

Focused ion beam fabricated bragg grating filters in relaxor ferroelectrics

Raghav Vanga ^{*}, Xiaoyue Huang, Ziyou Zhou

Physics Department, 118 Fisher Hall, 1400 Townsend Drive, Michigan Technological University, Houghton, MI 49931, USA

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ABSTRACT

In this paper, we discuss the fabrication and characterization of optical waveguide Bragg filters in ion-implanted PMN-32PT [$68\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{-}32\text{PbTiO}_3$] single crystal substrates. PMN-32PT possesses exceptionally high piezoelectric and electro-optic properties and has immediate applications in on-chip optical circuitry. We use commercial modeling programs to design the waveguide filter and fabricate the device using ion-implantation and nano-fabrication techniques. First, slab waveguides are created in $\langle 001 \rangle$ mirror polished substrates through He^+ ion-implantation process. He^+ implantation creates an optical barrier with reduced refractive index.

Second, ridge waveguides on the slab are fabricated through standard photolithography and dry etching techniques. Third, Periodic refractive index modulation (grating) on the top of the ridge waveguide is achieved through Focused Ion Beam [FIB] milling which is controlled by Nanometer Pattern Generation System [NPGS]. Photonic bandgaps are observed in 1480–1580 nm wavelength range in these filters. The experimental data shows excellent agreement with the theory.

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1. Introduction

There is a strong drive in the optics industry to develop multi-functional optical components that could be incorporated into an optical circuitry and communication applications. Optical waveguide filters form an essential component in wavelength de-multiplexing schemes and other wavelength filtering applications. Relaxors such as PMN-32PT [$68\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{-}32\text{PbTiO}_3$] possess a combination of exceptionally high piezoelectric, electro-optic, and dielectric properties when compared to other widely used crystals such as LiNbO_3 , BaTiO_3 , PZT etc., hence optical components fabricated using these crystals show the promise of multi-functionality devices operating at lower drive conditions. In this paper, we discuss the modeling, nano-fabrication and characterization of tunable optical waveguide filters in relaxor ferroelectric PMN-32PT single crystals fabricated using a focused ion beam system (FIB) [1–3].

In the last two decades photonic crystals (PhC) have gained a considerable interest because these nano-scale crystals offer a medium to control and understand various properties of light at optical wavelengths [4]. At optical wavelengths PhC's are nanometer scale natural or artificial periodic structures that prevent the propagation of certain frequencies of light in one or more directions, hence creating a photonic bandgap. An example of a one-dimensional photonic crystal is a Bragg grating filter on an optical

waveguide which consists of a quarter-wave stack forming highly reflecting dielectric mirrors. Light with appropriate wavelength (Bragg wavelength) incident normal to the stack undergoes a series of constructive and destructive interferences within the medium and results in a bandgap in the transmission spectrum. The Bragg wavelength is determined by the Bragg condition $2n_{\text{eff}}\Lambda = \lambda$ where n_{eff} is the effective index for the guided optical mode in the medium of propagation, Λ is the period of the Bragg grating, and λ is the wavelength of the light. Further, a transmission peak within the bandgap can be generated by introducing a phase shift of 180° at the centre of the grating stack. The phase shift is sometimes referred to as a defect or resonant cavity or Fabry–Perot etalon. A detailed mathematical treatment of the one-dimensional photonic crystal structure is presented elsewhere [5]. Several techniques using excimer laser [6], holography [7], photomask [8], e-beam lithography etc. have been used to realize nanometer scale periodic structures; each of these techniques have their pros and cons for specific applications. For instance, e-beam lithography is suitable for conventional conductive substrates such as doped silicon, however for non-conventional substrates such as PMN-32PT it is challenging to achieve high aspect ratio nano-features where surface charging effects dominate (during the step of polymer mask forming). Here we overstretch the versatility of the FIB in an unusual way to directly pattern 1D-photonic crystals (Bragg gratings) on the optical waveguides with extreme precision and user control. We control the line-width of the pattern and FIB milling fluence to achieve greater than 5:1 aspect ratio features [9]. Hitachi FB 2000A FIB used in this work is characterized with a beam brightness $\sim 10^6 \text{ A cm}^{-2} \text{ Sr}^{-1}$, current density $> 10 \text{ A cm}^{-2}$ and a beam

^{*} Corresponding author.

E-mail addresses: rvanga@mtu.edu (R. Vanga), xiahuang@mtu.edu (X. Huang), zzhou@mtu.edu (Z. Zhou).

diameter <10 nm. Gallium ions are accelerated to energies of 5–50 keV by an accelerating voltage of 30 kV and the gallium beam is rastered over the sample to create the photonic crystals. The beam diameter and beam current density are controlled through variable apertures ranging from 6–500 μm diameter.

2. Experimental

<001> oriented PMN-32PT ($10 \times 10 \times 0.5$ mm) single crystal plates are obtained from TRS Ceramics Inc. First, slab waveguides are created in these mirror polished crystal plates through He^+ ion-implantation process. He^+ ions are implanted at 5° off normal to the surface at energies 1.2 MeV, and 1.5 MeV respectively at implantation fluence of $5 \times 10^{16} \text{ cm}^{-2}$. He^+ implantation creates a film layer and a buried optical barrier layer $\sim 2 \mu\text{m}$ wide below the surface with fractional reduction in the refractive index having an asymmetric Gaussian profile. The exact refractive index of the film, the effective indices of the guided modes, and the thickness of the guiding film are determined using a Metricon 2010 prism coupler equipped with a 1543 nm laser source. Several ridge waveguides 400 μm long, 5 μm wide, and 0.5 μm tall are created using a series of microfabrication processes such as photolithography, plasma dry etching, facet polishing etc. TE and TM absorption losses are determined to be 3.75 dB/mm, and 3.70 dB/mm respectively. These losses are higher than desired; however efforts are underway to minimize these losses. A detailed description of the fabrication process of the waveguides is discussed elsewhere [1].

