

Recent progress in theory of nonlinear pulse propagation in subwavelength waveguides

(Invited Paper)

Shahraam Afshar V., Wenqi Zhang, M. A. Lohe, and Tanya M. Monro

Institute for Photonics & Advanced Sensing, School of Chemistry & Physics, The University of Adelaide
Adelaide, SA 5005, Australia

Email: shahraam.afshar@adelaide.edu.au

Abstract—High index subwavelength waveguides form a new platform for highly nonlinear photonic devices. This paper reviews the recent progress in the theory of nonlinear pulse propagation in these waveguides and highlights the opportunities that these waveguides have opened up in terms of active photonic devices.

Recently there has been significant interest in design and manufacturing of high index subwavelength waveguides mainly due to their extreme nonlinearity and possible applications for all optical photonic-chip devices. Examples of these waveguides include silicon, chalcogenide, or soft glass optical waveguides, which have formed the base for three active field of studies; silicon photonics [1], chalcogenide photonics[2], and soft glass microstructured photonic devices [3].

It has recently been shown that the standard (scalar) theory of nonlinear pulse propagation (SNPP), which relies on the well-known scalar Helmholtz equation [4], can not provide accurate descriptions of nonlinear phenomena in HIS-WGs [5], [6]. We have recently reported the development of a vectorial nonlinear pulse propagation (VNPP) model that can be employed to describe the nonlinear processes in any waveguides, especially in HIS-WGs. The new VNPP indicates that the propagating modes have significant components along the direction of propagation, which causes the propagating modes to be non-transverse. Based on VNPP, new vectorially based expressions of effective nonlinear coefficient, γ and Raman gain, g_R , have been given. Based on these expressions, we predicted significantly higher values of γ [5] and g_R [6] in the HIS-WG parameter regime compared to those predicted by SNPP. We attributed these results to the large z component of the propagating modes in the subwavelength regime. Fig. 1 left shows the predictions of VNPP and SNPP for the nonlinear coefficient, γ , of a nanowire, made of chalcogenide glasses, for different core diameters. Results in Fig. 1 left demonstrate that VNPP predicts much higher values for γ , in the subwavelength regime. In an attempt to confirm these results, we have been successful in fabricating a suspended subwavelength-core fiber made of bismuth glass [7]. Using this fiber, we have not only achieved a world-record nonlinearity in microstructured optical fibers [8], γ , but also been able to confirm the prediction of VNPP model for γ of subwavelength waveguides [9], see Fig. 1 right.

The new VNPP and vectorial definition of γ , lead to a

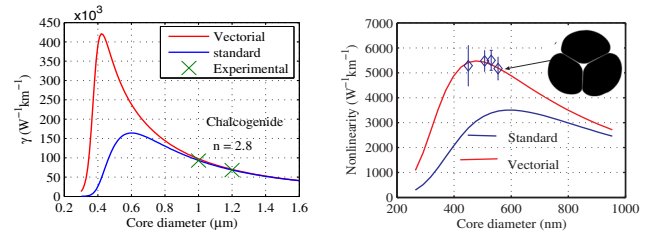


Fig. 1. (Left) γ for a chalcogenide nanowire as a function of core. (Right) γ as a function of core diameter for bismuth suspended core fibers. Experimental results are shown by diamond signs.

new regime of polarization switching which has not been observed before. According to VNPP, the interactions between polarizations of waveguide modes can be described by the following coupled nonlinear Schrödinger equations,

$$\frac{\partial A_j}{\partial z} + \sum_{n=1}^{\infty} \frac{(i)^{n-1}}{n!} \beta_{jn} \frac{\partial^n}{\partial t^n} A_j = i(\gamma_j |A_j|^2 + \gamma_c |A_k|^2)A_j + i\gamma'_c A_j^* A_k^2 \exp(-2i\Delta\beta_{jk}) \quad (1)$$

