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Demonstration of wide frequency bandwidth electro-optic response in SBN thin film waveguide

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ABSTRACT

The dynamic modulation of effective electro-optic (EO) coefficient in pulsed laser deposited SBN thin film was investigated using Senarmont Compensation method. Prism coupling technique was used to realize a waveguide to guide the light in SBN thin film. The dynamic variation of effective electro-optic coefficient over a wide frequency range (10 Hz–20 MHz) was investigated with the maximum value of 198 pm/V. This wide frequency bandwidth obtained in the present article opens up avenues to design an EO modulator using ferroelectric SBN thin film. A lower value of half wave voltage (38 V) along with high figure of merit ($0.9 \times 10^6\ V^2$) were obtained for the fabricated SBN60 thin film based EO modulator.

1. Introduction

With modernization, effective modulation of light waves over wide frequency range has become increasingly important in fiber–optic transmission systems [1,2]. Electro-optic (EO) modulators based on ferroelectric crystals such as PLZT [3] $LiNbO_3$ [4], $Sr_{1-x}Ba_xNb_2O_6$ (x= 0.4) [5] and $KTa_{0.65}Nb_{0.35}O_3$ [6], have proven their potential stemming from their tunable dielectric and electro-optic properties. However, the high cost involved in the growth of large sized single crystals limits their use in practical devices, especially in integrated photonic circuits or optical interconnects [7]. Thus, the guided optical wave modulators based on ferroelectric thin films have been extensively explored for the realization of efficient EO modulators operating over wider bandwidths with lower modulation voltages [8,9]. A strong optical confinement and high optical power density is achieved by the growth of epitaxial ferroelectric thin films on low refractive index substrates [7]. A compact and cost-effective optical system can be designed by positioning thin-film based optical devices simultaneously one after the other on a single substrate [10,11]. Since, thickness of the film is in comparison to the optical wavelength, the intensity of light in the film is very large because most of incident light energy is confined within the film. Due to which the required intensity in the film is achieved at a moderate laser power level. In order to couple the light wave propagating in free space media into a well-defined mode of the thin-film guide, coupling techniques like prism-film coupler, grating coupler etc. are exploited [12].

Amongst the known ferroelectric materials, $Sr_{1-x}Ba_xNb_2O_6$ (SBN), with x= 0.4, is an appealing material in coordinated optics and optoelectronics [13,14]. The lead-free composition, high value of linear EO coefficient (r_{33} = 420 pm/V), nonlinear optic coefficient (d_{33} = 12.8 pm/V), and a strong photorefractive effect [15] are some of the promising characteristics of bulk SBN. The value of r_{33} = 420pm/V at wavelength, $\lambda = 633\ nm$ is an order of magnitude higher than that observed in well-established EO materials such as $LiNbO_3$ and $LiTaO_3$ [16–18]. Strontium Barium Niobate (SBN) possesses a tetragonal tungsten bronze (TTB) structure with 4 mm symmetry group at room temperature [19]. The electrical and optical properties of SBN can be tailored in accordance with the Sr/Ba ratio which in turn modifies its Curie temperature (for $x \geq 25$, $T_c = 220°C$, $x \leq 75$, $T_c = 60°C$) [13]. SBN has been effectively used for the fabrication of low voltage EO waveguide devices with a very low half-wave voltage length product ($V_\pi L$) [13].

The electro-optic property of SBN has been of great interest among researchers. Trivedi et al. (1995) obtained a moderate value of EO coefficient (r_{33}) of SBN by utilizing a modulated reflection grating technique [5]. Koo et al. (2000) measured the value of effective electro-optic coefficient using the reflection configuration of a two-beam polarization interferometer [20]. Ponsard et al. (2011) simultaneously characterized the EO, converse-piezoelectric and electro absorptive effects in SBN thin film using Fabry–Perot reflective configuration [21]. Thus, SBN has proven its potential as a competent electro-optic material for achieving efficient modulation [21]. The dynamic variation plays a

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crucial role in real time measurements of the modulation properties. The frequency dispersion of EO coefficient over a wide frequency range is highly crucial for the development of devices such as modulators or Q-switch Pockels cells [25]. Huang et al. reported the frequency dependence of effective EO coefficient of SBN61 ($Sr_{0.61}Ba_{0.39}Nb_2O_6$) crystal using the waveguide based Senarmont compensator technique [26,27]. Consequently, in order to realize an efficient MEMS based EO modulator, it becomes very crucial to exploit EO active material in thin film form. However, no report is available in the literature on study of the dynamic response of electro-optic coefficient in ferroelectric SBN thin films [22–24]. The present study reports on the utilization of a simplistic approach for the investigation of dynamic EO effect in SBN thin film. Prism coupling technique employing Senarmont compensation method has been explored to study the dynamic variation of EO coefficient. The ease of alignment and measurement setup involved in utilized method makes it more attractive as compared to other available techniques [20,21,24].

In the present article, study of the frequency dependent EO coefficient of SBN60 ($Sr_{0.6}Ba_{0.4}Nb_2O_6$) thin films prepared using PLD technique in the direction of realizing an efficient EO modulator over a wide frequency range has been done. A simpler approach for realization of efficient EO modulator utilizing SBN thin film waveguide has been adopted. The dispersion of effective electro-optic coefficient has been investigated using Senarmont compensation method exploiting prism coupling technique. The role of piezoelectric displacements contributing to the effective EO coefficient has been discussed in detail. A wide frequency bandwidth EO modulator along with less propagation losses was achieved in the present work.

