Laser Beam Guiding by Self-Tightening Photonic Lattice

A. Apolinar-Iribe, F. Marroquín Gutierrez, N. Korneev, and Victor A. Vysloukh

***Abstract*—In this paper, we report experimental results on laser beam guiding by a self-tightening lattice photo induced in a strontium barium niobate (SBN) photorefractive crystal. In such setting, optical lattice (or periodical array of strongly-coupled waveguides) gradually transforms into array of weakly coupled ones. Experimental data are supported by computer simulation, which revealed crucial role of induced modulation instability in the strong laser beam guiding.**

***Index Terms*—Optical lattices, photorefractive medium, waveguiding array.**

I. INTRODUCTION

NONLINEAR propagation of light in a structure with periodically varying refractive index has attracted interest recently, holding strong promises for applications in photonics. In photorefractive media, it is possible to produce a periodic modulation of the refractive index by illuminating the material with a suitable pattern of interference fringes. The resulting periodic refractive profile acts as an array of optical waveguides (photonic lattice) for any probe beam entering the crystal. Note that photo-induced structures present possibilities to vary not only the lattice period and refractive index modulation depth but also the value and sign of nonlinearity. The advantage of this technique is a possibility to adjust lattice parameters (spacing and refractive index change), which permits to produce structures that might operate in regimes of weak as well as strong coupling between neighboring waveguides. Such structures allow the control of light propagation and provide a platform for experimental studies of fundamental physical phenomena. Spatial solitons propagation has been demonstrated recently in arrays of optically induced waveguides (see [1] for review).

In the simplest light-induced lattice, the solitons propagating in it do not disturb the grating. In photorefractive strontium barium niobate (SBN) crystal, this can be realized by selecting ordinary polarization for lattice waves [1]. The electro-optical coefficient for this polarization is weak, thus the fringes that form lattice do not change their shape in comparison with linear propagation, and the same refractive index pattern is induced by them with and without soliton.

On the other hand, extraordinarily polarized lattices would experience strong self-action and may interact with soliton beams. The strong but anisotropic electro-optic effect of the crystal leads to index changes predominantly for the extraordinarily polarized light. Thus, the periodic light pattern resulting from the multiple-beam interference will induce a periodic optical potential for any extraordinarily polarized probe beams. Moreover, these probe beams will experience strong nonlinear self-action at moderate (microwatt) laser powers. The clarification of conditions of robust propagation of such patterns is of considerable interest, because it allows extension of the concept of optically induced gratings beyond the limit of weak material nonlinearities.

Recently, 2-D nonlinear lattices with chessboard phase structure were demonstrated in highly anisotropic photorefractive media [2]. It was found that due to anisotropy of photorefractive response, refractive index modulation induced by periodic lattice is nonlocal, and it depends on the lattice orientation relative to the crystal axis. A variety of self-trapped periodic patterns were demonstrated by Desyatnikov *et al.* [3], including triangular ones produced by interference of six plane waves, and vortex lattices produced by waves with nested arrays of vortex-type phase dislocations.

Nonlinear photo-induced structures may interact with localized soliton beams. Localized beams produce strong deformations of periodic patterns, and under appropriate conditions, they can form composite states [4]. A variety of stationary composite "lattice–soliton" states of vector cubic nonlinear Schrödinger equation were found with Darboux transformation technique by Shin [5]. In focusing medium, such composite gap solitons supported by nonlinear lattices were observed in $LiNbO_3$ crystals possessing saturable defocusing nonlinearity. Such states appear when a single Gaussian beam is launched at a Bragg angle into a nonlinear lattice [6].

Here we report the experimental results on low-intensity laser beam guiding by the periodic array of self-tightening photo-induced lattices. The remarkable self-compression of periodic wave array during propagation in photorefractive SBN crystal (due to the drift-type focusing nonlinearity) is accompanied by decreasing of the lattice width and by growth of refractive index modulation depth. As a result, coupling of low-intensity light waves guided by neighboring lattices diminishes significantly and the number of modes potentially guided by individual lattice steadily decreases. The periodical array of strongly coupled multimode waveguides gradually transforms into an array of weakly coupled single-mode ones. This feature enriches possibilities of experimentation with

---

Manuscript received December 17, 2007; revised April 11, 2008. This work was supported by CONACyT under the Projects 39681 and 46552.

