Self-focusing effect in voltage-controlled PPLN waveguide arrays

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Self-focusing effect via Kerr nonlinearity is observed in periodically poled lithium niobate (PPLN) waveguide arrays formed by electro-optic effect. Voltage-control method is demonstrated to control the focusing and diffraction of light. Theoretical simulation results show good agreement with experimental results.

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Light can trap itself in intensity-dependent nonlinear waveguide arrays or lattices due to the balance between the linear coupling effect among adjacent waveguides and the nonlinear focusing effect[1]. Such self-localized light beams in discrete systems are known as discrete spatial solitons. The first experimental observation of discrete spatial solitons formed in AlGaAs waveguide arrays due to Kerr effect was reported by Eisenberg *et al*. in 1998[2]. Since then, many breakthroughs have been made such as the design of structures for diffraction[3], the first observation of anomalous diffraction[4], Floquet–Bloch solitons[5], and discrete solitons in nonlinear quadratic arrays[6]. Optical induction method[7,8] in photorefractive materials attracts much more attention in the past few years. Experimental observation in such materials are reported in one-dimensional (1D) and two-dimensional (2D) systems[9−15], while Kerr solitons are reported only in femtosecond (fs) laser written waveguides in fused silica[16,17]. Compared with the soliton of photorefractive nonlinearity, Kerr soliton is more sensitive to time, thus it can be generated immediately as light power increases, which is more practical for optical applications. However, Kerr soliton remains uncontrollable in waveguide arrays with fixed refractive index distribution. When discussing the discrete solitons of liquid crystal nonlinearity, a method has been reported[18,19], wherein the electrical field is applied on a well-designed and fabricated nemetic liquid crystal waveguide array to control light propagation as well as all-optical angular steering.

In this letter, periodically poled lithium niobate (PPLN) sample is chosen to form a waveguide array. We observe clear discrete diffraction and soliton-like self-focusing effect in the 1D periodic waveguide array with Kerr nonlinearity as well as its control by voltage, which is caused by the balance between the nonlinear effect and the linear coupling effect in PPLN waveguide array. To the best of our knowledge, no similar self-focusing effect has been reported in PPLN waveguide arrays. Compared with liquid crystal waveguide arrays[18,19], PPLN has the advantages of sharp refractive index contrast, high nonlinearity, and large electro-optic coefficient. In addition, the technology of fabricating PPLN is relatively mature to lower its cost, and the voltage-control method has a potential application in optical devices such as optical switching and filtering[20,21].

When a uniform electrical field is applied on a PPLN sample along the z axis, sharply extraordinary refractive index contrast appears between the positive and negative domains due to the linear electro-optic effect. Hence, the identical waveguides are positioned with equal distance between them. The refractive indices of the positive n_p and the negative n_g domains are determined as

$$\begin{cases} n_\mathrm{p} = n_\mathrm{e} - \dfrac{1}{2} n_\mathrm{e}^3 \cdot r_{33} \cdot E \\ n_\mathrm{g} = n_\mathrm{e} + \dfrac{1}{2} n_\mathrm{e}^3 \cdot r_{33} \cdot E \end{cases}, \quad (1)$$

where n_e is the refractive index of $LiNbO_3$ for transverse electric (TE) input light; r_{33} is its electro-optical coefficient; E is the applied electric field. These voltage-controlled refractive indices lead to a voltage-controlled coupling coefficient of the PPLN waveguide array. As in our experiment, the coupling coefficient C changes with the electrical field[22], as shown in Fig. 1. Self-focusing effect occurs when the power density of light increases. Therefore, if the light intensity is strong enough, spatial soliton can form due to the balance between the Kerr effect and the linear coupling effect. By changing the coupling coefficient, the control of the formation and collapse of solitons can be achieved through the electrical field. The discrete non-linear SchrÖdinger equation (DNLSE)[2] describes the evolution of light beam in the nth waveguide of the array

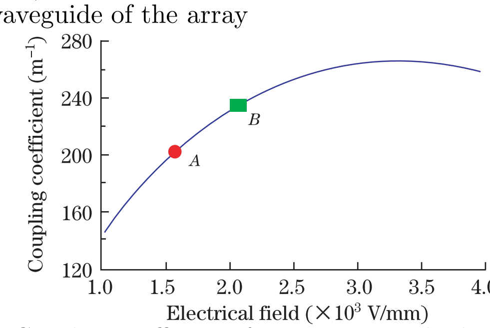

Fig. 1. Coupling coefficient of PPLN waveguide changes with electrical field. Points A and B are the correct electrical fields to control the soliton's formation and collapse in our experiment.