2. Experimental details

$Sr_{0.6}Ba_{0.4}Nb_2O_6$ (SBN60) thin films were prepared using pulsed laser deposition (PLD) technique utilizing a KrF excimer laser (wavelength, λ= 248 nm). The SBN60 target was prepared by solid state reaction route by mixing the $SrCO_3$ (99.9% pure), $BaCO_3$ (99.9% pure) and Nb_2O_6 (99.9% pure) powders in the ratio of 20.44:18.22:61.34 wt%. The mixture was calcined at a temperature of about 950 °C, pressed in the form of one-inch diameter circular disc and subsequently sintered at 1350 °C for 10 h. The formation of tetragonal tungsten bronze structure of SBN was confirmed in the prepared SBN60 target using X-ray diffraction (XRD) pattern. Fused silica was chosen as the substrate in order to study the optical and structural properties of the prepared SBN60 thin films. The target (SBN60) was ablated with the excimer laser (λ= 248 nm) with a fixed repetition rate of 10 Hz and the fluence of about 1.0 Jcm^{-2} on the target surface. Table 1 summarizes the optimized deposition parameters used for the growth of SBN60 thin films. The deposited SBN60 thin films were post annealed in air in a temperature-controlled furnace at 950 °C for about 3 h to improve the crystallinity.

Structural studies of the as prepared and post annealed films were performed using X-Ray diffraction (Rigaku, Ultima IV) technique. Atomic Force Microscopy (AFM) (Bruker, Dimension Icon) technique was used to investigate the surface morphology of the prepared film of SBN60 in non-contact mode. The thickness of the film was estimated to be 800 nm using Dektak 150 (Vecco, USA). The band gap of the film was calculated using the Tauc plot [28]. For studying the ferroelectric behavior SBN60 thin film was deposited at optimized parameters on platinized silicon substrate using PLD technique. Rf sputtering technique was used to deposit the top electrode of platinum using shadow mask of diameter 200 μm. The metal-ferroelectric-metal (MFM) configuration was then used to estimate the dielectric constant using keithley 4200 semiconductor characterization unit. Dielectric studies were performed to confirm the ferroelectric behavior of the prepared film.

Table 1
Optimized deposition parameters for growth of SBN film using PLD technique.

Chamber Parameters	Value
Oxygen pressure	10 mTorr
Target to substrate distance	5 cm
Substrate temperature	800$°C$

To measure the dynamic response of the effective electro-optic coefficient, the as-deposited SBN thin film acts a waveguide. The evidence of the number of modes excited are given by Prism coupling technique. The SBN60 thin film (or waveguiding layer) deposited over fused silica substrate is placed in the vicinity of a right-angled rutile prism maintaining a small air gap separation between the prism base and SBN thin film. High index Rutile prisms (**TiO_2**) are employed to obtain a bright streak of light referred as m-line as an output of the guided modes [29]. The waveguide modes are excited in the guiding layer only when the beam is incident at an angle greater than critical angle(θ_c). Theoretical simulations were performed using Opti-wave simulation software - Opti-FTDT to ensure the guiding of Transverse Magnetic (TM) modes in SBN60 thin film. The poynting vector and the refractive index profile were also investigated. After guiding the laser beam across the SBN60 thin film, the electrooptic measurements were carried out using experimental setup based on Senarmont compensator technique [26]. The experimental setup consists of a He-Ne Laser (Power = 2 mW, wavelength, λ = 633 nm), Polarizer, Analyzer, Quarter wave plate, SBN thin film sample and a Photodetector as shown in Fig. 1. Fig. 2 (a) shows the alignment of the optical components used in the experimental setup (Fig. 1). With respect to the principal birefringence axis of the SBN60 thin film, the axes of the polarizer and the quarter-wave plates used in the experimental setup are at 45°. The laser light was incident on the SBN thin film sample through a polarizer. The guided light from the SBN film is incident on a quarter wave plate which further introduces a phase shift of 45° between the ordinary and extra-ordinary ray. After passing of light through a crossed analyzer, it is detected using a photodetector. A lock-in amplifier (Stanford Research Systems, SR830) is connected to the output of photodetector to measure very small changes in the transmitted optical signal.

Two planar electrodes of Ag metal having a separation of about 5 mm between them were patterned on the surface of SBN60 thin film to apply an electric field of fixed amplitude (10 V) and varying frequency (10 Hz–25 MHz) using a function generator (Model: Tektronix AFB3021B). The transmitted light was passed through the quarter wave plate placed parallel to the optical axis of the SBN60 sample (Fig. 1). Finally, the light transmitted was detected after passing it through an analyzer using a photodetector (Make: Newport, Model: 818-UV). The photodetector signal was measured using the lock-in amplifier. Fig. 2(b) depicts the prism coupling arrangement used to couple the light across the SBN60 thin film. The ac electric field $\overrightarrow{E}$ is applied across two electrodes in x-direction with propagation of streak of light in z direction. In order to calculate the value of the effective electro-optic coefficient (r_c), the peak-to-peak transmittance voltage (V_{pp}) needs to be evaluated. Fig. 2 (c) shows the variation of the transmitted light intensity and the applied modulating voltage ($V_{app} sin\omega_m t$) having modulating frequency ω_m in Senarmont compensation method with $V_{app} \ll V_\pi$. The effective electro-optic coefficient in terms of V_{pp} and V_{out} can be represented as [26,27]:

$$r_c = -\frac{4\lambda}{\pi n_e^3}\left(\frac{t}{l}\right)\left(\frac{\Delta V_{out}}{\Delta V_{app} V_{pp}}\right) \quad (1)$$

where, λ corresponds to the wavelength of incident light, ΔV_{out} refers to the small change of the rms value of output voltage on application of electric field measured using the lock-in amplifier, ΔV_{app} represents the rms modulation voltage, V_{pp} refers to the transmittance voltage of half wave points corresponding to zero electric field, n_e is the effective refractive index of SBN thin film (2.21), t represents the thickness