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Photonic crystal Fano resonances for realizing optical switches, lasers, and non-reciprocal elements

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ABSTRACT

We present our work on photonic crystal membrane devices exploiting Fano resonance between a line-defect waveguide and a side coupled nanocavity. Experimental demonstration of fast and compact all-optical switches for wavelength-conversion is reported. It is shown how the use of an asymmetric structure in combination with cavity-enhanced nonlinearity can be used to realize non-reciprocal transmission at ultra-low power and with large bandwidth. A novel type of laser structure, denoted a Fano laser, is discussed in which one of the mirrors is based on a Fano resonance. Finally, the design, fabrication and characterization of grating couplers for efficient light coupling in and out of the indium phosphide photonic crystal platform is discussed.

Keywords: All-optical switches, Fano laser, grating coupler, wavelength-conversion, non-reciprocal transmission, photonic crystal membrane.

1. INTRODUCTION

Following the discovery of Fano resonances by Ugo Fano,¹ there have been numerous studies on Fano resonances in nanoscale photonic structures² such as in plasmonic nanoparticles, metamaterials and photonic crystals.³ Compared to the traditional Lorentzian resonances, the asymmetric Fano resonance lineshape attracted applications in switching, sensing and lasing²⁻⁵ due to its steeper slope. The origin of this asymmetry is the result of the interaction of localized states and a continuum of propagating modes creating constructive and destructive interference in close spectral separation.^{2,6} In this paper, we discuss Fano resonances in photonic crystal nanostructures. We discuss experimental demonstration of fast all-optical switches, non-reciprocal elements and a novel laser structure whose mirror is realized by sharp Fano resonances.

2. FANO STRUCTURE

The indium phosphide (InP) photonic crystal membrane device consists of a line-defect waveguide and a nanocavity side coupled to the waveguide as shown in Fig.1(a). The waveguide is formed by removing a single row of airholes and displacing the airholes above and below the waveguide towards the center in order to select the range of frequency bands supported by the waveguide around the optical communication C-band. The nanocavity is a H0 cavity meaning that no airhole is missing but the airholes around the cavity are shifted away from cavity center. Additionally, there is a single airhole placed in the middle of the waveguide shifted slightly to the left from the cavity center line. This is called a partially-transmitting element (PTE).^{4,7} This component mediates the coupling between the waveguide and the nanocavity depending on its size and location. Light is coupled from the left of the waveguide and is collected from the right side using grating coupled fiber.

A Fano resonance is the result of the interference between the discrete modes of the nanocavity and the continuum modes of the waveguide.^{6,7} Depending on the presence and the location the PTE in the waveguide, the resonance shape can be designed for the desired application. In this case, the PTE location is chosen so that the transmission minimum of the Fano resonance is blue shifted compared to the peak of the transmission⁸ as shown in Fig.1(b). The theoretical fit using finite-difference time domain (FDTD) method is also shown in the blue curve. It shows good agreement with the experiment. The estimated total quality factor (Q) is 940. The intrinsic quality factor calculated using FDTD method is 200,000.

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Figure 1. a) Scanning electron microscope (SEM) image of the photonic crystal Fano structure. The airholes have radius of 124 nm and a lattice constant of 447 nm. The partially-transmitting element (PTE) has radius of 121 nm. b) Measured Fano resonance at an OFF state (red) and FDTD simulation fit (blue). The dashed black line shows schematics of the shifted resonance at an ON state of the switch. The green dotted line shows the spectral location of the cw signal used for wavelength conversion experiment.

The key feature of our device is this Fano resonance that has large transmission variation of ≥ 25 dB within a spectral window of 1.8 nm. Employing carrier induced nonlinear effects in the nanocavity, it is possible to shift the resonance back and forth corresponding to the ON and OFF state of the switch. Strong build-up of intra-cavity field in the high quality factor nanocavity generates free carriers through two-photon absorption (TPA) due to high optical confinement.⁹ High density of carriers in the nanocavity region results in change in refractive index¹⁰ hence resonance shift.