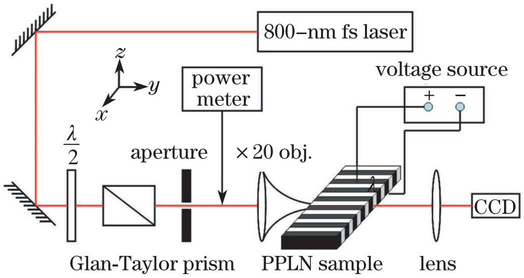

Fig. 2. Experimental setup. Nickel electrodes were constructed on both the $+z$ and $-z$ surfaces of the sample; electric field was applied along the z axis.

$$i\frac{\mathrm{d}E_n}{\mathrm{d}z}+\beta E_n+C(E_{n-1}+E_{n+1})+r\left|E_n\right|^2E_n=0, \quad (2)$$

where β is the linear propagation constant; C is the coupling coefficient related to the electrical field; r is connected with the nonlinear coefficient. The relations are shown as

$$C=\frac{2\kappa^2\gamma^2e^{-\gamma d_2}}{\beta(2+\gamma d_1)(\kappa^2+\gamma^2)}, \quad (3)$$

where $\kappa^2=n_{\mathrm{g}}^2k_0^2-\beta^2$; $\gamma^2=\beta^2-n_{\mathrm{p}}^2k_0^2$; d_1 and d_2 are the width of the negative and positive domains, respectively; k_0 is the wave vector. The split-step fast Fourier transform method (FFT)[23] is used to solve the above-mentioned DNLSE.

The schematic of the experimental setup for observing the self-focusing effect in PPLN waveguide arrays is shown in Fig. 2. The sample, with dimension of 20(L) × 6(T) × 0.5(W) (mm), had a period of 30 μm and a duty ratio of 1:1. Nickel electrodes were constructed on both the $+z$ and $-z$ surfaces. A voltage source was used to generate the electric field along the z axis of the PPLN. The light source was a Ti:sapphire oscillator that produces about 100-fs pulses at an 84-MHz repetition rate at wavelength of 800 nm, while the pulse peak power was about 70 kW. A half-wave plate and a Glan-Taylor prism were employed to adjust the injection power and the polarization. The light was coupled into one facet of the sample through a ×20 objective and imaged onto a charge coupled device (CCD) from the output facet through a lens. In addition, moving the input objective perpendicular to the beam can vary the propagation angle of the input beam. A power meter was used to test the real pulse power before it was coupled into the sample. The efficient pulse peak power in the experiment was adjustable from 1 to 20 kW. The diameter of light spot on the input facet is estimated to be about 15 μm. Taking the polarization effect into consideration, the highest power density in our experiment was 20 GW/cm^2, which was high enough to generate Kerr self-focusing effect and much less than the threshold of $LiNbO_3$[24] to avoid destroying the sample.

By launching a low-intensity light beam with peak power of about 1 kW into the sample facet with an applied electric field of 1.5 kV/mm (point A in Fig. 1), a linear coupling process was observed. In order to avoid the saturation of the CCD, we used an attenuating plate in our measurement. The output intensity distribution covering about nine channels similar to earlier experimental result reported in Ref. [8] was symmetric on the excited channel and possesses the characteristic twin lobes[2,8,10]. The waveguide array had a period of 30 μm and a length of 6 mm, resulting in a less coupling coefficient that limits the light to couple into more waveguides. When the light power increased from 1 to 20 kW, a highly localized self-focusing effect was observed, as shown in Figs. 3(c) and (d), demonstrating the possibility of discrete spatial solitons in PPLN waveguide arrays. Voltage control was attempted by increasing the electrical field to 2.2 kV/mm (point B in Fig. 1). Linear coupling coefficient increases to break the balance, thus the focused light diffracts again, as shown in Figs. 3(e) and (f). At such time, the light couples to more waveguides because the coupling coefficient is larger. The result is examined by comparing Figs. 3(b) and (f); it demonstrates that the focusing and diffraction of light can be easily controlled by electrical field in PPLN waveguide arrays.

