Electrically Tunable Fano Resonance Line Shapes by Using Racetrack Microresonator-Coupled Mach-Zehnder Interferometers with Embedded p-i-n Diodes

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ABSTRACT

We report our initial experimental demonstration of electrically tunable Fano resonance line shapes by using racetrack ring microresonator-coupled Mach-Zehnder interferometers with embedded p-i-n diodes on silicon-on-insulator substrates. Fano resonance observed at the interferometer output ports is due to interference between the guided lightwave that is coupled to the microresonator and the coherent lightwave guided in the interferometer reference arm. We apply a relative phase shift to the interferometer reference arm by current injection, thereby electrically tuning the Fano resonance line shape through free carrier plasma dispersion effect. Our initial experiments reveal different characteristic sharp asymmetrical resonance line shapes upon application of less than 1V forward biases across the embedded p-i-n diode.

Keywords: fano resonance, racetrack microresonator, Mach-Zehnder interferometer, electro-optic device, p-i-n diode.

1. INTRODUCTION

Fano resonance [1], characterized by sharp asymmetrical resonance line shapes, is ubiquitous in two-dimensional and three-dimensional optical resonator systems [2-11]. Fano resonance occurs as a resonance pathway interferes with a coherent background (non-resonance) pathway. Fano resonance exhibits asymmetrical line shapes that depend on the relative phase between the interfering pathways. Typical tell-tale sign of Fano resonance is a pronounced dip on either the short or long wavelength side adjacent to the resonance peak. Although Fano resonance has long been observed in various resonant optical configurations and devices including recent works on elastic light scattering from microresonators [2], waveguide-coupled microresonators [3, 4], Mach-Zehnder interferometer (MZI) coupled microresonators [5, 6], prism-coupled microresonators [7, 8], fiber-coupled microresonators [9], and in two-dimensional photonic crystal slabs [10] and photonic crystal microcavities [11], to the best of our knowledge electrically tunable Fano resonances in integrated optical resonator systems with no moving parts have yet been experimentally demonstrated. In this Summary, we report our initial experimental demonstration of such functionality using a racetrack microresonator-coupled MZI on a silicon-on-insulator (SOI) substrate. The interferometer phase shifter is realized by embedding a lateral p-i-n diode as in our previous work [12].

2. DEVICE DESIGIN AND FABRICATION

Figure 1 shows the design schematic of our initial electrically tunable Fano resonance device. We assume a silicon device layer (refractive index ~ 3.5) clad with silica (refractive index ~ 1.44). The MZI comprises input and output 3-dB directional couplers, one interferometer arm acting as the resonance pathway is evanescently coupled to a racetrack ring microresonator, and the other arm acting as the coherent background pathway is embedded with a lateral p-i-n diode for phase tuning. The MZI and ring waveguides are single-mode and have the same width of 0.4 µm. The p-i-n diode comprises 3-µm-wide highly-doped n^+ and p^+ regions along the two sides of the entire 600-µm-long intrinsic silicon waveguide (with a separation of $w_s = 0.5$ µm to reduce mode-field overlap with the absorptive doped regions). We introduce a relative phase shift to the guided mode through free-carrier plasma dispersion effect [13] by forward biasing the p-i-n diode. Inset shows a schematic cross-section of the lateral p-i-n diode embedded waveguide.

We fabricate the device on a SOI wafer with a 0.21 µm device layer and a 2-µm buried oxide layer. We employ photolithography (i-line) and RIE dry etching to form the device patterns with a slab thickness of 0.03 µm. We implant 1×10^{20} cm^{-3} phosphorous dopants for the n^+ region and 2×10^{19} boron dopants for the p^+ region. We etch the slab to form two stripes of 2-µm-wide trenches outside the entire doped regions for lateral

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electrical confinement. We clad the entire device with a silica upper cladding and provide electrical connections using patterned aluminum wires and pads.