3. GRATING COUPLER ON INP

Direct coupling from a line-defect photonic crystal waveguide to a single mode fiber (SMF) is inefficient due to optical mode profile mismatch, large effective refractive index and physical dimension differences.¹¹ Numerous efforts have been devoted to overcoming these issues. These include butt-coupling to inverse tapered waveguide section¹² using either lensed fiber or cleaved fiber with an objective lens, and vertical coupling using grating couplers. The use of grating couplers help to avoid sample cleaving. Hence, low-cost packaging and wafer scale testing is made possible.¹³ Compared to tapered mode adapters, grating couplers however have limited bandwidth¹³ and are usually designed for specific polarization orientation, for example, transverse electric (TE) mode. Here, we restrict our discussion to grating couplers.

Taillaert, D. et al.¹⁴ have experimentally demonstrated coupling efficiency $> 30\%$ with 1 dB bandwidth of 40 nm on silicon-on-insulator (SOI). Uniform fully-etched photonic crystal airholes in the SOI platform were demonstrated by Liu, L. et al.¹⁵ with coupling efficiency of 42% and 1 dB bandwidth of 37 nm. Ding, Y. et al.¹⁶ have experimentally demonstrated apodized grating couplers using fully etched photonic crystals on SOI with coupling efficiency of 67% and a 3 dB bandwidth of 60 nm. Grating coupler implementation on InP is more challenging than the SOI counterparts primarily because the InP platform has either InP or InGaAs as a substrate¹³ thus, increasing power leakage into the substrate limiting waveguiding and grating efficiency. Nevertheless, several efforts have been attempted at the realization of grating couplers on InP. For example, Van Laere, F. et al.¹⁷ demonstrated a polarization diversity grating with 47% coupling efficiency on a benzocyclobutene (BCB) bonded InP membrane. This approach involves a complicated sample alignment technique as the grating couplers are patterned before the sample is bonded to the substrate. Using a suspended InGaAsP grating coupler Chen, L. et al.¹³ demonstrated coupling efficiency of 40% with 3 dB bandwidth of 45 nm. These gratings, on the other hand, have mechanical disadvantage as the suspended membrane can easily be damaged by a coupling fiber during sample characterization.

In this work, we aim at implementing simple and efficient grating couplers for coupling light to and from an InP photonic crystal device. We set the main design requirement to be a single dry-etch fabrication step to

define photonic crystal membrane structure, wire waveguides and grating couplers. Since the photonic crystal waveguide has to be fully-etched, airhole based grating couplers become a better choice. This offers reduced fabrication complexity as opposed to the commonly used shallow etched grating bar design in silicon photonics.

Figure 2. a) Optical microscope image of the integrated device consisting of input and output grating couplers and photonic crystal waveguide membrane in the middle. The photonic crystal waveguide is $50 \mu\text{m}$ in length and the whole device is 1.9 mm long. b) Scanning electron microscope (SEM) image of the grating coupler. The inset shows the missing airholes (indicated in yellow circles) to form the periodic grating pattern. c) SEM image of the photonic crystal waveguide coupled to a wire waveguide.

3.1 Device Fabrication and characterization

The device consists of a photonic crystal membrane, input and output grating couplers, and wire waveguides connecting the photonic crystal membrane to the grating couplers as shown in Fig. 2. Sample preparation starts by BCB wafer bonding of a 2-inch InP wafer on to a 2-inch silicon wafer with $1.5 \mu\text{m}$ thick silicon dioxide layer deposited on top. After substrate removal process, a 340 nm thick InP (refractive index, $n \approx 3.17$) device layer sitting on low refractive index oxide layer ($n \approx 1.45$) is obtained. This hybrid platform is suitable for making efficient wire waveguides on InP since it provides high index core surrounded by low-index materials.

After silicon nitride deposition using plasma-enhanced chemical vapor deposition (PECVD), both the airholes for the photonic crystal membrane and the grating couplers together with the wire waveguides are all patterned using electron-beam lithography. After resist development, the silicon nitride hard mask is formed by reactive-ion etching (RIE) using the patterned resist mask. The pattern is then transferred to the InP layer using RIE dry etching step. Here, it is worth noting that a single InP dry-etch step is used to fabricate all the device components greatly reducing the fabrication complexity.