A. Apolinar-Iribe is with the Departamento de Física, Universidad de Sonora, CP 83000 Sonora, México (e-mail: apolinar@correo.fisica.uson.mx).

F. Marroquín Gutierréz was the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), CP 72000 Puebla, México. He is now with the Departamento de Mecatrónica, Universidad Politécnica de Pachuca (UPP), CP 42830 Hidalgo, México (e-mail: fmarroq@inaoep.mx).

N. Korneev is with the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), CP 72000 Puebla, México (e-mail: korneev@inaoep.mx).

V. A. Vysloukh is with the Departamento de Actuaría, Físicay Matemáticas, Universidad de las Américas (UDLA), CP 72820 Puebla, México (e-mail: victora.vyslooukh@udlap.mx).

Digital Object Identifier 10.1109/JQE.2008.2001948

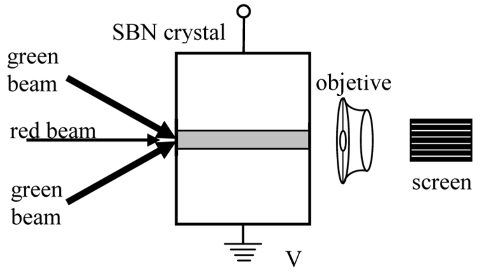

Fig. 1. Diagram of the experimental setup.

lattice solitons, including the case of discrete spatial solitons. It is worth noticing that self-compression is easily controlled by external voltage applied to photorefractive crystal, and also that self-tightening of guiding lattices facilitates low-intensity laser beam launching conditions. In practice, it is one more implementation of the tunable discreteness concept.

II. EXPERIMENTAL SETUP AND RESULTS

In our experiments, we were using a sample of photorefractive ferroelectric strontium barium niobate ($Sr_{0.61}Ba_{0.39}Nb_2O_6:SBN$) crystal sized at 5 mm × 5 mm × 5 mm with two silver paste electrodes deposited onto the faces of the crystal perpendicular to the c-axis. The high voltage was applied to them. The setup utilized in our experiments is depicted in Fig. 1. Additionally, the entire SBN crystal was illuminated perpendicularly to the optical axis with one expanded green beam (532 nm, 100 mW) of a frequency-doubled Nd : YAG laser to produce the uniform illumination of the interelectrode space. An obstacle produced a dark stripe (1.5 mm) through which the two writing green waves and the red wave pass. As a result of this arrangement, all the voltage applied to the crystal falls upon the 1.5-mm-wide stripe, which makes the electric field in this gap higher, and diminishes the risk of electrical breakdown.

Two beams, from a solid state laser (532 nm, 50 mW), with extraordinary polarization were crossing inside the crystal at a small angle (10^{-2}–10^{-3} rad) producing interference fringes with a typical period of 100 μm. Additionally, a relatively wide beam from the He–Ne laser (633 nm, 10 mW) with extraordinary polarization was fed into the region of green beams intersection.

The green fringes and the uniform red beam remain practically altered during propagation along the crystal in the absence of external voltage (Fig. 2). The high voltage (up to 1 kV) application along the c-axis of the crystal (perpendicular to the fringes) results in the formation of self-tightening waveguide array of the green fringes. The green fringes generated for different voltages at the output face of the crystal are displayed in Fig. 2(b). These fringes, projected with a microscope objective to a screen, are recorded with digital camera. The images of green fringes were taken with a digital camera placing a filter to block the red fringes and another filter was used to block the green fringes. The compression ratio was limited to approximately five by the development of transverse modulation instability [7], [8]. The red light beam was trapped by this array of self-tightening photo-induced lattices, and Fig. 2(a) shows the corresponding output intensity distribution. It can be seen that profiles of both output waves are not sinusoidal, but rather described by elliptical functions, and initially strongly coupled photo-induced waveguides transform into the well separated and practically decoupled ones. Notice that if the red beam is slightly tilted, the red light is still trapped inside the self-tightening green lattice at the crystal output.

