# Tunable photonic crystals based on ferroelectric and ferromagnetic materials by focused ion beam

**Ziyou Zhou**[1], **Xiaoyue Huang**[1], **Raghav Vanga**[1], **and Rong Li**[2]

[1]*Physics Department, Michigan Technological University, Houghton, MI 49931, USA*

[2]*Material Science and Engineering Department, Michigan Technological University, Houghton, MI 49931, USA*

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By making photonic crystals in ferroelectric and ferromagnetic materials, field-provoked tunability of photonic crystals is broadening the interest in new applications of on-chip photonic devices. We report a nano-precise fabrication of various designs of photonic crystals in these non-conventional materials using the focused ion beam milling technique. Standard methods are developed and parameters for different materials are calibrated. Optical responses such as bandgaps and polarization status changing from planar film waveguide system with these patterns have been examined on ferromagnetic materials.

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Photonic crystals (PhCs) are artificial periodic structures that forbid light propagation at certain frequency ranges along specific directions[1,2]. During the last two decades, integration of these structure became more and more attractive for many applications such as data communications and sensing including Faraday rotators, modulators, filters, and detectors. After the initial demonstration of tunability in PhC systems by John *et al.*, several PhC structures and tuning mechanisms were investigated widely[3,4]. Tunable PhCs with real time and on-demand control can greatly enhance the functionality of photonic devices and miniaturization of size.

In contrast to the use of conventional semiconductor substrates and infiltrated liquid or polymer, we hereby report the investigation of tunable PhCs directly utilizing ferroelectric and ferromagnetic materials with optical properties that can be strongly and easily manipulated by external field. The direct control to change the structure or refractive index of the PhCs material offers many advantages to form active field-controlling PhC applications.

In the present work, tunability through magnetic field is studied on ferromagnetic substitute ion garnet films, e.g., BiYIG ($(\mathrm{Bi,Y})_3\mathrm{Fe}_5\mathrm{O}_3$), which have high magneto-optic responses. The polarization status of output light can be modified and controlled throughout this medium by external magnetic field. This is due to the magnetically-provoked changes in each decomposed circular eigenmode indices. An on-chip magnetic-field-driven thin film optical isolator/switcher has been created through PhC planar waveguide[5−9].

$\mathrm{LiNbO}_3$ and lead magnesium niobate-lead titanate (PMN-PT) belong to ferroelectric materials, and they are highly piezoelectric and electro-optic single crystal materials. Transmission spectrum of PhC waveguide filter is sensitive to refractive index and structural changes induced due to the applied electric field. These kind of tunable optical filters are highly desired for integrated optical communication and light manipulation.

Since all the materials mentioned above are not as conventional substrates as semiconductor or polymer based materials, their conductivity, hardness, and film create difficulties in standard processing such as photo and electron beam lithography. These difficulties in e-beam lithography[6] include polymer mask formation, depth enhancement and pattern aligning. Compared with e-beam technology, focused ion beam (FIB) process does not have these problems and really provides a direct and fast way for PhCs patterning.

FIB uses a focused beam of gallium ions to raster over the surface of a sample so as to sputter atoms away. By its focused sputter effect, FIB can generate nano-resolution milling patterns. The beam current ranges from several picoamperes to tens of nanoamperes by changing the aperture size.

Ridge waveguides widths from 1 to 10 $\mu$m were patterned onto BiYIG, $\mathrm{LiNbO}_3$, and PMN-PT samples. The ridges were formed by standard photolithography and plasma etching. Sample facets were polished for optical end-fire coupling. PhCs were fashioned on waveguides by Hitachi FB-2000A at 30 kV. The designed computer aided design (CAD) patterns were transferred onto the samples through a nanometer patterning generation system working in conjunction with FIB.

In order to have more information on the depth of the grooves which affect the performance of the PhCs, we measured the depth through scanning electron microscope (SEM). The procedure is illustrated in Fig. 1.

