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Modeling of Complex Solitary Waveforms for Micro-Width Doped ZnO Waveguides

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ABSTRACT

The potential applications of metallic oxides as supporters of nonlinear phenomena are not novel. ZnO shows high nonlinearity in the range 600 - 1200 nm of the input wavelength [1]. ZnO thus make way to become efficient photoluminescent devices. In this paper, the above mentioned property of ZnO is harnessed as the primary material for the fabrication of waveguides. Invoking nonlinear phenomena can support intense nonlinear pulses which can be a boost to the field of communication. The modeling characteristics of undoped and doped ZnO also confirm the propagation of a solitary pulse [1]. An attempt to generalize the optical pattern of the doped case with varying waveguide widths is carried out in the current investigation. The variations below 6 um are seen to exhibit complex waveforms which resemble a continuum pulse. The input peak wavelength is kept constant at 600 nm for the modeling.

Keywords: Solitons; Nonlinear Optics; Doped ZnO Waveguides; Continuum

1. Introduction

ZnO has recently attracted wide interest for its unique properties and versatile applications in the fields of piezoelectric devices, light sensors, spintronics [2-10] and acoustic wave devices [11,12]. Nanostructured electrodes of ZnO have also been used as solar cells [13] with its physical and chemical properties that can be varied by adequate doping by cationic or anionic substitution. Doping with B or Mn decreased the resistivity [14,15] or introduced ferromagnetism [16] respectively. The optoelectronic properties are generally affected by impurities and defects. Impurity incorporation thus plays a dominant role in the possible applications of ZnO in the field of optoelectronics.

The effect of Ag as a Group 1 element is a candidate acceptor for ZnO. Ag doping could greatly increase the catalytic doping and photo activity in semiconductors [17,18]. The silver atoms may be incorporated into the lattice sites of ZnO only as the substitution of the Zn atom sites [19]. Thus the doping with Ag requires systematic investigation. The silver ions have novel applications of shifting the emission spectrum of doped ZnO beyond the UV-blue region making it a promising candidate for communication via the propagation of solitary pulses.

2. Theory

The Guiding Phenomena

For any waveguide a refractive index larger than the surroundings is needed. Planar waveguides allow confinement in one direction though diffraction may occur along the plane of the film. Fiber and channel waveguides allow cross-sectional dimensions with the size of confinement to be the order of the wavelength [20]. As a result higher intensities for a given input power can be supplied as the effective beam area is minimized in a waveguide. In effect, the guided wave field is maximum in the region of high index and decays with distance into the media of lower index. Nonlinearity can therefore be either in the core or the surrounding media. However dominance of the nonlinear phenomena with optimum efficiency is mostly seen in the core region.

The propagation constants with their corresponding eigen modes depend on the dimensions of the high-index (core) region, the geometry of the waveguide structure, and the refractive index of the wave guiding media. The modes, TE and TM with E or H in the plane of the surfaces, need to be orthogonal to one another and should occur in two unique polarizations. The two orthogonal modes dominate though the fields contain contribution from all three polarizations. Any degeneracy in the corresponding modes can cause birefringence which can be termed polarization preserving in that specification to support two orthogonally linearly polarized eigen modes [21].

Wave guiding can also introduce reduction in the spatial degrees of freedom which can in turn limit the propagation wave vectors to two dimensions in planar waveguides or to one dimension in fiber and channel guides. This greatly benefits nonlinear interaction associated with intensity dependant refractive index. Wave vector interactions that result can be accomplished by adjusting the lengths at which these wave vector interactions occur.

It is possible to excite the waveguide modes from the sides or from the ends of the waveguide. The angle of incidence is so chosen that only one mode is excited at a time for plane wave incidence. Optically aligning the waveguide to the incident beam allows almost all the guided-wave power to be launched in to lowest-order mode with appropriate polarization.

Many $\chi^{(2)}$ phenomena have been demonstrated in planar waveguides such as second-harmonic generation, difference frequency generation, optical parametric amplification and optical parametric oscillation. SHG has been widely studied of these, though restricted mainly to the field of integrated optics. As for the simplest case of SHG, a single fundamental guided wave is excited at $z = 0$ propagating to $z = L$ where it leaves the waveguide along with the second harmonic generated between 0 and L. The second harmonic power, $P(2\omega, z)$ is given in terms of the fundamental input power [21] $P(\omega, 0)$ by

$$P(2\omega, L) = (k_0 L)^2 \frac{d_{eff}^2}{n_{eff}^3} \frac{\sin^2\phi}{\phi^2} \left|K^2\right| P^2(\omega, L)$$

Here $P(2\omega, L)$ is the second harmonic power in terms of the fundamental input power $P(\omega, L)$ across the waveguide length L.