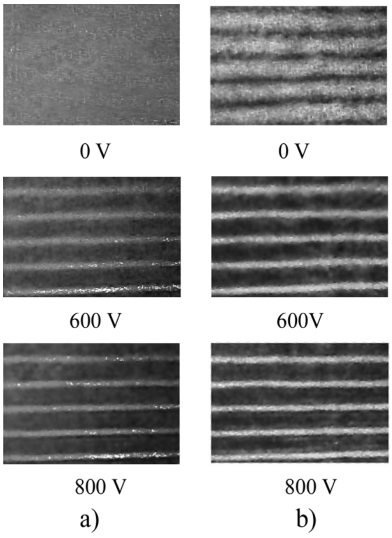

Fig. 2. Output fringes in the near field for different voltages: (a) red light and (b) green light.

Without the microscopic objective, higher diffraction orders can be observed in the far field. Dependences of the first-, second-, and third-order intensities on voltage are presented in Fig. 3(a), for the green light. Typical profile scans of the green fringes are presented in Fig. 3(b) for zero and high voltage applied. It is seen that the main effect of voltage application is simply the compression of fringes with corresponding growth in their maximal intensity.

III. COMPUTER SIMULATIONS

For computer simulations, we have selected the model [8]–[10] based on the system of coupled Schrödinger-type equations for normalized complex amplitudes of the lattice forming (green) wave q_G and the guided (red) wave q_R:

$$\begin{aligned} i\frac{\partial q_G}{\partial Z} &= \frac{1}{2}\frac{\partial^2 q_G}{\partial X^2} + R\frac{\mu|q_G|^2+\nu|q_R|^2}{1+\mu|q_G|^2+\nu|q_R|^2}q_G \\ i\frac{\partial q_R}{\partial Z} &= \frac{1}{2}\rho\frac{\partial^2 q_R}{\partial X^2} + \frac{R}{\rho}\frac{\mu|q_G|^2+\nu|q_R|^2}{1+\mu|q_G|^2+\nu|q_R|^2}q_R \end{aligned} \tag{1}$$

where transverse coordinate is normalized, so the green beam transverse amplitude, for $z = 0$, is $q_G(X,0) = \cos(X)$, longitudinal coordinate $Z = z/L_D$—to the diffraction length $L_D = k_G n_o x_0^2$, the contrast parameters are introduced as $\boldsymbol{\mu} = I_G/I_0, \boldsymbol{\nu} = I_R/I_0$ (I_0 is the intensity of the uniform background illumination and I_G is the peak intensity of the lattice and I_R is the intensity of guided red wave), and $\boldsymbol{\rho} = k_G/k_R, k_G$ and k_R are corresponding wave numbers. The nonlinearity parameter $R = L_D/L_{NL}$, where $L_{NL} = (k_G\boldsymbol{\delta}n_0)^{-0}$ is the