The grooves with the designed widths were patterned near the mirror-finishing polished facet edge as shown in Fig. 1(a). By milling a large cube of material at the edge, the cross-section profile of gratings can be imaged from the facet side as shown in Fig. 1(b). Then the sample was observed by SEM and the depth of the grooves

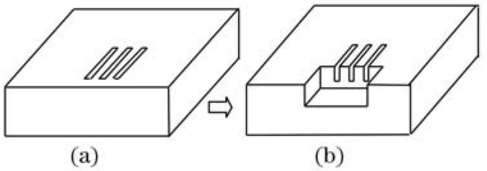

Fig. 1. Methods of measuring groove depth. (a) The grooves were milled at the edge of the facet; (b) a large cube was removed by milling. The depth was then measured by SEM.

was measured. Typically the grooves are about ~ 150 nm wide and ~ 700 nm deep. These dimensions are too narrow and deep for atomic force microscope (AFM) depth measurements.

Since there is surface implantation and redeposition accompanied with ion milling, we found that acid post-treatment is necessary and the result is sharper and more defined.

Patterned samples of BiYIG are immersed into a solution of ortho-phosphoric acid maintained at 75 °C for 10 − 15 seconds. Under SEM as shown in Fig. 2, the debris was removed away and grooves become wider and deeper as compared with the shape before etching. We notice an enhancement in the optical response, which will be discussed later. Different etchant has to be chosen for different materials such as HF for $LiNbO_3$ and HCl for PMN-PT.

In this FIB/NPGS system, the exposure dose for each point that the focused ion beam impinges on is determined by the product of beam current and exposure time. Arrays of these overlapped bombarded points form the grooves of the designed width. With fixed line spacing at 3.7 nm in the NPGS system, the total exposure dose on each row, which is called "line dose", can be a standard caliber for FIB milling calibration of each material. This calibration is very important to more complicated PhC structures whose depths require varieties at one shot[10].

Figure 3 shows the dependence of groove depths on line doses. Squares and triangles represent for the depths dependent on line doses in BiYIG and $LiNbO_3$ respectively with the designed line width of 100 nm, while circles for PMN-PT with line width of 80 nm. The tendencies of depth with increasing line dose show the ranges of depth from 400 to 800 nm for BiYIG and $LiNbO_3$ and from 200 to 600 nm for PMN-PT at typical line doses from 50 to 200 nC/cm. Less hardness makes PMN-PT curve far below the other two. The trend toward saturation for all materials is due to the dramatical aggravation of redeposition and backscattering when ions milling takes place deeper into the materials.

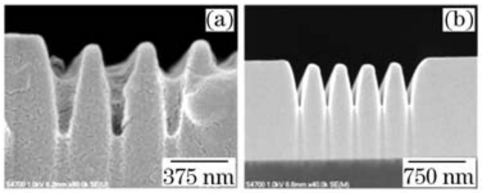

Fig. 2. Cross-sections of gratings in BiYIG sample (a) before etching and (b) after etching.

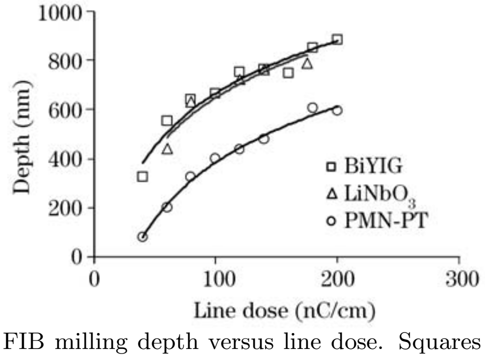

Fig. 3. FIB milling depth versus line dose. Squares and triangles represent for the depths dependences of line doses in BiYIG and $LiNbO_3$ respectively with the designed line width of 100 nm, while circles for PMN-PT with line width of 80 nm.