The power scaling of the Second Harmonic generation is enables characterization and generalization of the waveguides. Here the waveguide figure of merit is given by $\frac{d_{eff}^2}{n_{eff}^3}$ where n_{eff} is the effective index and d_{eff} the effective waveguide thickness.

Φ is the phase vector, for the simplest SHG condition in terms of the guided wave vectors, $\Phi = 0$, $\Phi = 0.5(\beta_2 - 2\beta_1)$ where 1 and 2 refer to the fundamental and harmonic respectively.

The overlap integral [21], a concept unique to waveguides is given by

$$K = \int_{-\infty}^{\infty} \mathrm{d}x \int_{-\infty}^{\infty} \mathrm{d}y \frac{\mathrm{d}_{ijk}}{\mathrm{d}_{eff}} e_i(2\omega) e_j(\omega) e_k(\omega) \cdot f_i(x, y) f_j(x, y) f_k(x, y)$$

where the terms govern the *product* of the field distributions across the waveguide; the latter if negative reduces the value of K in effect.

The overlap integral is usually small for the field distribution modes. It seems that the existence of modes with different values of the effective index facilitate phase matching. In this case, the overlap integral is extremely reduced or even zero.

In planar waveguides, the angles at which the mode intersections associated with phase matching occurs must be very small so as to satisfy the minimum thickness for the film as required for phase matching. This condition equally lets the birefringence and material dispersion to be quite small [20,21].

3. Doped ZnO on Silica Substrates: Modeling in the Dispersive Regime

The propagation characteristics of the guided wave are obtained provided the guided-wave field satisfies the proper boundary conditions at the interface of two different media (*i.e.*, tangential electric and magnetic-field vectors must be continuous across the boundary) and necessary radiation conditions.Along a straight line path, every component of the electromagnetic wave that propagates may be represented as $f(u, v)e^{-i\beta z}e^{i\omega t}$ [10], where z is chosen as the propagation direction and u, v are orthogonal coordinates in a transverse plane. β is the propagation constant and ω is the frequency of the wave. However, the fundamental property of a planar waveguide is the relation between the number and nature of the waveguide modes propagated and its refractive index [22].

For nonlinear waveguides, integral representations for the longitudinal electric and magnetic fields satisfy the appropriate wave equations and all the necessary boundary conditions. By approximate expansions of these fields and employing the analytic continuation technique [23], the relevant integral equations may be reduced to linear algebraic equations which may be solved to obtain the propagation constants.

The field mode distributions of doped ZnO in the 800 - 1200 nm of the input wavelength have shown increased nonlinear effects. 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. [24, 25]. The doped waveguides can be used for making inexpensive optical devices. The field modes for a doped ZnO waveguide structure, $n_2 = 2.099$, show dispersive behavior in accordance with linear losses and two photon absorption around 1000 nm. However, we have considered variations with waveguide width of 0.6 micrometer and less for an input wavelength of within 600 nm. This was so chosen so as to minimize the dispersive effects and oscillatory behavior of solitary pulses beyond these dimensions [26].

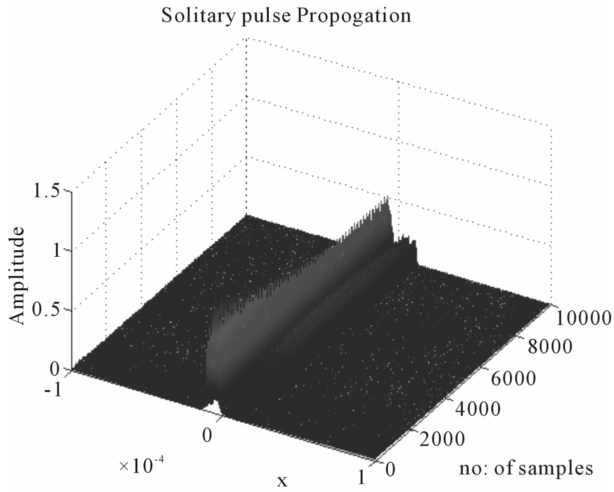
4. Solitary Pulses in Doped ZnO: The Route to Supercontinuum

The interplay of dispersion and nonlinear self-action in wave dynamics has been a major area of interest across many branches of physics since the Fermi-Pasta-Ulam work. Localized nonlinear waves have been often referred to as solitary waves, however today the term' soliton' has been extended over the nonintegrable cases as well. Optical solitons in fibers have been researched much over the years as potential information carriers (Mollenauer and Gordon 2006; Agrawal in 2007). Octave wide spectral broadening was later observed in the beginning of the 21st century which was extensively studied and came to be known as Supercontinuum.