in which $A_{j,k}$ ($j, k = 1, 2$ and $j \neq k$) are the amplitudes of the fields with two polarizations, β_{jn} are the n -th order propagation constants of the two polarizations, $\Delta\beta_{jk} = \beta_j - \beta_k$ is the linear birefringence, γ_j , γ_c and γ'_c are the effective nonlinear coefficients representing self phase modulation, cross phase modulation and coherent coupling of the two polarizations, respectively [4]. The vectorial definitions of γ_1 , γ_2 , γ_c , and γ'_c in VNPP model show that in general $\gamma_1 \neq \gamma_2 \neq \frac{3}{2}\gamma_c \neq 3\gamma'_c$ which is contrary to what is commonly used in SNPP. SNPP uses the approximations, $\gamma_1 = \gamma_2 = \gamma$, $\gamma_c = 2\gamma'_c = (2/3)\gamma$, which is based on the fact that (a) the waveguide material is isotropic and has only electronic-based Kerr nonlinearity, (b) the two polarized modes have same effective mode area [5]. These approximations work well with low index contrast and large dimension waveguides but are no longer appropriate for HIS-WGs. VNPP model and the resultant inequality $\gamma_1 \neq \gamma_2 \neq \frac{3}{2}\gamma_c \neq 3\gamma'_c$ indicate that optical waveguides with isotropic and electronic-based Kerr nonlinear materials can also display anisotropic nonlinearity due to the difference in the mode field distributions and the z -component (along the direction of propagation) of eigenmodes of the two polarizations.

It can be shown that Eqs. (1) lead to two classes of steady polarization states, one of which is unstable and results in polarization switching [10], [11]. We focus on this class of steady state but unstable solutions which do not exist if $\gamma_1 = \gamma_2 = 3/2\gamma_c = 3\gamma'_c$, which is the common assumption of SNPP. For these steady state and unstable solutions, polarizations with certain initial powers P_1 and P_2 and phase difference $\Delta\phi$ do not change as they propagate through a waveguide. Any small perturbations in powers or phase difference push the fields away from these steady states, however, the fields do not become chaotic, rather both the powers and phase difference are periodic functions. The period T can be expressed as a function of the waveguide parameters, initial power and phase of the input fields.

For switching solutions, the phase difference between the two polarization vectors experiences abrupt phase shifts through π as the light propagates within the waveguide. As a result, the state of polarization flips between two well-defined polarization states, where the flipping angle depends on fiber parameters and initial condition. Figure 2 shows an example of switching behavior of the polarization state for which the $a = b = 2$ with $p_{10}/(p_{10} + p_{20}) = 1/2$ and $\Delta\phi = (\phi_{10} - \phi_{20}) = 10^{-4}$. Here a and b are dimensionless parameters related to the input power and the parameters of the fiber by $a = -\Delta\beta/\gamma'_c P_0 - (\gamma_c - \gamma_2)/\gamma'_c$ and $b = (\gamma_1 + \gamma_2 - 2\gamma_c)/2\gamma'_c$ and $p_{10}, \phi_{10}, p_{20},$ and ϕ_{20} are initial powers and phases of the two polarizations. This example corresponds to a linearly polarized input laser beam in which the polarization vector makes an angle of 45° to either of the principle axes of the waveguide. We plot $v = p_1/(p_1 + p_2)$ and $\cos(\theta/2 = \Delta\phi)$ as functions of dimensionless length $\tau = 2\gamma'_c P_0 z$, showing the periodicity of these functions and the switching behavior of $\cos(\theta/2 = \Delta\phi)$. Since $v_0 = 1/2$, the angular flipping of the polarization vector is $\pi/2$, because $\cos(\theta/2 = \Delta\phi)$ flips between values ± 1 as shown in the inset of Fig. 2. This in principal can lead to optical limiting or switching devices [12].

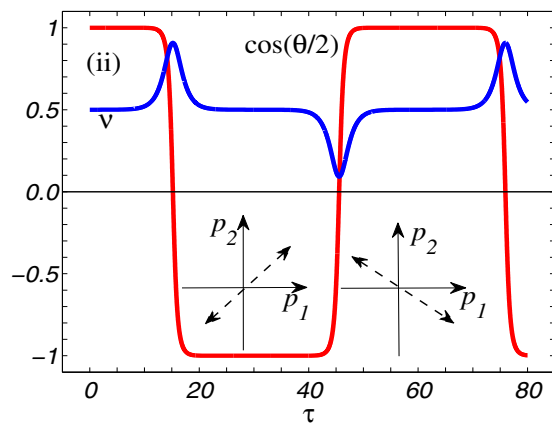


Fig. 2. (a) v and $\cos(\Delta\phi)$ as functions of normalized length τ . The polarization state flips by $\pi/2$ as the laser light propagates.

I. CONCLUSION

High index contrast and subwavelength dimension waveguides have opened up a new era in the field of nonlinear guided optics both in terms of fundamental theories and applications. We have presented a new vectorial nonlinear pulse propagation (VNPP) model to describe nonlinear processes in these waveguides, demonstrated significant differences between the predictions of VNPP and SNPP for Kerr nonlinear coefficient and Raman gain, γ, g_R , respectively, confirmed experimentally the prediction of VNPP for higher γ , compared to that of SNPP, and predicted a new regime of nonlinear polarization switching.

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