

Comparison of wave evolution in triangular index planar waveguides using different metal oxide cores

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Abstract— Waveguides fabricated with nonlinear materials have potential applications to act as inter connectors, optical switches and routers. In the present study planar waveguides of nonlinear metal oxides MgO, TiO₂ and ZnO as core material with a triangular refractive index profile are modeled for various input wavelengths. The variation in refractive index with input wavelength induces nonlinearity in these waveguide structures. A numerical continuation procedure is employed using an initial soliton solution for a triangular refractive index profile. An oscillatory wave path in the waveguide structures is seen to result. By doping an increase in refractive index of the core is achieved whereby oscillatory nature can be eliminated.

Index Terms—Oxide waveguides, doped ZnO, high refractive index oxides, nonlinearity, waveguide modes, soliton.

I. INTRODUCTION

Nonlinear optics has revolutionized telecommunications and computer technology today. The long interaction lengths and small cross-sections in waveguides allow attainment of high peak intensities for low energy optical pulses. This also compensates the weak nonlinearity in many transparent optical materials. It is highly possible that the linear technology may be replaced by a nonlinear one with the latter transmitting trains of pulses as solitary waves^[1]. The materials formed from group II-VI elements are potential candidates for various photoluminescence studies. The bonding in these materials is partly ionic due to the result of electronic charge transfer from group II to IV atoms. Further semiconductor nanoparticles of group II-VI compound have band gaps greater than 1 eV^[2,3] making them efficient light emitters. Some of the exciting properties exhibited by these nanoparticles are blue shift of optical absorption spectrum^[3], size dependent luminescence^[4], enhanced oscillator strength and nonlinear optical effects^[3,4]. Particularly, nanostructured semiconducting materials offer large optical nonlinear susceptibility and ultra fast response^[2, 6]. They can also be used for the realization of thermally stable and frequency selective lasers and photo detectors whose performance have been found to be modulated drastically by the shapes and sizes of nanocrystallites^[18]. In this context ZnO is a direct band gap semiconductor with an energy gap of 3.37 eV and a large exciton binding energy of 60 MeV at room temperature, which is 2.4 times the effective thermal energy ($K_{BT} = 25\text{MeV}$) at room temperature with a bi-excitation energy of

ZnO being 15 MeV^[11]. MgO is another promising material which has a wide gap of 7 eV. The unique properties make these oxides promising candidates for applications in optical and optoelectronic devices^[6,7,8]. These materials provide the basis for many nonlinear optical devices as well^[23]. For instance transverse linear refractive index variations in nonlinear media profile such as a triangular profile can vary soliton properties in such media. An oscillatory nature for soliton is reported in such media^[19]. The period of such oscillation is determined by the waveguide parameters as well as the soliton amplitude^[27]. Second order optical response is seen in ZnO thin films grown by laser deposition^[28], reactive sputtering^[29], spray pyrolysis^[30] etc. Second Harmonic Generation measurements strongly depend on the material crystalline structure. The crystalline nature of metal oxides such as MgO, ZnO etc. offer the possibility of structural analysis pertaining to SHG in these structures^[31,32,33] in the near IR^[35] and mid IR regions^[34,35]. The refractive index variations in silicon based devices have dominated the micro electronics industries to a greater extent. Nevertheless these nanostructured materials are useful for several applications, understanding of nonlinear properties is essential for exploring other possible applications. The present work is aimed to compare the nonlinear properties of ZnO, MgO and TiO₂ metal oxides through simulation. The oscillatory nature will be studied with respect to various initial soliton solutions for the numerical continuation. The field mode distributions for an incident wavelength between 400 nm– 600 nm will be simulated and compared with relevance to solitary propagation.