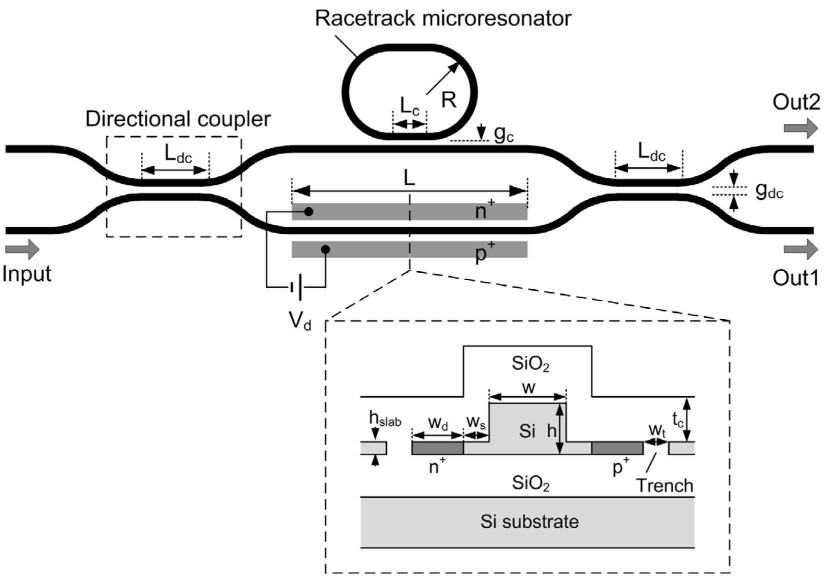

Figure 1. Schematic top-view of a Mach-Zehnder interferometer side-coupled with a racetrack ring microresonator. Inset: schematic cross-sectional view of the lateral p-i-n diode integrated to the non-resonance arm. $L_{dc} = 20\ \mu m$, $g_{dc} = 0.4\ \mu m$, $R = 25\ \mu m$, $L_c = 10\ \mu m$, $g_c = 0.35\ \mu m$, $w = 0.4\ \mu m$, $w_d = 3\ \mu m$, $w_s = 0.5\ \mu m$, $w_t = 2\ \mu m$, $h = 0.21\ \mu m$, $h_{slab} = 0.03\ \mu m$.

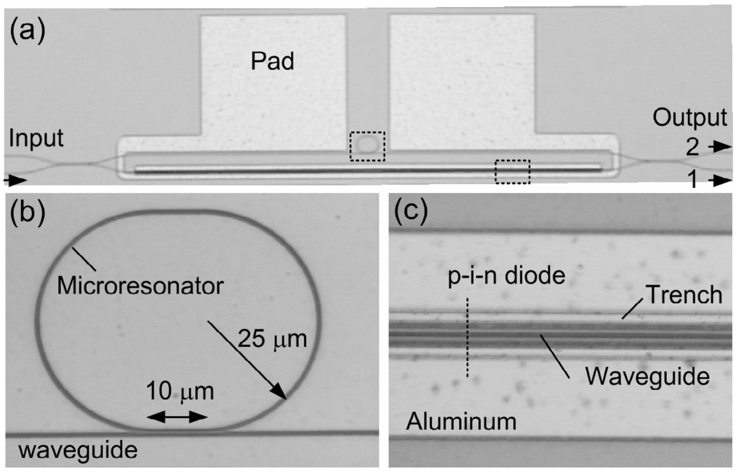

Figure 2. (a) Microscope top-view of the fabricated device. (b) Microscope zoom-in view of the straight waveguide (resonance arm) coupled racetrack microresonator. (c)Microscope zoom-in view of the p-i-n diode embedded in the non-resonance arm.

Figure 2*a* shows the top-view optical micrograph of our fabricated device. Figure 2*b* shows the zoom-in view optical micrograph of the waveguide-coupled racetrack microresonator. The curved waveguide radius is 25 µm and the lateral interaction length is 10 µm. Figure 2*c* shows the zoom-in view optical micrograph of the lateral p-i-n diode. The two wide aluminum lines are connected to the underneath n^+ and p^+ doped regions with ohmic contact.

3. INITIAL RESULTS AND DISCUSSION

Figure 3*a* shows the initially measured TE-polarized (electric field parallel to the chip) output-port spectra (out1 and out2) of our racetrack microresonator coupled MZI with the p-i-n diode forward-biased at $V_d = 0.87$ V. The extinction ratio of the near symmetrical resonance dip in the out1-port spectrum exceeds ~ 5 dB and the quality factor Q is ~ 10^4. In contrast, out2-port shows a complimentary near symmetrical resonance peak.

At $V_d = 0.91$ V, we observe a pronounced asymmetrical Fano resonance line shape in the out1-port spectrum. A distinct dip is adjacent to the resonance peak. The asymmetrical resonance line shape observed at out2-port is almost complimentary with that at out1-port. The voltage dependent asymmetrical resonance line shapes thus represent the first experimental demonstration of an electrically tunable Fano resonance line shape based device. Further systematic measurements are required at various bias voltages, and to isolate the line shape dependence on possible current-induced thermal phase shifts.