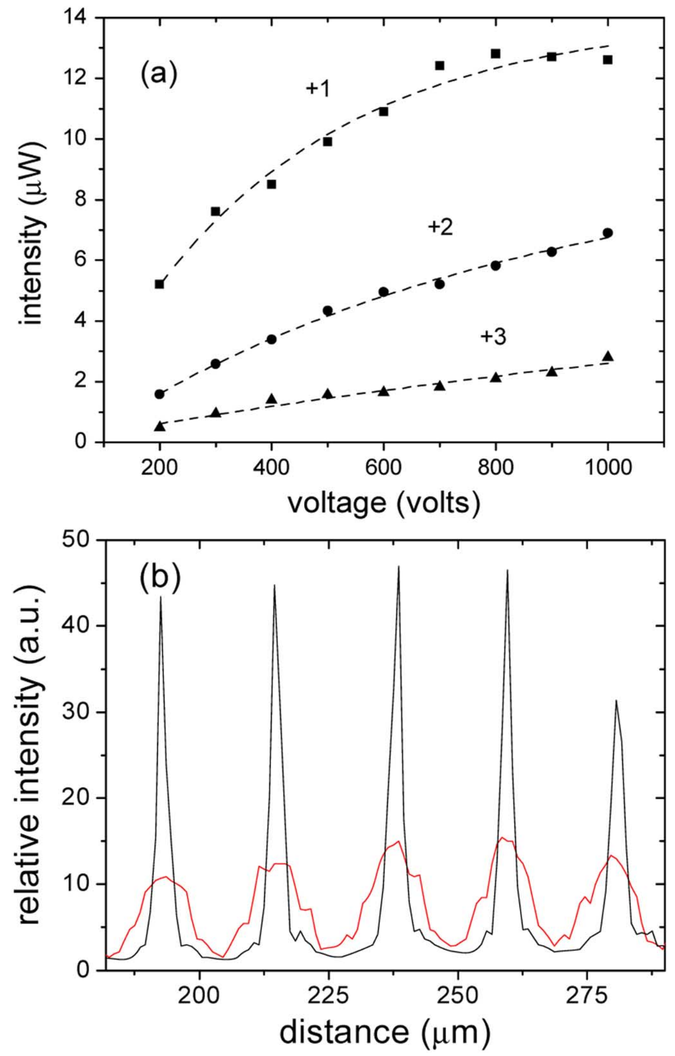

Fig. 3. (a) Intensities of higher orders as a function of voltage applied to the crystal and (b) self-compression of green interference fringes for 0 and 1000 V. The beams intensity after the crystal without external voltage is 92 μW.

self-phase modulation length, $\boldsymbol{\delta} n_0 = r_0^3 E/2, r$ is an effective electro-optic coefficient, and E is the static electric field ($E = V/L$, where V is the external applied voltage and L is the transverse width of the crystal). Equations in (1) were integrated by the beam-propagation method with initial conditions $q_G(X,0) = \cos(X), q_R(X,0) = \exp[-(X/a_0)^2], a_0 \gg 1$ that corresponds to harmonic input grating and Gaussian input beam with a_0 the radio beam.

Note that both waves were launched into the SBN crystal with polarization corresponding to the maximal value of electro-optical coefficient $\boldsymbol{r} = 280$ pm/V, the typical value of diffraction length was $L_D = 7$ mm, the contrast parameter $\boldsymbol{\mu} \cong 0.1, \boldsymbol{\nu} = 0.5$, the nonlinear parameter was varied within the interval $0 < R \leq 50$, and its maximal value corresponded to the static electric field $E \cong 400$ V/mm. For all computer simulations, we neglected wavelength dependence (or dispersion) of the refractive index as well as dispersion of the electro-optic coefficient, taking into account that the relative wavelength difference is not big (around 16%).

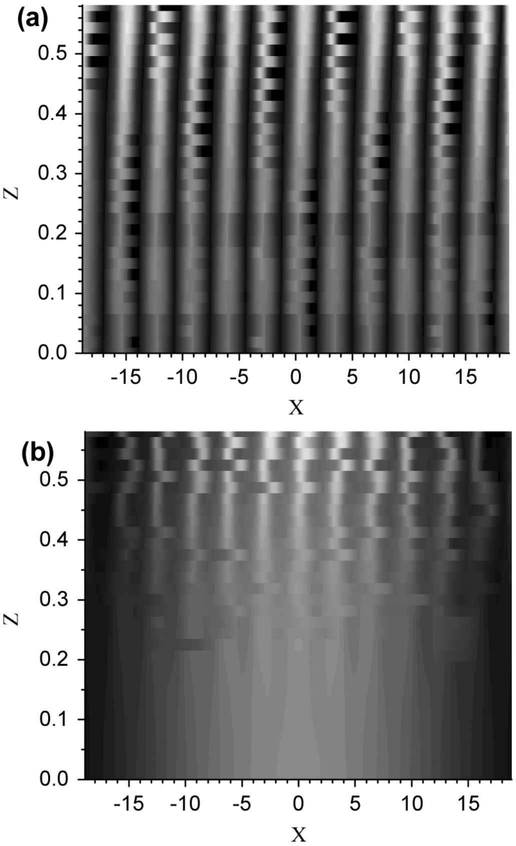

Fig. 4. (a) Computer simulation of self-compression of green interference fringes and (b) cross focusing of wide red Gaussian beam at $R = 20, \mu = 0.25$, and $\nu = 0.125$.

