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High extinction ratio bandgap of photonic crystals in LNOI wafer

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ABSTRACT

A high-extinction-ratio bandgap of air-bridge photonic crystal slab, in the near infrared, is reported. These structures were patterned in single-crystalline $LiNbO_3$ film bonded to $SiO_2/LiNbO_3$ substrate by focused ion beam. To improve the vertical confinement of light, the SiO_2 layer was removed by 3.6% HF acid. Compared with photonic crystals sandwiched between SiO_2 and air, the structures suspending in air own a robust photonic bandgap and high transmission efficiency at valence band region. The measured results are in good agreement with numerically computed transmission spectra by finite-difference time-domain method. The air-bridge photonic crystal waveguides were formed by removing one line holes. We reveal experimentally the guiding characteristics and calculate the theoretical results for photonic crystal waveguides in $LiNbO_3$ film.

1. Introduction

Photonic crystals, with spatially periodic refractive index, can minimize the integrated optical circuits to a scale of light wavelength. In general, photonic crystal technology can realize a packing density with four to five orders of magnitude higher than conventional arts. The most prominent property is photonic band gap, a range of wavelength in which the light propagation is forbidden, regardless wave vector or polarization state [1]. Although three-dimensional (3D) photonic crystals can completely control light propagation, two-dimensional slab structures are simple to fabricate with the mature planar process technology. Photonic crystal slab can also realize 3D control of light propagation, which has two-dimensional periodicity in plane and total reflection in the third dimension.

Lithium niobate ($LiNbO_3$) is a kind of versatile materials in integrated optics due to its excellent electro-optic and nonlinear-optics properties [2]. Photonic crystal slab based on $LiNbO_3$ can enhance optical nonlinearities [3] and electro-optic tunability [4,5]. There are several methods to study photonic crystals in $LiNbO_3$. Photonic crystals have been made by focused ion beam (FIB) milling in annealed proton-exchanged $LiNbO_3$ waveguide [6]. Photonic crystal slab has been made in single-crystalline $LiNbO_3$ thin film bonded on a $LiNbO_3$ using adhesive polymer benzocyclobutene [7]. We also have fabricated photonic crystal slab in a single-crystalline $LiNbO_3$ film bonded to $SiO_2/LiNbO_3$ substrate (LNOI) with FIB milling [8]. Photonic crystal waveguide has been demonstrated in $LiNbO_3$ freestanding thin film with ion beam enhanced chemical etch [9]. To improve vertical confinement of light, the SiO_2 layer can be removed by HF acid, ammonium fluoride-hydrofluoric acid mixture or KOH in LNOI wafers [10–12].

Photonic crystal waveguide is a new kind of optical device, with characteristics of compact, lossless, and broadband guiding of light. The defect introduced into photonic crystals can create an optical waveguide for light propagation. The mechanism of photonic crystal waveguide is different from the traditional waveguide with total internal reflection. When there is a guiding mode dropped into the band gap, the mode can be confined highly [1]. Photonic crystal waveguide shows an ability to confine light with a low group velocity. The nonlinear effects can be enhanced because light is spatially compressed and the intensity of light is enhanced by low velocity [4].

In this paper, we report the fabrication of photonic crystal slab and photonic crystal waveguide in LNOI wafer with 500 nm $LiNbO_3$ membrane. The air-bridge structures are used to achieve better optical confinement. We demonstrate the optical characteristics of these optical structures. There are several characteristics in our work: a high extinction ratio and broad photonic band gap owing to a large index contrast vertically; a low loss of slab mode after HF etch; the guiding characteristics of photonic crystal waveguide in $LiNbO_3$ film.

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2. Experiments and details

The LNOI samples with 500 nm $LiNbO_3$ membrane were fabricated by smart cut technology in the research center of Nanoln. A 2 μm SiO_2 layer was coated on a $LiNbO_3$ handle. So, the $LiNbO_3$ membrane was sandwiched between air and SiO_2. According our calculations, the SiO_2 layer is thick enough and the light cannot couple into the handling $LiNbO_3$. The other fabricated conditions could be consulted for further details in previous literature [8,13]. End-face polishing of x-cut LNOI by SiO_2 suspension liquid has been done before our experiments.

Photonic crystal structures were fabricated by FIB milling with focusing gallium ions. The probe current of etching air holes was about 90 pA. An appropriate current of 6500 pA was used to fabricate ridge waveguide. The detailed experiment conditions were described in our paper [8]. However, compared to that work, some improvements of the structures were showed in the following. After removing the metal coating, samples were immersed in 3.6% HF acid at 28 °C and the SiO_2 layer was removed under the photonic crystal structure in several minutes. The air-bridge photonic crystal structures were formed.

