Micromechanical Structures for Photonic Crystal Waveguide Switches

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Abstract

We report design and fabrication process of MEMS (Micro Electro Mechanical Systems) actuators for a new type of optical switch integrated with photonic crystal (PhC) waveguides. Thin film poly-silicon electrostatic microactuator (either a cantilever or a bridge style) is placed over a PhC waveguide to induce optical modulation by means of mechanical motion in the evanescent fields. For low voltage operation (< 10 V dc), we have used electrostatic simulation to design optimal parameters for the MEMS movable parts. Measurement using Laser Doppler Vibrometer has shown 15 nm mechanical motion of the modulator tip with a drive voltage of only 1 V.

Keywords: Optical MEMS, Electrostatic Actuators, Optical Modulation, Photonic Crystal

1 INTRODUCTION

Most switching boards of the fiber optic network today are made of solid-state switching devices that utilize opto-electronic (OE) and electro-optic (EO) conversion of very fast (< 100 ps) switching speeds. A drawback of such system, however, is the relatively narrow bandwidth compared with the potential of optical fiber itself. To enjoy the full bandwidth of the fiber optic communication system, optical switches and other passive components should be as transparent as possible; in other words, all-optical fiber networks are sought for the future broadband communication [1]. Optical switches by the microelectromechanical systems (MEMS) are the most suitable engineering solution from the bandwidth point of view, as optomechanical spatial light modulation is free from the bottleneck of OE and EO conversions.

Planar lightwave circuits (PLC) are known to have very small optical insertion loss to compose a complex optical passive devices such as wavelength multiplexer, demultiplexer, and crossconnects with the cost of relatively large device footprint associated with the minimal possible waveguide curvature for integrated lightwave circuit design. On the other hand, optical waveguide made of photonic crystal (PhC waveguide)[2] can be designed to have very sharp bending corners with ideal zero insertion loss, leading to a very small optical circuit system.

A part of our research group has proposed a new concept of ultra small optical modulation devices that combined a PhC waveguide with an integrated micromechanical modulator[3]; a piece of silicon is suspended over a PhC waveguide, and the effective refractive index is modulated by means of the mechanical oscillation of the silicon piece in the evanescent field over the waveguide. By designing an appropriate waveguide circuits (Mach-Zehnder interferometer) with this phase modulator, one may construct intensity modulator as well as optical switch. As there is no OE or EO conversions are involved, the modulator/switch system can be of all-optical. Different from the conventional optical MEMS devices, this scheme does not require large (micron) scale but that in the submicron range, which would be compatible with very low drive voltage and fast operation speed. Here in this paper, we propose a new fabrication process that is compatible to develop such MEMS-PhC devices by using the poly-silicon surface micromachining with the silicon-on-insulator (SOI) bulk micromachining technique. A proof-of-concept model of MEMS-PhC mechanical device has been developed, and its electromechanical characteristics have been tested. The concept of MEMS modulator combined with the conventional optical waveguides has been proposed by R. Dangel and W. Lukosz in 1997 [4]. In contrast to this, the originality of our study is to make yet smaller optical lightwave system by using the PhC waveguide and small MEMS modulator that could be potentially as small as the pitch of the photonic crystals.
2 Design of Micro Mechanical Actuator

Figure 1 shows a schematic illustration of the MEMS–PhC device. A micro piece of silicon is suspended over a photonic crystal waveguide, where no optical loss is induced when no voltage is applied in between the cantilever and the ground substrate (or the waveguide). Once the piece is brought into the evanescent field over the waveguide with the aid of electrostatic attraction force of an applied voltage, optical power is transferred to the micro piece and hence the optical power traveling in the waveguide decreases.

Figure 2 shows the results of numerical simulation of optical modulation. Silicon piece of 5 μm wide and 10 μm long (in parallel with the waveguide) is placed at a 300-nm height over the PhC waveguide, and optical transmission loss has been estimated by the FDTD method [Iwamoto]. Optical attenuation as large as 15 dB is calculated when the silicon piece is brought into a full contact with the waveguide. By gradually changing the position in between, attenuation can be controlled in an analog manner [3].

Figure 3 shows schematic illustration of two possible types of designed electrostatic actuators (a cantilever type and a bridge type) based on the results of Figure 2. Once the electrostatic attraction force becomes greater than the restoring force of the spring, the modulator piece is spontaneously pulled-into the counter electrode (the PhC waveguide or the ground substrate). A very simple analytical model of the gap-closing electrostatic actuator shows that pull-in occurs when the actuator’s displacement is equal with 1/3 of the initial electrostatic gap. If we set the initial electrostatic gap to be 300 nm, the stable range would be only the first 100 nm displacement (which corresponds to the gap of 300 nm to 200 nm). In this range of operation, optical intensity has been calculated to roll down to 5 dB loss.
Figure 4 (a) and (b) show the results of electrostatic displacement of the cantilever and bridge modulator, respectively, using the identical design parameters of Fig. 2. Pull-in voltages of the cantilever type are in the range of 9.4 V to 4.4 V, depending upon the structural and sacrificial layer thicknesses around 300 nm. Pull-in voltages of the bridge type (from 9.9 V to 4.6 V) have been calculated higher than those of cantilevers when the device footprints (beam length) are set almost equivalent.

3 Fabrication process of MEMS structures

Figure 5 shows a fabrication process of the MEMS-PhC device. In the process of making the modulator mechanism, we start with a silicon-on-insulator (SOI, 200-nm-thick active layer) wafer of nanometer scale PhC waveguide (hole size 400 nm in diameter) that has been prepared by the electron-beam (EB) pattern generator and deep reactive-ion etching (DRIE). Patterns of relatively larger size (such as contact pads and driving electrodes) are separately prepared on the identical SOI layer by the conventional photolithography steps and silicon dry etching (or reactive ion etching, RIE). A sacrificial silicon-oxide (300 nm in thickness) is deposited by the low-pressure chemical vapor deposition (LPCVD), and processed by photolithography to make anchoring sites for micromechanical components, which are made of an LPCVD poly-silicon layer (500 nm in thickness) in the subsequent steps. For successful finish of sacrificial release, we have employed a newly developed technique using vapor of hydrofluoric acid to selectively remove the underlying silicon-oxide layer without causing sticking of the released structures [5].

Figure 5. Fabrication process chart
Figure 6 (a) and (b) show SEM (scanning electron microscope) images of the two types MEMS-PhC modulators. The microstructures were released in vapor HF without causing serious damage to the photonic crystal structures. When the structure released, the BOX (Buried Oxide) layer under the SOI layer is etched at the same time through air holes of photonic crystals. Therefore, photonic crystals waveguide are finished in a shape of the air bridge structure. For optically coupling the PhC waveguide with a lensed optical fiber, the edge of the waveguide is to be optically polished before finally releasing the mechanically movable structures.

4 Electromechanical Characteristics

Figure 7 shows a preliminary electrostatic actuation test which has shown 13 nm or larger mechanical motion of the poly-silicon cantilever (typical 50 μm long 5 μm wide, and 0.5 μm thick) controlled by a dc driving voltage of 1 volt. Mechanical resonance has been found at 1 kHz or higher.

5 Summary

It proposed the design and fabrication process of electrostatic actuators (cantilever type and bridge type) to unite the MEMS structures and PhC waveguide. Displacement by electrostatic actuation and the optical modulation simulation were estimated, and the optical modulation of appox. 15dB showed in every several volts. Moreover, moving parts fabricated with the silicon micromachining process, and the electromechanical characteristic was evaluated.

REFERENCES