Fig. 4(a) illustrates the results of computer simulation of the self-compression of green interference fringes, and Fig. 4(b) shows dynamics of the red Gaussian beam guided by periodic array of self-tightening lattice. Good agreement with experimental data (Fig. 3) and a surprisingly high contrast of red beam guiding should be pointed out. Fig. 5 illustrates propagation dynamics in a spectral domain. The self-compression of the lattice and trapping of a wide Gaussian beam by array of photo-induced waveguides are accompanied by generation of successive sidebands of the spatial spectra.

The physical picture of high-contrast laser beam guiding by periodic array of self-tightening photo-induced waveguides is far from being trivial. When $\nu \rightarrow 0$ [low-intensity guided beam; see Fig. 6(a)] the mechanism is related to the well-known phase-amplitude conversion: phase perturbation induced due to the cross-phase modulation on the red wave by more intensive green wave transforms into the amplitude perturbation at the distance $L \approx (L_D L_{NL})^{1/2}$. In its pure form, this mechanism might be realized in the limit of the low-intensity guided beam ($\boldsymbol{\nu} \rightarrow 0$) but it leads to relatively low-contrast guiding [Fig. 6(a)]. In other words, it is simply transitory excitation of linear modes of the array of photo-induced waveguides by a wide Gaussian beam, which is governed by the corresponding overlap integral of modal distribution and exiting beam.

When $\nu \rightarrow 0$ (intensive guided beam), the modulational instability enters the scene. It is was shown [7] that for a single

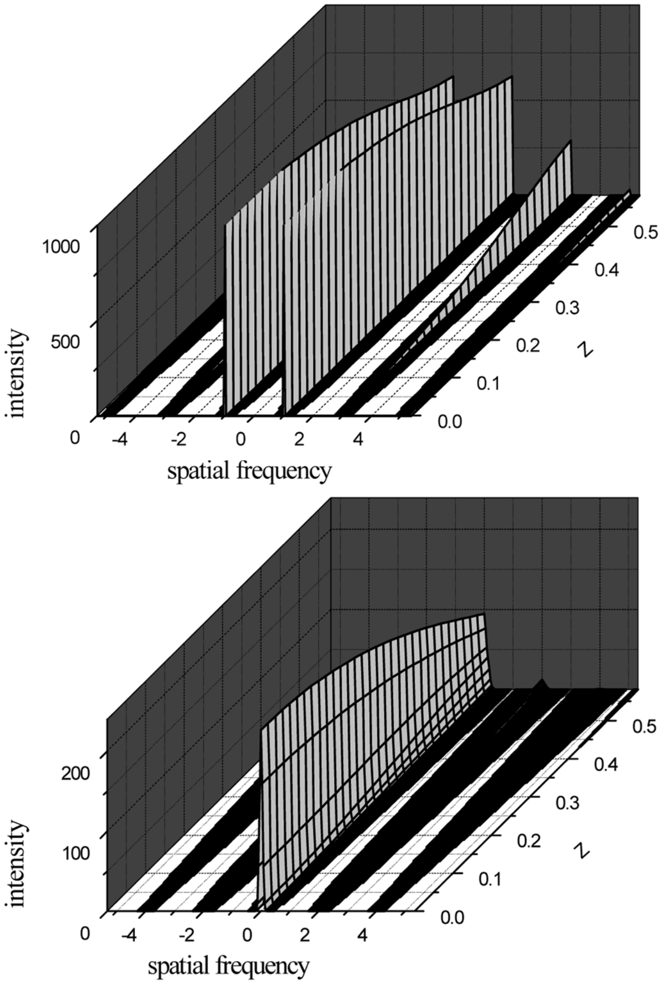

Fig. 5. Calculated enrichment of spatial spectra for (a) green interference fringes and (b) single red beam along the propagation path. The values of parameters are $R = 20, \mu = 0.25,$ and $\nu = 0.125$.