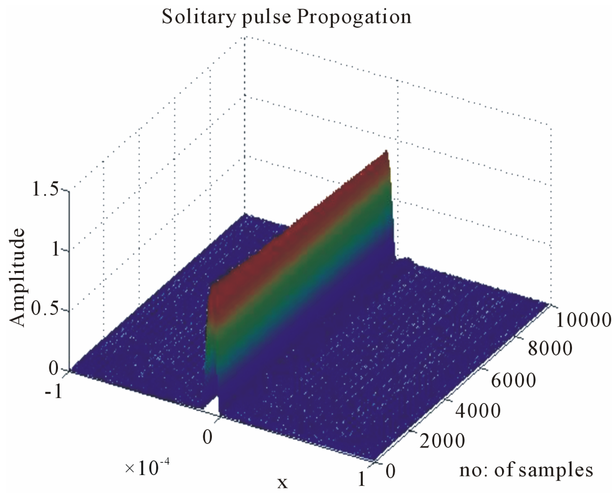
The first experiments of Supercontinuum inadvertently marked the presence of solitons in the process. A fiber with high nonlinearity and the GVD point close to the pump wavelength has large potential for harnessing. Fibers with silica cores (~1 - 5 μm) of a few microns in diameter have been studied extensively with a variety of sources. Investigations with Femtosecond pulses with wavelength around 800 nm (Ranka *et al.*, 2000) and with nanosecond microchirp lasers close to 1 μm (Stone and Knight 2008) gave much promising results. The dispersion profile in the latter exhibited intense supercontinua extending towards the shorter "bluer" wavelengths (Harbold *et al.*, 2002; Efimov *et al.*, 2004).

The modeling of ZnO and the doped structure (Ag-ZnO) confirm the possible passage of a solitary pulse [1]. The solitons show a self-consistency, characteristic of its self-guided nature, to be a mode of the linear waveguide it induces [1,2]. The length of the passage may be extended using a doped form of the initial waveguide. The field mode distributions are found to vary with the input power and the wavelength. Solitons if incorporated in waveguides can revolutionize optical communication systems with their ability to carry information over long distances without a change in shape.

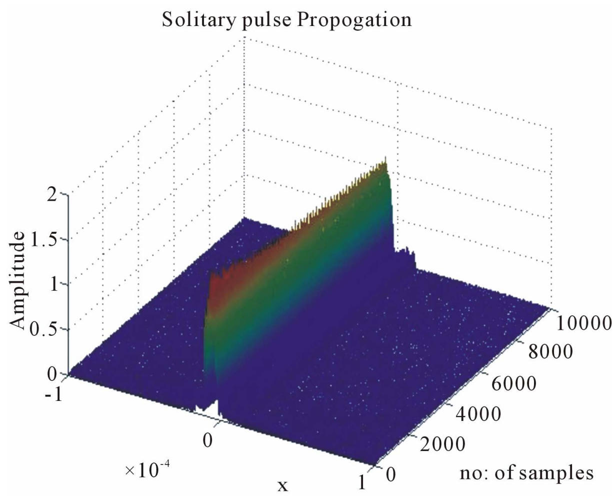
In the current investigation, an index contrast of glass (1.456) to that of air in addition to the increased nonlinearity of the material of the waveguides provides high modal confinement and significant contribution to dispersion. The width of the waveguide structures are varied within and below the 6 μm scale when a continuum pulse is seen to propagate (**Figures 1(a)-(c)**) with variation in the refractive index governing the waveguide width. The width variations show a continuum spectra for the silver doped ZnO structure which confirms the possibility of a supercontinuum in these structures. The propagating pulses retain a continuous solitonic path thus enabling



(a)