Soliton-like behaviors are mostly reported in $LiNbO_3$ waveguide arrays for photorefractive nonlinearity, both optically induced[9,10] and due to metal ion doping[11]. The refractive index change by the photorefractive nonlinearity is in a saturable form, $\Delta n=-0.5n^3\gamma E_{\mathrm{pv}}I/(I+I_{\mathrm{d}})$[25], with γ being the electro-optical coefficient, E_{pv} the light-induced photovoltaic field, I the light intensity, and I_{d} the dark irradiance. Therefore, there is a need to examine carefully whether it is the Kerr nonlinearity or the photorefractive nonlinearity that dominates. In our experiment, light focuses into the central waveguide as soon as the electrical field increases. Because Kerr effect occurs at once whereas the photorefractive nonlinearity needs long time to meet the saturation condition, it is clear that self-focusing exhibits Kerr nonlinearity. Furthermore, photorefractive nonlinearity is weak but not negligible. In this experiment, the number of output light is limited by the low coupling coefficient of PPLN waveguide arrays, which indicates that only few output light is observed.

To provide comparison, we simulate the beam propagation in the waveguide array. According to the previous reports[22,23,26], the nonlinear coefficient in Eq. (2) can be illustrated as

$$r=\frac{\omega_0n_2}{cA_{\mathrm{eff}}}, \quad (4)$$

where ω_0 is the angular frequency of the input light; n_2 is the nonlinear coefficient of PPLN material; A_{eff} is the common effective area of the waveguide modes. Although

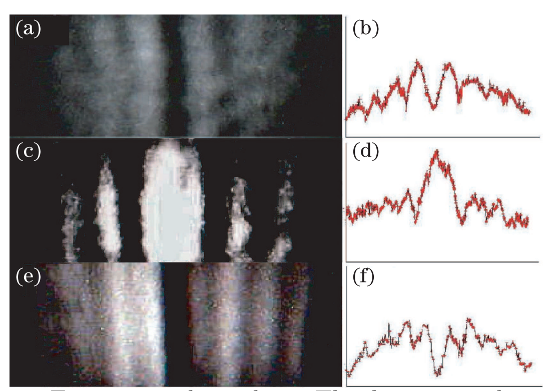

Fig. 3. Experimental results. The linear coupling effect with (a) P = 1 kW and (b) E = 1.5 kV/mm; Kerr soliton with fixed electric field at (c) P = 20 kW and (d) E = 1.5 kV/mm; soliton collapse with (e) P = 20 kW and (f) E = 2.2 kV/mm.

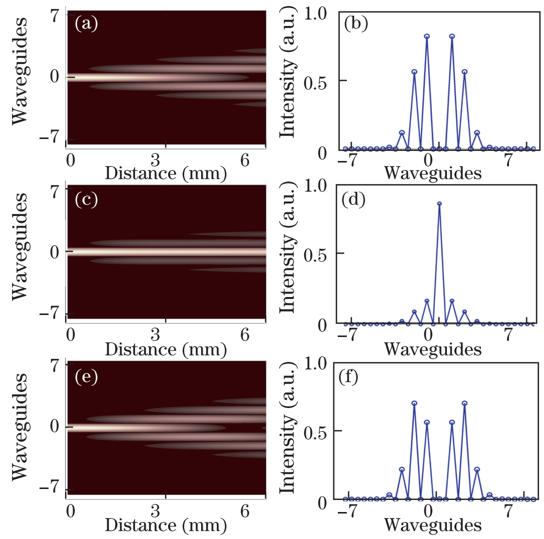

Fig. 4. Theoretical simulation for discrete diffraction with (a) $P = 1$ kW and (b) $E = 1.5$ kV/mm; discrete spatial Kerr soliton with (c) $P = 20$ kW and (d) $E = 1.5$ kV/mm; soliton collapse with (e) $P = 20$ kW and (f) $E = 2.2$ kV/mm.

n_2 of PPLN is very small, the nonlinear coefficient r is high enough because of the smaller common effective area of the waveguide modes A_{eff} in our experiment. In the simulation, the nonlinear coefficient r is calculated to be $0.413\ \text{W}^{-1}\cdot\text{m}^{-1}$. The calculated results (Fig. 4) show good agreement with the experimental result. Figs. 4(a), (b), (c), and (d) correspond to point A in Fig. 1, while Figs. 4(e) and (f) correspond to point B in Fig. 1. The discrete spatial soliton originated from the balance between the nonlinear effect and the linear coupling effect in PPLN waveguide array. By changing the electrical field between points A and B, the formation and collapse of solitons can be controlled accurately. Furthermore, this voltage-control method can select the output light distribution and the output channel for a single optical signal continuously, which has a potential application in optical switching and filtering.

In conclusion, we demonstrate experimentally and theoretically Kerr self-focusing effect in voltage-controlled PPLN waveguide arrays by electro-optical effect. By changing the electrical field, we observe the focusing and diffraction of light, which provides a method to control solitons in waveguide arrays. As this voltage-control method in PPLN waveguide arrays is easy to operate and can select the output state accurately, it may improve the possibility of the practical application of PPLN in optical switching and filtering in the future.