beam in a saturable nonlinear medium, amplitude perturbations grow within the instability frequency band $0 < \boldsymbol{\Omega} < \boldsymbol{\Omega}_{CR}$. In the absence of the lattice $(q_G \rightarrow 0)$, the critical frequency is given by $\boldsymbol{\Omega}_{CR} = 2(Rf)^{1/2}$, where $f = \boldsymbol{\nu} q_0^2/[1 + \boldsymbol{\nu} q_0^2]^2$, and $q_0 \sim 1$ is the amplitude of perturbed red wave. Inside this instability band, amplitude perturbations grow exponentially with the rate $\boldsymbol{\gamma} = \boldsymbol{\Omega}(\boldsymbol{\Omega}_{CR}^2 - \boldsymbol{\Omega}^2)^{1/2}$, so typically, phase-amplitude conversion produces periodical seed perturbations that are further exponentially amplified due to the modulation instability scenario finally producing a high-contrast red wave guiding [Fig. 6(b)].

IV. CONCLUSION

Concluding we point out that results of computer simulations are in a good agreement with experimental data in a space domain (near field) as well as in a spectral domain (far field). Uncovered here, the high-contrast laser beam guiding by periodic array of self-tightening photo-induced waveguides definitely enriches possibilities of light-by-light control and switching. For instance, turning on the green guiding lattice produces more then ten times red beam intensity growth in many lattice sites that is especially interesting for parallel processing of information.

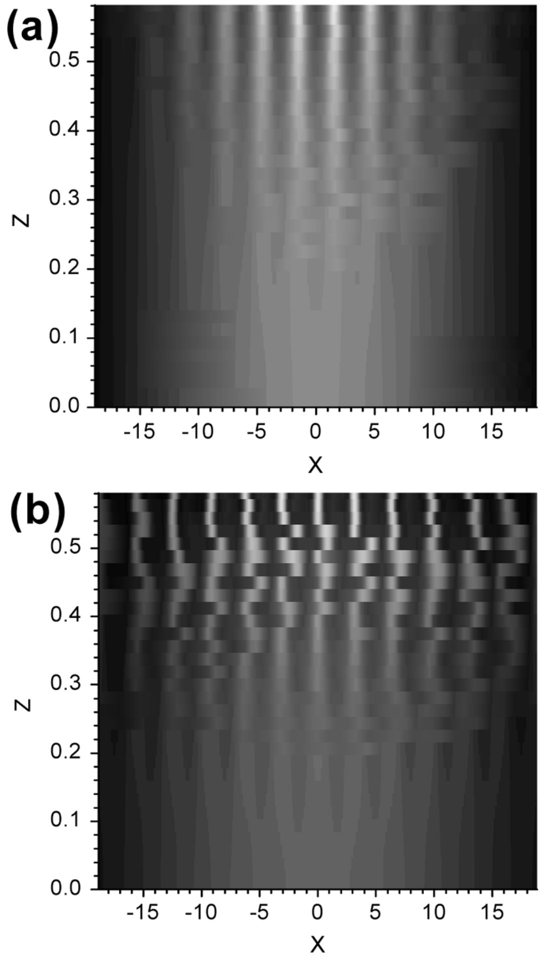

Fig. 6. (a) Cross focusing of low-intensity $(\nu = 0)$ and (b) high-intensity $(\nu = 0.125)$ wide Gaussian beam at $R = 20$ and $\mu = 0.25$.

REFERENCES

[1] J. W. Fleischer, M. Segev, N. K. Efremidis, and D. N. Christodoulides, “Observation of two-dimensional discrete solitons in optically induced nonlinear photonics lattices,” *Nature*, vol. 422, p. 147, 2003.

[2] A. S. Desyatnikov, D. D. Neshev, Y. S. Kivshar, N. Sagermerten, D. Träger, J. Jägers, C. Denz, and Y. V. Kartashov, “Nonlinear photonic lattices in anisotropic nonlocal self-focusing media,” *Opt. Lett.*, vol. 30, p. 86, 2005.