II. THE TRIANGULAR REFRACTIVE INDEX PROFILE

The role of light is important in the context of nonlinear realm as it modifies properties such as refractive index, absorption and mode field distributions of the medium. A spatial soliton can be considered as a state of self-trapped optical beam. A soliton is formed as a result of robust balance between the diffraction and self-focusing induced due to nonlinearity^[19]. The material dispersion is due to the index of the core; $\bar{n}(\omega) = n_1(\omega) - \delta n_w(\omega)$ where $n_1(\omega)$ is the index of the core (contributing to material dispersion) and $\delta n_w(\omega)$ contributes to waveguide dispersion with

$\bar{n}(\omega)$ as the mode index ^[1]. In a nonlinear dielectric which has a focusing nonlinearity, a light beam may be naturally confined as a result of a balance struck between diffraction and nonlinear focusing ^[36]. In a nonlinear bulk media, a soliton retains its shape and velocity throughout its path ^[20]. A transverse linear refractive index variation is significantly important in such media as it affects the various soliton properties. Also, a soliton in a homogeneous medium with a local nonlinearity may be treated as a particle moving with constant velocity. However, this nature can be easily perturbed so as to disturb the soliton transversal velocity, if an inhomogeneous refractive index variation is induced in the local nonlinear medium ^[24]. For a nonlocal nonlinear medium, the refractive index modulation may be modeled with a slight perturbation of the Nonlinear Schrodinger Equation (NLSE) ^[25]:

$$i \frac{\partial A}{\partial z} + \frac{1}{2} \frac{\partial^2 A}{\partial x^2} + |A|^2 A = -VA \quad (1)$$

where $V = \Delta n(x) + n_{non}(x)$. The latter nonlocal component is $\mu \frac{\partial |A|^2}{\partial x}$ with μ denoting the magnitude of nonlocal nonlinearity. The linear refractive index distribution having a triangular profile ^[19, 26]:

$$\Delta n(x) = \begin{cases} 0 & x < -b \\ \Delta n_0 \left(1 + \frac{x}{b}\right) & -b \leq x < 0 \\ \Delta n_0 \left(1 - \frac{x}{b}\right) & 0 \leq x < b \\ 0 & x \geq b \end{cases} \quad (2)$$

Here, the parameter μ tends to take a small value when nonlocal nonlinearity is small as compared to the local one and $2b$ denotes the normalized width of waveguide. Thus, optimizing the width of waveguide can bring about variations in the maximum refractive index, Δn_0 and the Gaussian index distribution in effect. The refractive index profile $\Delta n(x)$ also varies according to maximum variation in the refractive index which is of relevance to the current investigation. With respect to varying mode field distributions, this gives a validation for the possibility of solitary passage in such structures. The propagation characteristics of guided wave are a result of guided-wave field satisfying proper boundary conditions at the interface of two different media and necessary radiation conditions ^[9]. However, the fundamental property of a planar waveguide is the relation between the number and nature of waveguide modes propagated and its refractive index. The number of modes the waveguide can support depends on the waveguide parameter $V = 2\pi \frac{2L}{\lambda} \sqrt{n_0^2 - n_1^2}$ where L is the path length; n_0 is the index of the guiding layer, n_1 the index of the cladding layer and λ is the vacuum wavelength of light. Optical nonlinearity in waveguides allows switching actions

