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Author

Bui, Thanh Tung, Dzung, Viet Dao, Ikeda, Taro, Kanamori, Yoshiaki, Hane, Kazuhiro,
Sugiyama, Susumu

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Longitudinal strain sensitive effect in a photonic crystal cavity

Bui Thanh Tung[a], Dzung Viet Dao[a], Taro Ikeda[b], Yoshiaki Kanamori[b], Kazuhiro Hane[b], Susumu Sugiyama[a]*

[a]*Ritsumeikan University,1-1-1 Noji Higashi, Kusatsu, 525-8577, Japan*
[b]*Tohoku University, 6-6-01 Aobaku Aramakiaza Aoba, Sendai, 980-8579 Japan*

Abstract

This paper reports the theoretical and experimental investigations of the strain-induced resonant wavelength shift effect of a 2-D photonic crystal (PhC) cavity for strain sensing applications. Strain sensitivity of a high quality factor PhC cavity is studied based on finite element method (FEM) and finite difference time domain (FDTD) simulations. The results show that the resonant wavelength of cavity is proportional to the application of strain. Linear relationships between strain applied and shift of resonant wavelength were obtained. Accordingly, it is possible to detect the strain by determining resonant wavelength shift. The test device was realized on silicon-on-insulator for experimental investigation. The sensitivity to longitudinal strains was determined to be 0.95 pm/μ-strain.

Keywords: Photonic crystal; cavity; FDTD; strain sensing.

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1. Introduction

Integrated photonic crystal (PhC) sensors have been attracting an increasing interest in recent years due to their significant advantages such as accuracy, compactness, immunity to electromagnetic waves and so on [1]. PhC structures had been considered for bio and chemical sensing by detecting the refractive index change due to molecules immobilization in the PhC structures [2]. Mechanical sensing effects of PhC structures were also reported so far [3-5]. However, in these work, experimental results had not been reported. In this study, strain sensing ability of a PhC nanocavity is investigated both theoretical and experimentally by measuring the strain-induced shift of resonant wavelength of the cavity. High-

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* Corresponding author. Tel.: +81-77-561-2845; fax:+81-77-561-2854.
E-mail address: sugiyama@fc.ritsumei.ac.jp

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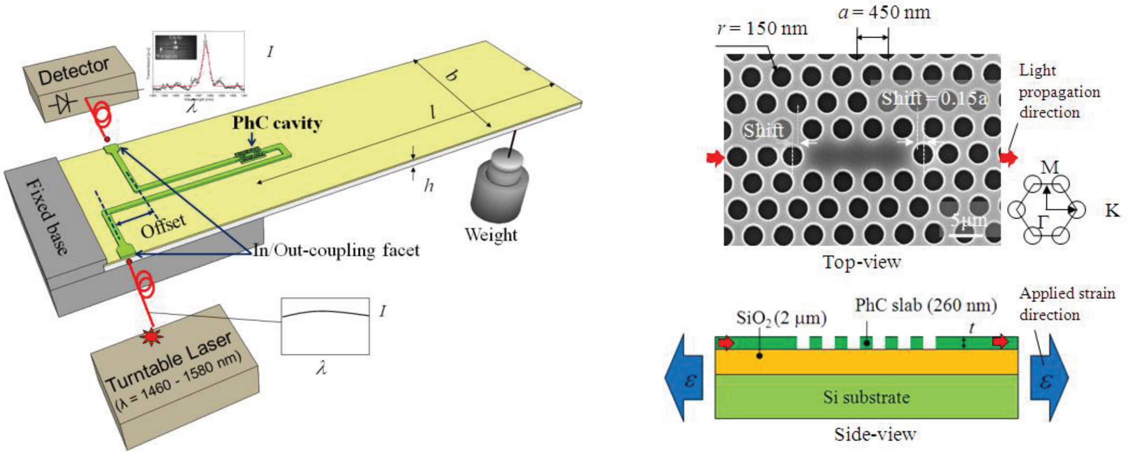
resolution strain sensors are supposed to be obtained by taking the advantages of the low-noise optical measurement, high accuracy of frequency shift measurement technique, and high quality factor (Q-factor) of PhC nanocavities [6, 7].