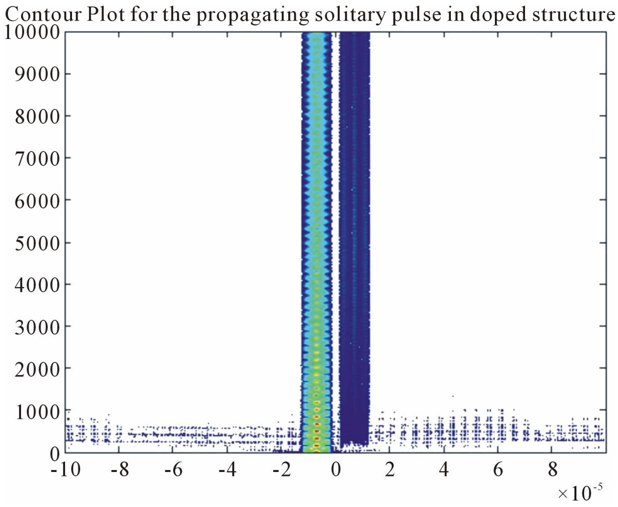


(b)

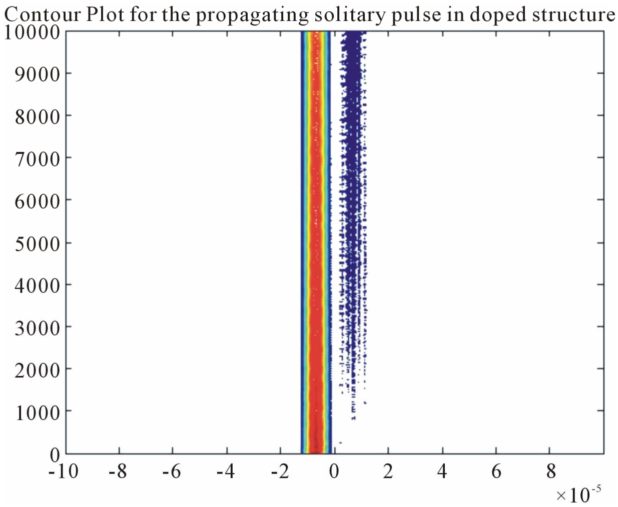


(c)

Figure 1. (a) Solitary propagation for *w* = 1 um at 600 nm peak input wavelength; (b) for *w* = 3 um at 600 nm peak input wavelength; (c) for *w* = 5 um at 600 nm input wavelength.



(a)



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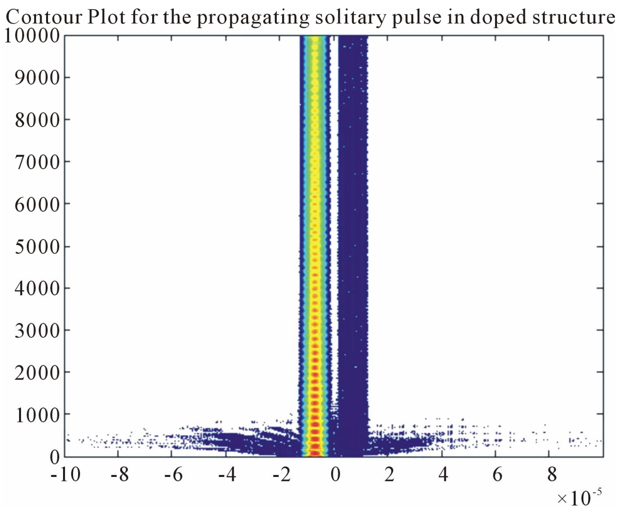

(c)

Figure 2. Contour plots for the propagating continua pulses at (a) *w* = 1 um (b) 3 um (c) 5 um for the input wavelength of 600 nm.

the basic need of low losses in communication. The refractive index of the doped structure (n_2 = 2.099) is particularly important with relevance to the fact that it prevents the dispersive spreading of the radiation waves within the short wavelength range of the continuum. The change in refractive index is seen to exert an inertial force which further ensures a dispersionless propagation of the radiation (**Figures 2(a)-(c)**). Sub-wavelength diameter nanowires have proved to offer effective nonlinearities and interesting dispersion profiles [27]. Such structures enabled ultra-efficient octave spanning for nanosecond and femto second input pulses [28].

In the **Figures 1** and **2** it can seen that an initial pulse, which has an input wavelength of 600 nm, takes form as a solitary pulse when it propagates through the waveguide length. The soliton stability is improved as the width of wave guide is increased which can be directly seen from the figures. The amplitude of the pulse can be optimized using the refractive index variations.

5. Conclusion

Earlier studies carried out in this regard had confirmed solitons for an input wavelength between 800 nm and 1000 nm [1]. In the present study we have varied the waveguide width within a micro range thereby varying the nature of the continuum passing through the waveguide. The doped ZnO waveguide widths below 6 um were considered in the present investigation. The onset of a solitary pulse which was confirmed to be stable without dispersion around 600 nm was exploited. The variation in the solitary propagation resembles closely to continuum propagation.

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