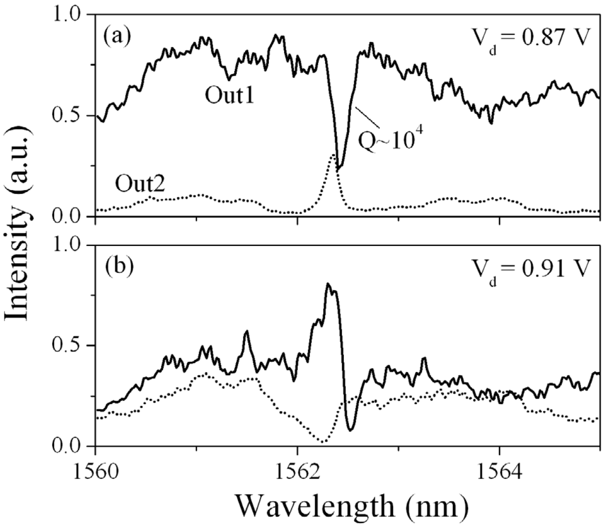

Figure 3. Measured TE-polarized output-port spectra for a MZI-coupled racetrack microresonator with bias voltages of (a) $V_d = 0.87$ V, and (b) $V_d = 0.91$. Solid lines: out1-port spectra, dotted lines: out2-port spectra.

4. SUMMARY

In summary, we experimentally demonstrated an initial electrically tunable Fano resonance line shape based device by using a racetrack microresonator coupled Mach-Zehnder interferometer with an embedded lateral p-i-n diode on a silicon-on-insulator substrate. The line shape tuning was realized by controlling the free-carrier plasma dispersion phase shift in the non-resonance pathway. Our initial experiments indicated that Fano resonance line shapes were tuned from an inverted symmetrical dip to a characteristic asymmetrical line shape under an applied voltage between 0.87 V and 0.91 V.

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REFERENCES

[1] U. Fano: "Effect of configuration interaction on intensities and phase shifts," *Phys. Rev.,* vol. 124. pp. 1866 1961.

[2] A.W. Poon: "Optical resonances of two-dimensional microcavities with circular and non-circular shapes," *PhD thesis, Yale University*, 2001.

[3] S. Fan: "Sharp asymmetric line shapes in side-coupled waveguide-cavity systems," *Appl. Phys. Lett.*, vol. 80, pp. 908-1000, Feb. 2002.

[4] C.Y. Chao, L.J. Guo: "Biochemical sensors based on polymer microrings with sharp asymmetrical resonance," *Appl. Phys. Lett.,* vol. 83, pp. 1527-1529, Aug. 2003.

[5] Y. Lu, J. Yao, X. Li, P. Wang: "Tunable asymmetrical Fano resonance and bistability in a microcavity-resonator-coupled Mach-Zehnder interferometer," *Opt. Lett.*, vol. 30, pp. 3069-3071, Nov. 2005.

[6] N.K. Hon, A.W. Poon: "Silica polygonal micropillar resonators: Fano lineshapes tuning by using a Mach-Zehnder interferometer," *in Proc. Photonic West conference, San Jose, California,* Jan. 2006.

[7] H.T. Lee, A.W. Poon: "Fano resonances in prism-coupled square micropillars," *Opt. Lett.,* vol. 29, pp. 5-7, Jan. 2004.

[8] H.T. Lee, L. Zhou, A.W. Poon: "Fano resonances in prism-coupled multimode square micropillar resonators," *Opt. Lett.,* vol. 30, pp. 1527-1529, July 2005.

[9] A. Chiba, H. Fujiwara, J. Hotta, S. Takeuchi, K. Sasaki: "Fano resonance in a multimode tapered fiber coupled with a microspherical cavity," *Appl. Phy. Lett.,* vol. 86, 261106, Jun. 2005.

[10] W. Suh, O. Solgaard, S. Fan: "Displacement sensing using evanescent tunnelling between guided resonances in photonic crystal slabs," *J. Appl. Phy.,* vol. 98, 033102, Aug. 2005.

[11] A.R. Cowan, J.F. Young: "Optical bistability involving photonic crystal microcavities and Fano line shapes," *Phy. Rev. E.,* vol. 68, 046606, Oct. 2003.

[12] L. Zhou, A.W. Poon: "Waveguide-coupled microdisk resonators with selectively integrated p-i-n diodes," *in Proc. Group IV Photonics 2005,* Antwerp, Belgium, Sept. 2005.

[13] R.A. Soref, B.R. Bennett: "Electrooptical effects in silicon," *IEEE J. Quant. Electron,* vol. 23, pp. 123-129, Jan. 1987.