The test structure used to investigate the strain sensing effect in this study is a cantilever, which is fixed at one end as shown in Fig. 1(a). The PhC cavity structure, as the strain sensing element, is placed along the cantilever, at the center, near its fixed-edge to achieve strains. By loading of standard weights to the tip of cantilever, longitudinal strains (strain direction parallels with light propagation) are created in the PhC structure. Both ends of the PhC cavity are connected to a ridged waveguide system ending in a cleaved facet. These facets are used for coupling light to the device. The out-coupling facet is also offset from the in-coupling facet so as to prevent direct propagation of the incident ray to the lensed fibers at the output. By monitoring the change of transmitted light, i.e. resonant wavelength, applied strains can be measured.

2. Photonic crystal cavity structure

The cavity structure in this work is created by removing three air holes along the ΓK direction in a 2-D triangular lattice PhC slab, as shown in Fig. 1(b). The radius of the air holes and lattice constant are r = 150 nm and a = 450 nm respectively. The in-plane confinement of light is guaranteed by the PhC structure, while the out-of-plane confinement is due to the total internal reflection at the Si–SiO_2 and Si–air interface.

The behavior of the PhC cavity is modeled and analyzed using 2-D FDTD method. The equivalent 2-D structure was obtained by the effective refractive index approximation [8]. The effective refractive index of air/260nm-Si/SiO_2 is derived as 2.98. The Q-factor of the cavity is enhanced by tuning the cavity length d, which is achieved by shifting the outer holes, thus introducing dislocations in the lattice [9]. Simulation results show the highest Q-factor was obtained when the two outer holes were shifted by 0.15a from the original lattice positions. Fig. 2(a) shows the transmission spectral of this cavity. The analysis performed in this work was concentrated on the TE polarization light. Due to the measurement equipment, i.e. working range of the tunable laser, resonant wavelengths in the range of 1460–1580 nm can be observed and monitored during the application of strain.

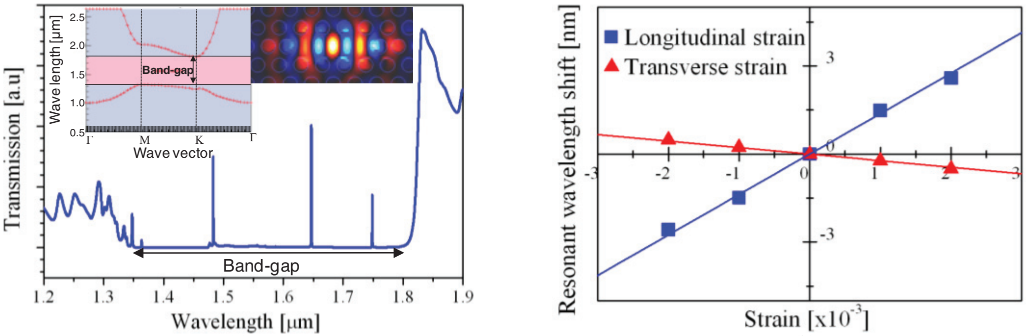


(a) (b)

Fig. 1. Schematic view of the strain detection testing system based on PhC cavity. (a) A cantilever bending system and measurement set-up. (b) Configuration of the PhC cavity.

3. Simulation of strain-induced resonant wavelength-shift

Under an applied load as shown in Fig.1(a), the mechanical stress/strain is generated at the position of the PhC cavity, resulting in the geometry change of the PhC, both in the position and shape of air holes. By applying FEM analysis, the geometric changes due to applied strains are determined. The strain-induced new positions and shape of air holes are used as input parameters for 2-D finite difference time domain (FDTD) simulation using CrystalWave^{TM}. Fig.2(b) depicts the simulation results of PhC geometry under elastic strains corresponding to longitudinal and transverse directions. Young's modulus of 169 GPa and Poisson's ratio of 0.28 were used for silicon.