The final step in the fabrication is the selective membranization of the photonic crystal region. Positive photoresist (AZ5214E) is spin coated and a membranization window is formed by photolithography process. The sample is membranized using hydrofluoric acid (HF) solution as wet-etchant. This step leaves the photonic crystal membrane to float in air while the wire-waveguides and the grating couplers are still supported by the silicon oxide layer underneath.

As shown in Fig.2(a), the fabricated device is typically 1.9 mm long. This length is chosen so that to allow enough space to couple two fibers during measurement. The photonic crystal membrane is $50 \mu\text{m}$ long and $20 \mu\text{m}$ wide. The grating area is $12 \times 20 \mu\text{m}^2$. Fig.2(b) shows the scanning electron microscope (SEM) image of the fully-etched grating coupler. The inset shows a closer view of the grating structure. The yellow circles show the missing airholes in order to create periodic index perturbation. Fig.2(c) the SEM image of the wire waveguide

Figure 3. (a) A schematic diagram of the device including the cross-sectional view of the sample layers. (b) Simulated plot of buffer silicon oxide layer thickness underneath InP layer versus normalized coupling efficiency. (c) Measured and simulated coupling efficiency for a device with input and output grating couplers and a waveguide in between. For this device the Photonic crystal waveguide is removed. The grating couplers have a 3 dB bandwidth corresponding to 40 nm.

to photonic crystal waveguide connection. A schematic diagram of the device showing the cross-section of the device is shown in Fig. 3(a).

To further increase the coupling efficiency, a 100 nm thick Aluminum (Al) bottom mirror is implemented¹⁴ so that radiated power into the substrate will reflect back to the grating coupler. In order to ensure constructive interference at the grating interface, the buffer oxide layer thickness is carefully selected based on the calculations using the calculated plot shown in Fig. 3(b). Here, we have selected $1.5 \mu\text{m}$ for the highest coupling efficiency and sufficiently large separation from the membrane.

The total insertion loss is measured to be 6.6 dB. This corresponds to a coupling efficiency of 47 % per grating coupler. Here, the insertion loss is the total loss including the coupling and propagation losses in the waveguide. Measured and simulated coupling efficiencies are compared in Fig. 3(c) for a device with input and output grating couplers connected with a wire waveguide. The coupling angles for the measurement and simulation are different due to slight change of the airhole dimensions from the design target during fabrication. The measured 3 dB bandwidth is close to 40 nm which is suitable for the Fano resonance based devices we are considering. When the photonic crystal waveguide is included as in Fig. 2, the insertion loss increases up to 12 dB. These additional losses are mainly due to the wire-photonic crystal waveguide interface. Further optimization of this interface should be done for increased coupling efficiency.

4. WAVELENGTH-CONVERSION

All-optical switching was demonstrated at 10 and 20 Gbit/s data transmission rate by Yu, Y. et al.⁴ using a Fano resonance. Fig. 4(a) shows the wavelength-conversion experimental setup and the resulting measured eye diagrams. A 10 Gbit/s RZ-OOK modulated data signal is amplified before combining it with a low power cw probe signal using a 3 dB coupler. The polarization of both signals are aligned to the TE-like polarization of the photonic crystal membrane waveguide mode. The modulated pump signal is spectrally located at the peak of the Fano resonance while the cw probe signal is located at the transmission minimum of the Fano resonance

shown in Fig. 1(b). The pump signal is modulated by a pseudo random bit sequence (PRBS) length of $2^{31} - 1$. When the pump signal represents a logical bit 1, it will induce a resonance shift due to the nonlinear effects in the nanocavity resulting in maximum transmission for the cw probe signal. This corresponds to the ON state of the Fano switch indicated by the dashed black line in Fig. 1(b). When the pump signal represents a logical bit 0, the resonance will not shift due to less optical power coupled to the nanocavity. This in turn suppresses the transmission of the cw probe corresponding to the OFF state of the Fano switch. The wavelength converted data signal is separated from the pump signal using a bandpass filter and it is detected by a 10 Gbit/s receiver.

The received signal is quantitatively analyzed using bit-error ratio (BER) measurements shown in Fig. 4(b). Wavelength conversion with energy consumptions of 60 and 151 fJ/bit is demonstrated.⁴ A power penalty of approximately 3 dB compared to the back-to-back (B2B) measurements was obtained at a BER of 10^{-9} . These results demonstrate the potential of photonic crystal Fano resonance based switches for fast all-optical modulation.