[3] A. S. Desyatnikov, N. Sagermerten, R. Fischer, B. Terhalle, D. Träger, D. D. Neshev, A. Dreischuh, C. Denz, W. Krolikowski, and Y. S. Kivshar, “Two-dimensional self-trapped nonlinear photonic lattices,” *Opt. Exp.*, vol. 14, p. 2851, 2006.

[4] A. S. Desyatnikov, E. A. Ostrovskaya, Y. S. Kivshar, and C. Denz, “Composite band-gap solitons in nonlinear optically induced lattices,” *Phys. Rev. Lett.*, vol. 91, p. 153902, 2003.

[5] H. J. Shin, “Solutions for solitons in nonlinear optically induces lattices,” *Phys. Rev. E., Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 69, p. 067602, 2004.

[6] T. Song, S. M. Liu, R. Guo, Z. H. Liu, N. Zhu, and Y. M. Gao, “Observation of composite gap solitons in optically induced nonlinear lattices in LiNb03:Fe crystal,” *Opt. Exp.*, vol. 14, p. 1924, 2006.

[7] D. Iturbe-Castillo, M. Torres-Cisneros, J. J. Sánchez-Mondragón, S. Chávez-Cerda, S. Stepanov, V. A. Vysloukh, and M. Torres-Cisneros, “Experimental evidence of modulation instability in a photorefractive $\mathrm{Bi}_{12}\mathrm{TiO}_{20}$ crystal,” *Opt. Lett.*, vol. 20, p. 1853, 1995.

[8] A. Apolinar-Iribe, N. Korneev, V. A. Vysloukh, and C. M. Gomez-Sarabia, “Transverse modulational instability of periodic light patterns in photorefractive strontium barium niobate crystal,” *Opt. Lett.*, vol. 27, p. 2088, 2002.

[9] V. Aleshkevich, V. Vysloukh, and Y. Kartashov, “Cnoidal waves compression by means of multisoliton effect,” *Opt. Commun.*, vol. 185, p. 305, 2000.

[10] N. Korneev, A. Apolinar-Iribe, V. A. Vysloukh, and M. A. Basurto-Pensado, “Self-compression of $1+1$D cnoidal wave in photorefractive BTO crystal: An experimental evidence,” *Opt. Commun.*, vol. 197, p. 209, 2001.

A. Apolinar-Iribe received the Ph.D. degree in optics from the National Institute of Astrophysics, Optics and Electronics (INAOE), Puebla, México, in 2000.

Currently, he is a Lecturer and Researcher at the Department of Physics, Universidad de Sonora, Sonora, México, and he is responsible for the Laboratory of Nonlinear Optics. His current research interests are in the areas of nonlinear guided waves and nonlinear optics.

F. Marroquín Gutiérrez graduated in electronics from the Instituto Tecnólogico de Tuxtla Gutierréz, Chiapas, México, in 2000 and received the M.Sc degree from the National Institute of Astrophysics, Optics and Electronics (INAOE), Puebla, México, in 2004, where he is currently working towards the Ph.D. degree in optics.

He is an Educator at the Department of Mechatronics, Universidad Politécnica de Pachuca (UPP), Hidalgo, México.

Nikolai Korneev graduated from Leningrad State University, St. Petersburg, Russia, in 1985 and received the Ph.D. degree in physics from Ioffe Physico-Technical Institute, St. Petersburg, Russia, in 1996.

He joined the Institute of Astrophysics, Optics and Electronics (INAOE), Puebla, México, in 1993. He has published more than 50 research papers. His current research interests are in the areas of nonlinear optics, photorefractive crystals, and chaos.

Victor A. Vysloukh received the Ph.D. degree in physics from the USSR Academy of Science, Moscow, Russia, in 1991.

From 1992 to 2002, he worked at the Institute of Astrophysics, Optics and Electronics (INAOE), Puebla, México, and the Research Center in Engineering and Applied Sciences (CIICap), México. In 2002, he joined the Department of Physics and Mathematics, Universidad de las Américas Puebla (UDLA), Cholula, México. He has published more than 170 research papers. His research interests include nonlinear guided waves, nonlinear optical phenomena, and spatial solitons.