(a) (b)

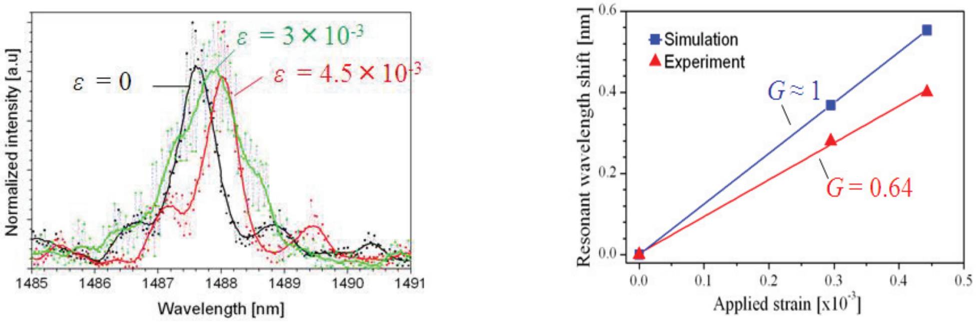
Fig. 2. FDTD simulation results. (a) Transmission spectrum of the cavity. The insets show the band structure (left) and the intensity profile of a degenerate mode (right). (b) Resonant wavelength shift vs. applied strains.

Strain makes the total refractive index changes due to the two effects: change of geometry of the holes lattice, and change of refractive index of the material. However, because the PhC structure consists of periodically-distributed air holes on Si slab, the stress/strains are distributed non-uniformly in the Si slab, and therefore, the refractive index of material is also distributed non-uniformly in the material. This makes the simulation becomes difficult and not yet be solved completely.

4. Measurement results and discussion

The PhC cavity was realized using electron beam lithography (EBL), plasma etching and cleaving processes; and characterized using an end-fire measurement system (Fig. 1(a)). Polarized tunable light (with a wavelength of λ = 1460–1580 nm) from a tunable laser source was coupled to a lensed fiber and after that to the in-coupling facet of Si waveguide. The light after transmitted through the PhC structure is coupled into another lensed fiber at the out-coupling facet and then guided onto the photo detector (Agilent 8164A).

Strain of approximately 3×10^{-3} and 4.5×10^{-3} were applied to the cavity by consecutively suspending of standard weights to cantilever tip. The transmission spectra of the PhC structure at these different applications of strain were measured to determine the strain-induced resonant wavelength shift effect of the PhC cavity structure. Fig. 3(a) shows the resonant peaks corresponding to the applications of longitudinal strains. A resonant peak at a wavelength of 1487.55 nm was obtained with a Q-factor of 4500 at free stress/strain state. It can be clearly seen that when a tensile stress was applied to the PhC cavity, the resonant peak shifted to a longer wavelength. This agrees well with the simulation results. The shift was measured to be 0.95 pm/μ-strain. On the basis of these measurement results, the gauge factor was calculated to be G = ($d\lambda/\lambda$)/ε = 0.64.



(a) (b)

Fig. 3. (a) Measurement results show the spectral of resonant wavelength corresponding to the application of strains. (b) Strain induce shift in the resonant wavelength.

The measured shifts of resonant wavelengths and the calculated gauge factor were smaller than the simulated values. The reason could be the mismatch between the calculated and actual strain, and the imperfections of the fabricated structure.

5. Conclusion

We presented the investigation of the strain sensing effect in a Si PhC resonant cavity. By simulation, the linear relationship between applied strains and the resonant wavelength shift of cavity was obtained. Fabrication of a PhC optical cavity structures was also implemented to confirm this sensing effect. The fabricated PhC cavity was characterized using end-fire measurement system. Strain sensitive and gauge factor of this cavity in case of application of longitudinal strain were determined to be 0.95 pm/μ-strain and 0.64, respectively.

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