Figure 4. a) The experimental setup for 10 Gbit/s wavelength conversion. A 10 Gbit/s pump signal is amplified and polarization controlled before combining with a continuous-wave input signal. After wavelength conversion by the Fano switch, the pump signal is filtered out and the receiver detects the converted signal. The eye diagrams show modulated pump and wavelength converted signals. b) The bit-error ratio measurement for 10 Gbit/s wavelength conversion. The black line shows back-to-back measurement while the blue and red lines show wavelength conversion with energy consumptions of 60 and 151 fJ/bit respectively.

5. NON-RECIPROCAL TRANSMISSION

Here, we exploit the transmission direction dependence of the Fano structure for realizing diode-like operation where the transmission from left to right differs from the transmission from right to left. A continuous wave (CW) laser slightly blue detuned from the minimum of the Fano resonance is coupled to the device. For forward

transmission (shown in the green curve in Fig.5(a)), light is coupled from the left and collected from the right port as shown in Fig.1(a). For backward transmission (shown in the red curve in Fig.5(a)), light is coupled from right side and collected from the left side. For both cases, the output power initially increases linearly with the input power. When the input power is high enough to cause resonance shift due to nonlinear effects in the nanocavity, the transmitted output power is greatly enhanced creating a step-like transmission. Bistability is inferred by measuring the output power for both increasing and decreasing input powers shown by the blue arrows. This bistability region is indicated by shaded areas.

One important difference between the forward and backward transmission is that there is a range of input power regions where the backward transmission is suppressed by around 30 dB compared to the forward transmission. The energy coupled to the nanocavity is highly dependent on the direction of propagation due to the asymmetric decay ratio resulting from the position and size of the asymmetrically-placed partially transmitting element (PTE). The difference in the intra-cavity field strength in turn causes different nonlinear resonance shifts inducing large non-reciprocal transmission ratio (NTR).¹⁸ Therefore, the device acts as a diode in a certain power range.

Figure 5. a) Non-reciprocal transmission using Fano resonance. Measured forward (green lines) and backward (red) output power transmission is plotted as functions of input power. The bistability region for both transmission direction is indicated by the shaded areas. The non-reciprocal transmission region is between these two shaded areas showing a non-reciprocal transmission ratio of more than 30 dB. b) A schematic diagram of the Fano laser. It consists of a standard photonic crystal left mirror, while the right mirror is realized by a nanocavity side coupled to a line-defect waveguide forming a Fano structure. Three layers of quantum dots are embedded in the entire membrane to act as active material.

6. FANO LASER

A schematic diagram of the Fano laser is shown in Fig.5(b). It is a 250 nm thick InP photonic crystal membrane device with a line defect waveguide. The membrane consists of three layers of InAs quantum dots as gain material. The left mirror is a broadband mirror realized by blocking the waveguide. The unique characteristics of this laser comes from the narrowband right mirror⁵ which is a result of the Fano resonance. At the resonance frequency of the H0 nanocavity, the power reflection is largest. A direct consequence of this narrowband mirror is the single mode operation of the laser. The sample is optically pumped using continuous-wave light from top using an objective lens. The pumping area is indicated by the red circle in Fig.5(b). When combined with the optical nonlinearities inside the nanocavity, the laser can be operated in a self-pulsing mode with repetition rates in the gigahertz regime.⁵

7. CONCLUSION

We have presented our work on photonic crystal Fano resonance based devices. Fast all-optical switching at 10 Gbit/s data transmission rate is demonstrated through wavelength-conversion experiments. The combination of an asymmetric structure and cavity-enhanced nonlinearities is shown to allow the realization of diode-like behavior, with a large difference in the forward and backward transmission. A novel laser concept employing

a Fano resonance as a narrow band mirror is presented, and allows the realization of self-pulsing nanolasers. Furthermore, fully-etched uniform grating couplers for these InP photonic crystal platforms have been demonstrated with a coupling efficiency of 47%. For increased coupling efficiency, apodized grating coupler design is recommended as it offers better mode matching between the radiation mode and the fiber mode.¹⁶

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