All-Optical Tunable Photonic Crystal Cavity

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Abstract—**We demonstrate an ultra-small photonic crystal cavity with two resonant modes. An all-optical tuning operation based on the free-carrier plasma effect is, for the first time, realized utilizing a continuous wave light source. The thermo-optical effect is minimized by isopropanol infiltration of the photonic crystal structure.**

Keywords-All-optical devices; integrated optical devices; microcavity devices; photonic crystal.

I. Introduction

Photonic crystal (PhC) cavities, which offer high quality factors (Q) and small modal volumes (V), have been used in many applications including ultra-small filters, low-threshold lasers, photonic chips, nonlinear optics and optical information processing [1]. Recently, an all-optical switch based on a PhC cavity with two resonant modes has been demonstrated [2],[3]. Typically, a four-hole defect (L4) cavity is necessary to support two resonant modes. Here we demonstrate a PhC cavity with only three missing holes (L3) supporting two resonant modes. The smaller cavity mode volume makes it more suitable for this application due to the enhanced light confinement. In this paper, we experimentally demonstrate all-optical tuning of the proposed photonic crystal cavity based on the plasma effect from free carriers generated by two-photon absorption (TPA).

II. Design

Fig. 1(a) shows a schematic of the proposed structure consisting of a triangular-lattice of air holes with a line-defect (W1) waveguide and an L3 cavity. The dispersion diagram for the structure is shown in Fig. 1(c). Here we investigate the waveguide band in two spatial regions (waveguide region and cavity region). The solid lines are the bands for the W1 waveguide region and the upper blue one shows the waveguide mode within the band-gap. Since the L3 cavity is of the size of the light wavelength, only one resonant mode is supported within the pass band of the W1 waveguide. This mode can be seen as a dip in the transmission spectrum (the upper dotted line in Fig. 1(c)). On the other hand, the cavity region can also be considered as two coupled W1 waveguides. The band of such a coupled waveguide structure is plotted as the two blue dashed lines illustrated in the dispersion diagram (see Fig. 1(c)). One can see that the waveguide modes are different from those of a single W1 waveguide. In this case, photons with a specific frequency can only exist in the cavity region due to the mode-gap (MG) effect [1]. Thus, the frequencies that photons can take in this cavity region become quantized due to the short length of the cavity region in the Γ-J direction. Therefore, another resonant mode is formed below the cut-off frequency of the W1 PhC waveguide as the lower dotted line shown in Fig. 1(c).

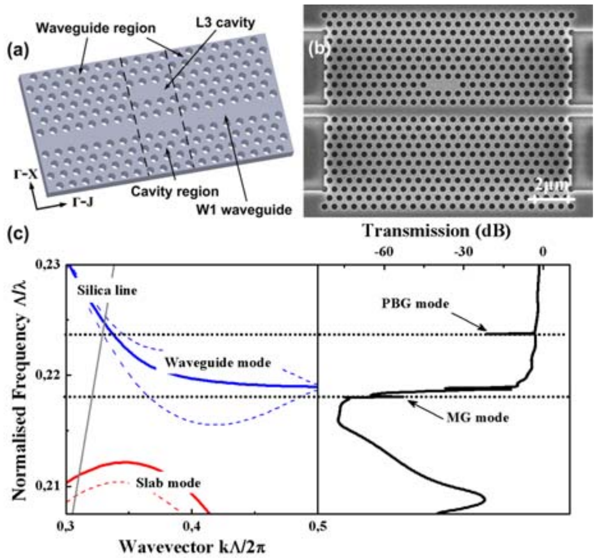

Figure 1. (a) Schematic of the L3 based PhC cavity. (b) SEM picture of the fabricated structure. (c) (Left) Dispersion diagram for the PhC structure in waveguide region (solid lines) and the cavity region (dashed lines). (Right) Simulated transmission for the proposed structure.

III. Experiment

The photonic crystal structure is fabricated in silicon-on-insulator (SOI) material with a top silicon thickness of 340nm and a 1-µm buried silicon dioxide (see Fig. 1(b)). The lattice constant of the structure is 380nm and the diameter of the holes is 220nm. The length of the whole PhC structure is 10µm. Fig. 2(a) shows the measured transmission spectrum of the fabricated structure for the TE mode. As we expected, there is one notch above the cutoff frequency due to the PBG effect of the L3 cavity, which is denoted as PBG mode in Fig. 2(a). One can also find that there is one peak below the cutoff frequency. This is the resonant mode (MG mode) due to the MG effect. The loaded Q factors for the two modes are 11,000 and 8,800, respectively. The Q factors are comparable to the cavity used for all-optical switching in [2], but V is smaller in our L3 cavity, which makes it possible to further reduce the operation power in the all-optical switch and memory applications since the operation energy scales as V/Q^2 in the device.