The Bragg filter is modeled using R-Soft, a commercial modeling package. GratingMOD feature of the R-Soft is utilized to design and simulate the grating structure; GratingMOD uses the Coupled Mode Theory (CMT) to simulate the propagation of guided modes through the grating. The essential parameters such as the grating period, grating depth, length of the grating, position and length of the resonant cavity etc. needed for the fabrication are obtained from the model. Once the waveguides are tested for good optical waveguiding/optical confinement, additional sample preparation is done for the FIB patterning. PMN-PT is soft material; hence for handling purposes, the samples are bonded to a $6 \times 5 \times 0.5$ mm handle silicon substrate using silver epoxy. The mounted sample is sputter coated with a 50 nm of gold layer using a Hummer sputtering machine; gold layer prevents electrical charge build up on the sample during FIB patterning.

The 1-D photonic crystals are fabricated on the top of the waveguides using Hitachi FB 2000A FIB equipped with Nanometer Pattern Generation System (NPGS). The FIB used in this research is equipped with onboard CAD software. However, the resolution of the patterns created using this software is not sufficient for the grating patterning. For the 200 μm long grating pattern a 256 sq. μm scan area must be used, but this would result in 500 nm resolution per pixel and is not suitable for grating with periodicities ~ 330 nm. Hence, the NPGS (Nanometer Pattern Generation System) from J.C. Nability Company is used as the software control for the design and fabrication of the grating patterns. A $200 \times 5 \mu\text{m}$ long grating (~ 600 periods) with grating periodicity set to 330 nm, line width to 80 nm and the length of the resonant cavity set to $4.5 \times$ period grating pattern with a resonant cavity at the center of the grating is designed. The FIB fluence needed to obtain the desired grating depth during FIB milling is previously determined using a FIB/SEM based cross-sectional examination approach. In this method, the PMN-PT sample is facet polished on one side to mirror finish. Grating patterns are patterned one the sample very close to the polished edge at different line doses. Using M1–300 beam cubes are milled on the patterns to reveal the groove depths. Fig. 1 shows the grating groove depth plotted as a function of the FIB dose for few selected substrates for two different FIB

apertures. The waveguide to be patterned is centered in the fabrication window, and the grating is fabricated by simultaneously running the NPGS run file as well as the FIB beam [10–12].

Fig. 2 shows the waveguides and close up view of quarter wave stack, and the resonant cavity. A magnified view of the grating is also shown in the figure to illustrate the high spatial resolution of the nanometer patterns. Guided modes are excited in the ridge waveguides using the end-fire coupling. This technique allows for coupling light wave with profile similar to the guided mode profile. The optical response of the system including transmission spectrum, and beam spot profile is studied using a tunable laser with a range from 1480 to 1580 nm. The laser has a 0.001 nm wavelength resolution and 7.9 mW (9 dBm) maximum/0.079 mW (–11 dBm) minimum output power. Light coupling into the waveguide is achieved by carefully adjusting the x, y, z stage controls. The input polarization from the laser is set by a digital polarizer controller (Agilent 11896A) at 0.3 mW laser power. The output laser beam from the waveguide is focused onto a 50% non-polarizing beam-splitter using a $10 \times$ microscope objective, which divides the beam into two halves. One beam is analyzed by a motorized rotating Glan–Thompson polarizer with sub-degree precision and recorded by a photo detector (Ophir PD300-IR) with nW-resolution and 15 Hz sampling rate. The other beam is used to monitor the shape and intensity. The recording camera (Hamamatsu) is very sensitive and is equipped with beam profile analyzer software (Spiricon LBA-710PC) in a computer.

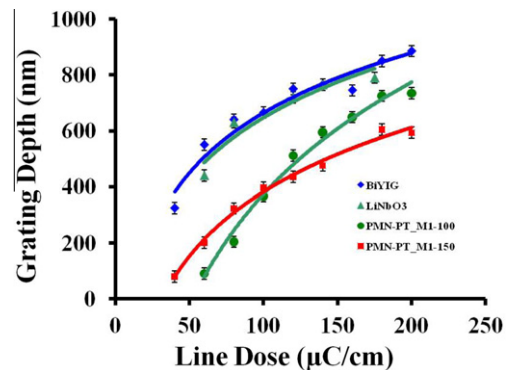


Fig. 1. Calibration plot showing the depth of the grating as a function of FIB line dose.

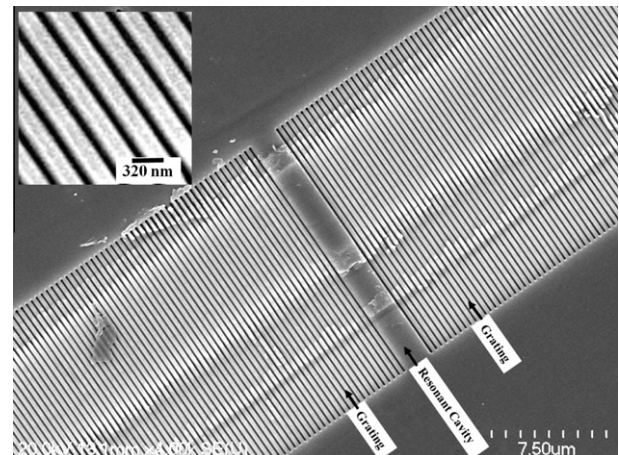


Fig. 2. SEM micrograph showing grating patterns fabricated on optical waveguides.

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