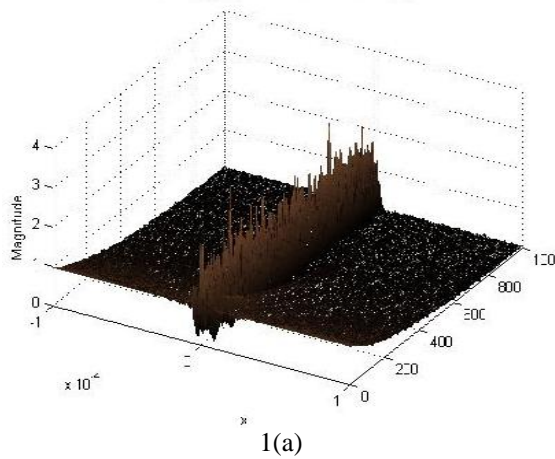
as an integrated structure which are critical to a high-speed communications network ^[36]. The intrinsic $\chi^{(3)}$ nonlinear response induces an intensity dependent change in the mode propagation constant. A thin planar waveguide is a sandwiched structure with a core having the highest refractive index. With air as the upper cladding, confinement of the mode is enhanced, as in the present investigation. This acts in itself as a waveguide structure with the role of upper cladding. The confinement of light employing total internal reflection as in optical fibers is the same in such a waveguide also ^[21,35,36]. In the case with arbitrarily shaped fibers and waveguides, integral representations for the longitudinal electric and magnetic fields are needed to satisfy the appropriate wave equations and all boundary conditions. The envelope of a TE wave transmitting in a nonlinear dielectric with refractive index $n^2(x, |F|^2)$ is given as ^[36]

$$2i\beta \frac{\partial F}{\partial z} + \frac{\partial^2 F}{\partial x^2} - (\beta^2 - n^2(\frac{c}{\omega} x, |F|^2))F = 0 \quad (3)$$

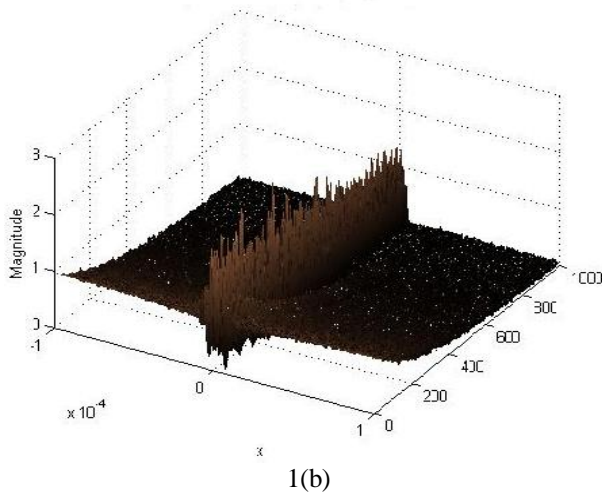
By employing the analytic continuation technique, the relevant integral equations may be reduced to linear algebraic equations which may be solved to obtain the propagation constants¹⁰. In this work, numerical analysis of ZnO, MgO and TiO₂ waveguide structures is carried out. The mode field distributions were plotted using Matlab ^[37,38]. The dependence of field distributions with input wavelength and refractive index is plotted. ZnO with a refractive index value, $n_2=1.975$ and MgO with a refractive index of 1.7375 were considered. Also a considerable increase in a doped structure of ZnO with silver (SZO), $n_2=2.0037$ was compared with that of TiO₂, $n_2=2.49621$ (Fig 3(a) and (b)) ^[38, 39]. The silica substrate with a lower refractive index was taken to be $n_1=1.456$. The waveguide structure was completed by considering a lower refractive index of air cladding, $n_3=1.000$.

In the above simulations, we have considered two separate initial single soliton solutions, $u(x,0) = A \operatorname{sech}^2\left(\frac{x-x_0}{w_0}\right)$ and $u(x,0) = A \operatorname{sech}(A(x-\bar{x}_0))$ where A and \bar{x}_0 represents the amplitude and initial position of the soliton respectively. The evolution of a spatial soliton for various metal-oxide-core waveguide materials are demonstrated in Figure 4(a-d). For a higher refractive index ZnO, less dispersive characteristics compatible with the mode field distribution is observed. In Fig (4(c) and 4(d), an oscillatory nature of the soliton ^[19, 27] is seen. It is not symmetric around the oscillation centre which can be accounted to the asymmetric nature of the waveguide with $n_3=1.000$ (air) as the upper cladding. The simulations were modeled for a waveguide width of 0.5um and an input wavelength of 500 nm ^[38]. The increase in the input wavelength to 600 nm produced increased dispersive effects due to incompatibility with the waveguide width. The nature of the evolving pulse by

varying the waveguide width is also analyzed here. The oscillatory nature may not be quite useful for long distant communication, as is seen to be more pronounced when the local nonlinearity, μ is increased.