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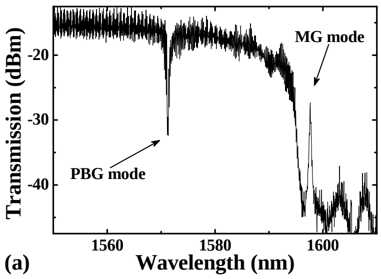

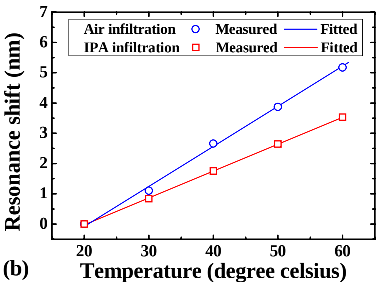

Figure 2. (a) Measured transmission spectrum of the fabricated structure (b) Measured resonance shift with different temperature for different infiltrations.

In the above measurement, the optical power was kept low during the wavelength sweeping of a tunable laser to avoid any nonlinear effect in the cavity. When the light intensity in the cavity increases, the enhanced light-matter interaction will result in TPA. The free carriers generated by TPA induce a decrease of the refractive index. However, TPA also introduces heat, and the thermo-optical (TO) effect increases the refractive index of silicon. Normally, the TO effect dominates over the plasma effect. Thus, to observe the carrier effect, an ultra-short pulsed light source is needed to avoid the slow thermal effect (in the order of a microsecond) [4]. The carrier effect can induce optical bistability in the cavities which has been demonstrated for many applications including optical switching, memory and fundamental logic functions, such as a flip-flop. However, the TO effect prevents the carrier-induced bistability from operating at steady state. Typically, the holding time for the steady state is less than 10ns [4]. This hampers the applications mentioned above. Since the TO coefficient of Si material is positive, infiltration for the air holes of the PhC cavity with a liquid of a negative TO coefficient can be used to reduce the temperature dependence of the PhC cavity [5]. In our experiment, the PhC holes were infiltrated with isopropanol (IPA). Fig. 2(b) shows the resonance (PBG mode) shift with temperature before and after the IPA infiltration. It is seen that the temperature dependency of the resonance has been decreased after the infiltration, which would make the carrier effect dominate as shown below in the measurement results.

To achieve all-optical tuning, we choose the PBG mode for the control wavelength and MG mode for the signal wavelength. As the light intensity at the PBG mode increases in the cavity, the TPA-induced free-carrier effect will change the refractive index of cavity which also affects the resonance wavelength of the MG mode. In our experiment, one laser with fixed wavelength at 1570.8nm was used as the control light. The intensity of the light was controlled by a combination of an optical amplifier and an attenuator. Another tunable laser with a low power was used to sweep wavelength around the MG mode. Fig. 3 shows the measured resonance shift for the MG mode. A clear blue-shift of 1nm is observed by applying 13dBm input power, which is an evidence of the dominant carrier effect induced by TPA in the proposed device since the TO effect results in a resonance red-shift. To our knowledge, this is the first experimental demonstration of all-optical tuning by carrier effect for a silicon PhC cavity using a continuous wave (CW) laser source. This will make it more practical to utilize the carrier-based bistability in some applications. Though the required power to realize the carrier-based all-optical tuning for the device using CW laser is relatively high, the problem can be resolved by using ultra-high Q factor L3 cavity [6].

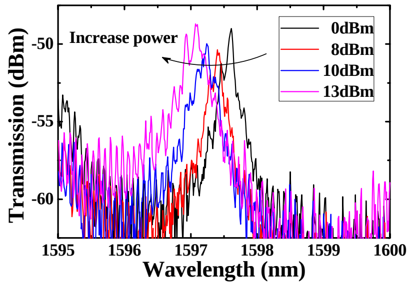

Figure 3. Measured resonance blue-shift of the MG mode with different input power for the PBG mode.

IV. Conclusion

We have demonstrated a PhC L3 cavity supporting two resonant modes with ultra-small V. It is also demonstrated that the temperature dependence of the device could be reduced by infiltrating the air hole with isopropanol. By minimizing the thermo-optical effect, we experimentally demonstrated all-optical tuning operation for the PhC cavity by the plasma effect of free carriers induced by TPA. This is the first experimental demonstration, to our knowledge, of carrier-based all-optical tuning using a CW laser source. We believe that the device is of potential use for many applications including all-optical switching, memory and fundamental logic functions.

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