The cross sections of air holes are showed in Fig. 1(a), viewed at 60°. Conical sidewall is the common problem of using FIB etching, caused by inevitable redeposition during milling. The sidewall angle from vertical direction is about 7.5°. The lattice constant is 560 nm and the planned diameter of air hole is 260 nm. Fig. 1(b) shows the slab surrounded by air after the SO_2 layer removed by 3.6% HF acid. In order to observe the cross section after chemical etch, the air hole structure was cleaved by FIB. The impurities in holes were gold particles during gold film fabrication. The diameter of air holes became larger than that before HF acid etch, because the redeposition materials and the damage layer formed during FIB milling were etched away by 3.6% HF acid. In previous study, 3.6% HF acid can etch amorphous $LiNbO_3$ formed by ion implantation, but the etching rate of perfect $LiNbO_3$ is very low [14]. The etching rate is sufficiently low to prevent the damage of fragile $LiNbO_3$ membrane. So, it is necessary to design a slightly smaller hole size in the initial FIB milling.

After 3.6% HF acid etch, the overall appearance of a suspended $LiNbO_3$ photonic crystals membrane, between a pair of waveguides, is showed in Fig. 2(a). The SiO_2 layer under air holes was removed out completely during the selective wet etching. Based on theoretical calculation, the photonic crystal lattice was triangular array, with 17 × 16 air holes, and light propagated along ΓK symmetry direction. For in- and out-coupling of the laser light, the conventional ridge waveguides with 7 μm width and 0.8 mm length were fabricated by FIB milling. With the same condition, the photonic crystal waveguides were formed by removing one line air holes in Fig. 2(b). To enhance coupling efficiency, the light was coupled into photonic crystal waveguide by a tapered ridge waveguide that gradually narrowed down to the width of photonic crystal waveguide.

3. Results and discussion

In the same LNOI wafer, three kinds of transmission spectra were measured from three different devices: (1) photonic crystals without defect, (2) photonic crystal waveguide and (3) ridge waveguide without photonic crystal structure. The transmission efficiency with unit dB was the ratio of transmission spectrum (1) to (3). We also defined the guiding efficiency as the ratio of spectrum (2) to (3). Transmission spectra of the air-bridge photonic crystal slab are showed in Fig. 3(a), measured by a set-up (Santec TSL-210) with tunable near infrared laser from 1260 to 1630 nm. The black solid line is an experimental transmission spectrum of air-bridge photonic crystal slab. A robust band gap with a maximum extinction ratio about 30 dB at around 1317 nm is demonstrated. In the gap region, light cannot transmit through the photonic crystals, whereas the high-transmission region is regarded as the slab mode outside the band gap. As far as we know, this is the largest experimental ratio for photonic crystal band gap in $LiNbO_3$ compared with previous works so far [6–8]. It is suggested that this device can confine light well. The bandwidth at half maximum is from 1280 to 1510 nm. To test the rationality of results, theoretical calculation was performed by three-dimensional finite-difference time-domain (FDTD) method. In this process, perfectly matched layers are used to absorb outgoing wave and to avoid unwanted reflection from the edges. The red short dash line represents simulated spectrum for the air-hole array with period constant $a = 560$ nm and diameter $d = 322$ nm. The diameter becomes larger than the planed one ($d = 260$ nm), due to etch of 3.6% HF, which is in accordance with the measured results experimentally. By contrasting experimental spectrum to the simulated one, the transmission efficiency meets each other very well at both conduction band (CB) and valence band (VB). The intensity attenuation ratio of the band gap also agrees with the simulated one. However, there is a little difference between these two spectra. We think it is caused by differences of holes array and the conical shape

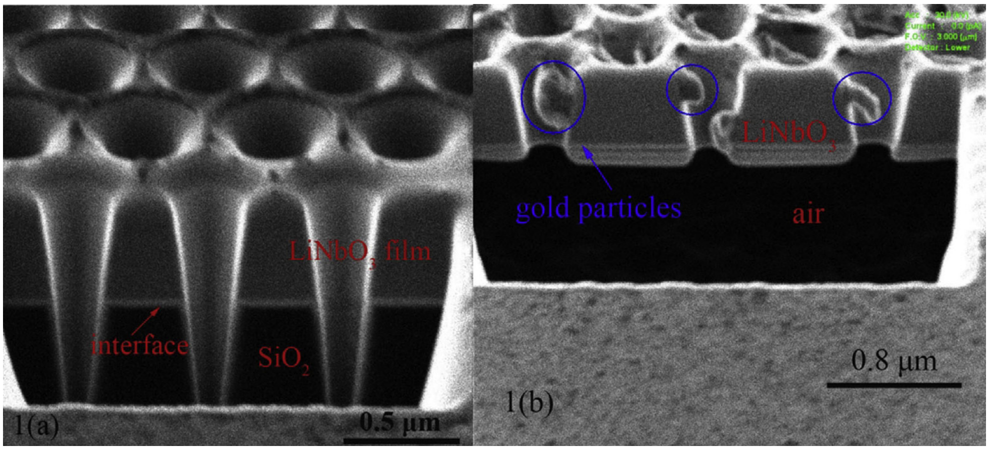

Fig. 1. Cross sections of air holes with SiO_2 layer (a) and without SiO_2 layer after etch by HF acid (b).