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References

1. D. N. Christodoulides and R. I. Joseph, Opt. Lett. **13,** 794 (1988).
2. H. S. Eisenberg, Y. Silberberg, R. Morandotti, A. R. Boyd, and J. S. Aitchison, Phys. Rev. Lett. **81,** 3383 (1998).
3. H. S. Eisenberg, Y. Silberberg, R. Morandotti, and J. S. Aitchison, Phys. Rev. Lett. **85,** 1863 (2000).
4. T. Pertsch, T. Zentgraf, U. Peschel, A. Brauer, and F. Lederer, Phys. Rev. Lett. **88,** 093901 (2002).
5. D. Mandelik, H. S. Eisenberg, Y. Silberberg, R. Morandotti, and J. S. Aitchison, Phys. Rev. Lett. **90,** 053902 (2003).
6. T. Pertsch, U. Peschel, F. Lederer, J. Meier, R. Iwanow, and G. Stegeman, in *Proceedings of Nonlinear Guided Waves and Their Applications* NLTUA1-1 (2002).
7. N. K. Efremidis, S. Sears, D. N. Christodoulides, J. W. Fleischer, and M. Segev, Phys. Rev. E **66,** 046602 (2002).
8. Z. Chen and K. McCarthy, Opt. Lett. **27,** 2019 (2002).
9. J. W. Fleischer, T. Carmon, M. Segev, N. K. Efremidis, and D. N. Christodoulides, Phys. Rev. Lett. **90,** 023902 (2003).
10. J. W. Fleischer, M. Segev, N. K. Efremidis, and D. N. Christodoulides, Nature **422,** 147 (2003).
11. F. Chen, M. Stepi, C. Ruter, D. Runde, D. Kip, V. Shandarov, O. Manela, and M. Segev, Opt. Express **13,** 4314 (2005).
12. H. Martin, E. D. Eugenieva, Z. Chen, and D. N. Christodoulides, Phys. Rev. Lett. **92,** 123902 (2004).
13. D. N. Neshev, T. J. Alexander, E. A. Ostrovskaya, Y. S. Kivshar, H. Martin, I. Makasyuk, and Z. Chen, Phys. Rev. Lett. **92,** 123903 (2004).
14. B. Hanna, W. Krolikowski, D. Neshev, A. Sukhorukov, E. Ostrovskaya, and Y. Kivshar, Opto-electron. Rev. **13,** 85 (2005).
15. M. Matuszewski, C. R. Rosberg, D. N. Neshev, A. A. Sukhorukov, A. Mitchell, M. Trippenbach, M. W. Austin, W. Krolikowski, and Y. S. Kivshar, Opt. Express **14,** 254 (2006).
16. A. Szameit, D. Blomer, J. Burghoff, T. Schreiber, T. Pertsch, S. Nolte, A. Tunnermann, and F. Lederer, Opt. Express **13,** 10552 (2005).
17. A. Szameit, I. L. Garanovich, M. Heinrich, A. Minovich, F. Dreisow, A. A. Sukhorukov, T. Pertsch, D. N. Neshev, S. Nolte, W. Krolikowski, A. Nnermann, A. Mitchell, and Y. S. Kivshar, Phys. Rev. A **78,** 031801 (2008).
18. A. Fratalocchi, G. Assanto, K. A. Brzdakiewicz, and M. A. Karpierz, Appl. Phys. Lett. **86,** 051112 (2005).
19. A. Fratalocchi, G. Assanto, K. A. Brzdakiewicz, and M. Karpierz, Opt. Express **13,** 1808 (2005).
20. R. A. Vicencio, M. I. Molina, and Y. S. Kivshar, Opt. Lett. **28,** 1942 (2003).
21. A. Sukhorukov and Y. Kivshar, Opt. Lett. **30,** 1849 (2005).
22. X. Gu, X. Chen, Y. Chen, Y. Xia, and Y. Chen, Chin. Opt. Lett. **1,** 671 (2003).
23. G. Agrawal, *Nonlinear Fiber Optics* (Academic Press, New York, 1995).
24. Z. Chen, M. Segev, D. W. Wilson, R. E. Muller, and P. D. Maker, Phys. Rev. Lett. **78,** 2948 (1997).
25. H. T. Hsieh, D. Psaltis, O. Beyer, D. Maxein, C. von Korff Schmising, K. Buse, and B. Sturman, Opt. Lett. **30,** 2233 (2005).
26. X. Deng, H. Lao, and X. Chen, Appl. Opt. **48,** 3731 (2009).