.2mW and response time of 33.3 µs has also been reported [17]. Of the demonstrated thermo-optic switches, the Fano switch is the most compact structure with low power consumption and a moderately fast response time.

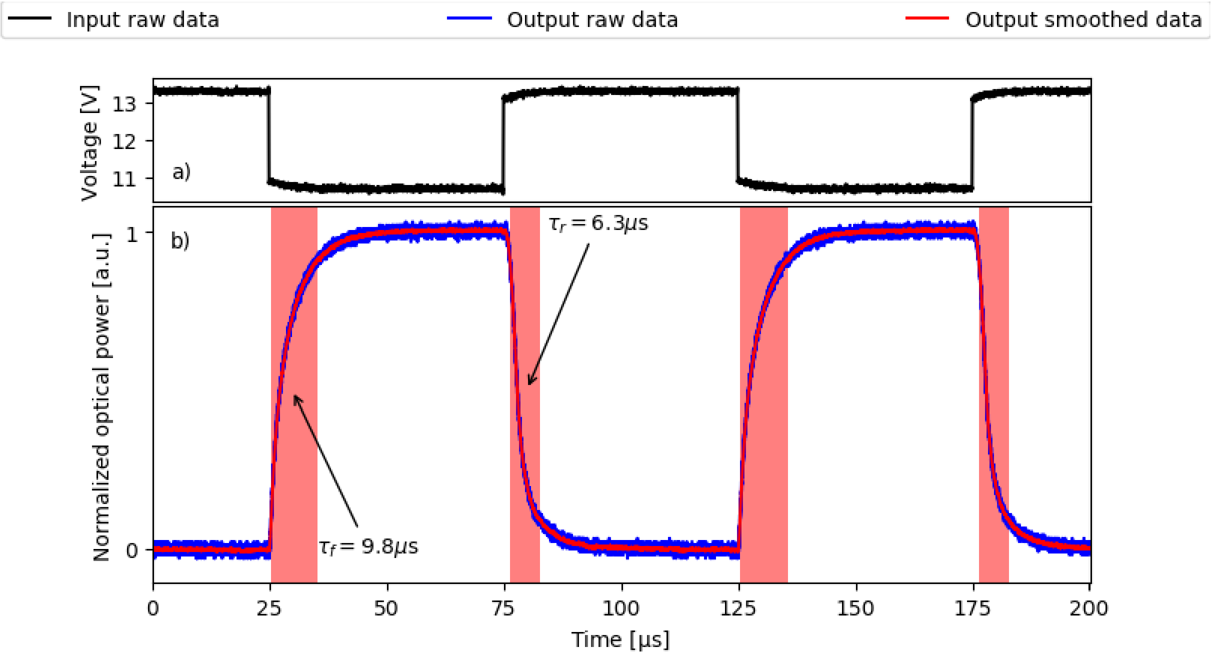

Figure 3: Oscilloscope traces of a) the applied voltage and b) the output signal generated by the photodiode. A 10.8V bias voltage is mixed with a 10 kHz, peak-to-peak voltage of 2.5 V and 50% duty cycle pulsed signal from the AWG and applied to the p-i-n junction. The recovery (fall) and rise time are calculated on a smoothed version of the output signal at $\tau_f = 9.8\ \mu s$ *and* $\tau_r = 6.3\ \mu s$.

Further improvements of the performance could be achieved by fabricating devices where the heating is localized to the nanocavity. In addition, metal contacts compatible with RF probes or wire bonding can be used for efficient electrical injection. Finally, the devices should be designed to aim for a resonance in the C-band, where amplification and filtering mechanisms are commonly available in order to exploit the best of the device.

4. CONCLUSION

We have demonstrated thermo-optic switching using a Fano resonance realized in an ultra-compact InP photonic crystal membrane structure. With sub-miliwatt of electrical power, we were able to switch the optical output of the device with a total response time of 16.1 µs and an extinction ratio of ~30 dB.

ACKNOWLEDGEMENTS

Financial support from Villum Fonden (grant number 8692) via the Nanophotonics for Terabit Communications (NATEC) centre of excellence.

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