Optical responses including transmission and tunability are studied by a setup for film ridge waveguide with end-fire fiber coupling from a tunable laser source. After fine polish of both waveguide facet ends, the linear polarized light in transverse electric (TE) mode is coupled into the center of waveguide through single mode lensed fiber and a polarization controller. The external fields were provided either by magnetic coils set that was parallel to the waveguide axis or electrodes integrated aside the waveguide. The output light from the waveguide was converged by an objective lens and is focused onto an intensity detector and a charge coupled device (CCD) camera through a 50% beam splitter. So far, tests on polarization rotation from ion garnet have been reported[6−9] while others are still in the progress. The following measurements are all from ion garnet samples. A digital controlled polarization rotation system is used for polarization status tracking when external magnetic field is applied.

Typical PhC structures are shown in Fig. 4(a). The gratings were fabricated along the top of waveguide with resonant cavity breaking the periodicity in the middle. The resonant cavity can introduce a transmission peak into the bandgap as shown at 1548 nm position of dark plot in Fig. 4(b). Multiple stopbands have been observed in PhC waveguide on the substituted ion garnet films as shown in Fig. 4(b). Past work has revealed that those stop-bands correspond to waveguide modes coupling through backscattering[9]. The grey plot in Fig. 4(b) is the transmission intensity taken from same structure as the dark one but without proper etching. By comparing both of them, the transmission is highly enhanced up to 10 times as well as the bandgap contrast up to 6 times. After cleaning, improved structure reduces the effective mode indices. As a result, about

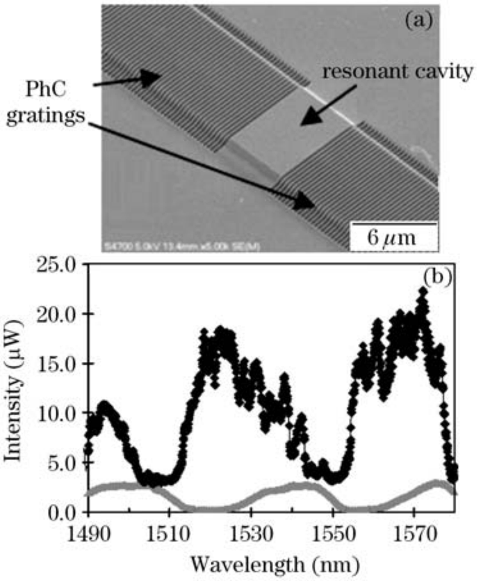

Fig. 4. (a) SEM image of planar ridge BiYIG waveguide with PhC/resonant cavity on top. (b) Intensity transmission spectra over 1490 − 1580 nm wavelength. Grey plot is taken before etching while dark one is after etching.

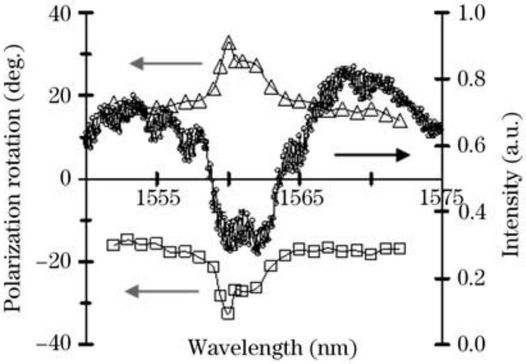

Fig. 5. Polarization rotation spectra over wavelength of $1550-1575$ nm. The intensity bandgap structure is shown in dark circles; squares represent for each polarization rotation status with external saturation fields parallel to light propagation while triangles for one with opposite way.

10-nm bands left-ward shifts occur in the plots.

Because of photon trapping and wave-vector splitting between Bloch modes of opposite helicity[11], rotation can be enhanced within PhC stopband. Rotation up to 45° has been achieved by proper design of PhC in ion garnet film as shown in Fig. 5. By switching external saturated magnetic field (∼ 300 gauss), symmetric opposite polarization rotation plotted in triangles and squares respectively show up near the bandgap plotted in dark circles, while around 2 times of rotation enhancement appears within the bandgap.

Photonic crystals have been successfully patterned on non-conventional materials, e.g., BiYIG, $LiNbO_3$, and PMN-PT, by focused-ion-beam and the parameters have been calibrated as an importance to future work. So far, successful tunability of enhanced polarization status has been achieved in ion garnet film sample under alternative external magnetic field.

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