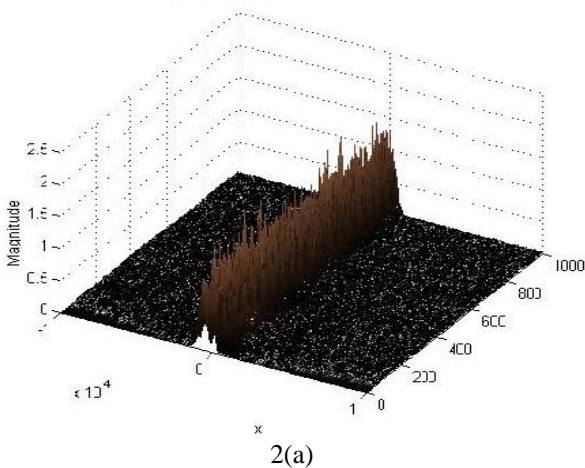


1(a)

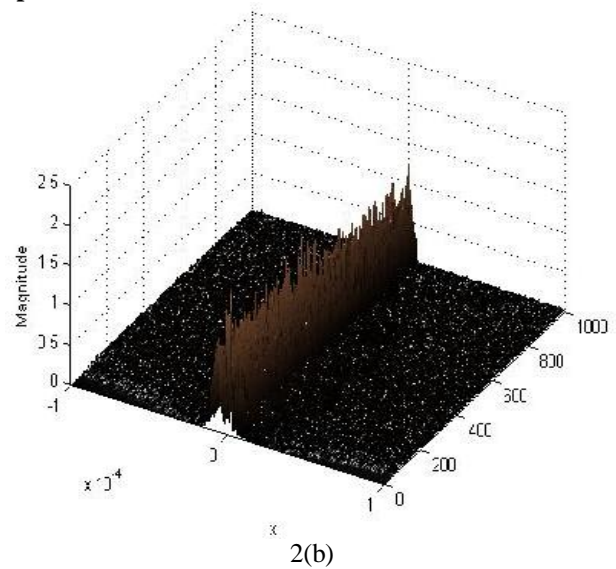


1(b)

Fig 1: Magnitude of propagating solitary pulse with single soliton solution $u(x,0) = A \operatorname{sech}(A(x-x_0))$ for (a) MgO core waveguide structure ($n_2=1.7375$) (b) for ZnO core waveguide structure ($n_2=1.975$)



2(a)



2(b)

Fig 2: Magnitude of propagating pulse with an initial soliton solution $u(x,0) = A \operatorname{sech}^2\left(\frac{x-x_0}{w_0}\right)$ for (a) MgO core waveguide structure ($n_2=1.7375$) (b) for ZnO core waveguide structure ($n_2=1.975$)

III. ANALYSIS OF HIGHER REFRACTIVE INDEX CORE WAVEGUIDES

Experimental analysis of Ag doped ZnO has revealed interesting changes in physical and chemical properties at the nano scale such as crystallinity, optical transmittance, absorption and refraction patterns etc.^[11-12]. These doped waveguides thus in effect can be used for making inexpensive optical devices. The dispersive behavior in accordance with linear losses and Two Photon Absorption (TPA) can be seen around 1000 nm, as per literature. However, we considered variations with wavelength and refractive indices, with the waveguide full width kept at 500 nm. This was chosen so as to minimize the dispersive effects and to study the propagation of solitary pulses within these structures. The elliptical field distributions were observed to enable a solitonic wave profile of amplitude:

$A(x) = A_0 \operatorname{sech}(x/a)$ where the radius of the core, a is taken so as to enable nonlinear effects^{38, 39}. In the case with TiO_2 having $n_2 = 2.49621$, it exhibited a lower dispersive regime when compared to the undoped variants. TiO_2 can thus prove to be a worthy candidate for fabrication of nonlinear waveguides which can facilitate the passage of solitary pulses. It may be remembered that if the nonlocal effect exceeds the effect of the linear refractive index profile, then there is a possibility for the soliton to exceed from the waveguide. The importance of increasing the refractive index via doping, thus becomes prevalent. Increasing the refractive index increases solitary confinement. The initial soliton solution with a variation in the waveguide width can yield a passage of a soliton, for the otherwise oscillatory nature in the case of a triangular refractive index profile.

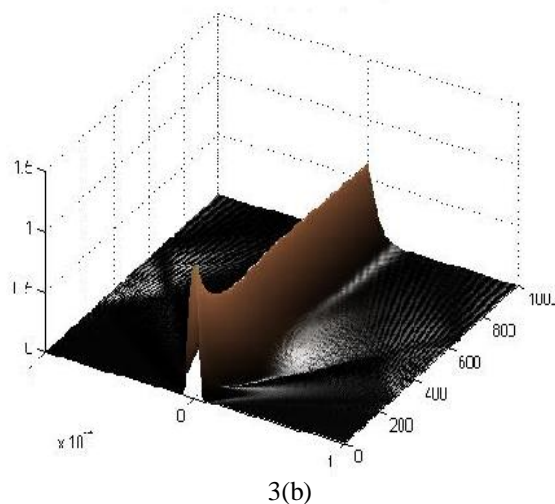
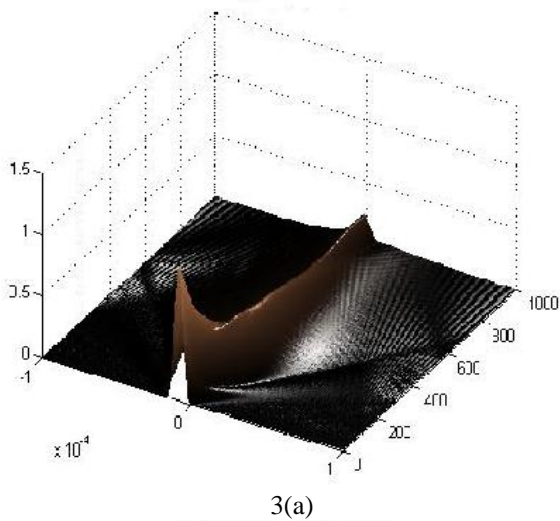


Fig 3: Possibility of a soliton path in a higher index TiO₂ core by optimizing the waveguide width to 0.6 um with an initial soliton solution $u(x,0) = A \text{sec} h^2 \left(\frac{x-x_0}{w_0} \right)$
 (a) SZO core (n₂= 2.0037) (b) TiO₂ core (n₂= 2.49621)

IV. CONCLUSION

The research studies on interaction of optical fields with nonlinear media are of great importance now days. The present investigation focuses on the possibility of propagation of intense optical fields through nonlinear media and their applications in various fields such as soliton fission, superluminescence etc. The nonlinear waveguides were simulated using Matlab with air as the upper cladding, n₃= 1.000. The waveguide width (FWHM) was kept constant at 500 nm, so as to induce nonlinear effects. In a lower refractive index, MgO (1.7375), dispersive effects were seen to be enhanced whereas in a higher refractive index, TiO₂, reduced dispersive effects were noticed. The triangular refractive index profile in the undoped waveguide structures traced an oscillatory soliton path. This can be eliminated by optimizing the waveguide width and the input wavelength upon propagation in such profiles. The variation

in the waveguide width in addition to an enhanced refractive index (local nonlinearity) boosts the propagation of a solitary pulse across the length of the waveguide. Also this supports the fact of a diminishing nonlocal effect due to an increase in the maximum refractive index variation.

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