Soliton formation and collapse in tunable waveguide arrays by electro-optic effect

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Light propagation in periodically poled lithium niobate (PPLN) waveguide arrays is numerically investigated. By employing the concept of a linear focusing effect, we propose a brand new method to control discrete diffraction and spatial solitons in PPLN waveguide arrays by electrical field. Simulated results are presented, and the principle is discussed to demonstrate the feasibility of the method.

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1. Introduction

In the early days of nonlinear optics, two kinds of optical solitons had been predicted, spatial and temporal, where the diffraction and dispersion can be balanced by the nonlinear effect, respectively [1,2]. One kind of spatial soliton, called an optical Kerr soliton, exists in a Kerr medium where diffraction is confined to one transverse dimension and has been observed experimentally in CS2, glass, semiconductors, and polymer waveguides [3–6]. In 1988, an idea that light could trap itself in nonlinear optical waveguide arrays or lattices was suggested [7]. Similar to spatial solitons in a continuous medium, this self-localization takes place when the on-site nonlinearity exactly balances the discrete diffraction arising from linear coupling effects among the adjacent waveguides. After 10 years' theoretical research and technology progress in fabrication of precision-made defect-free waveguide arrays, Eisenberg *et al.* reported the experimental observation of discrete spatial solitons in AlGaAs waveguide arrays for the first time in 1998 [8]. Since then, a lot of breakthroughs were made, such as the first observation of anomalous diffraction and diffraction management [9,10], Floquet—Bloch solitons [11], discrete solitons in nonlinear quadratic arrays [12], and photorefractive arrays [13,14]. All of these phenomena are based on periodic structures, and these solitons were known as lattice solitons [15]. In fact, solitonlike behavior in periodic structures has been reported in some nature systems, such as molecules [16,17], charge density waves [18], spin waves [19], arrays of Josephson junctions [20,21], and even Bose–Einstein condensates [22,23]. Optical solitons have attracted more and more attention for their potential application in optical networks, and relevant research results were reviewed quite recently in [24]. Light propagating in periodic structures exhibits new characteristics that cannot be found from its counterpart in homogeneous materials. In periodic structures, not only are the soliton phenomena attractive, but also the coupling effects between adjacent waveguides (linear diffraction) work. Thus, periodic structures can provide a unique way for controlling light propagation. Research showed that soliton switching and filtering can be completed by use of such structures [25,26]. As we know, it is very interesting and useful to control or switch discrete diffraction and spatial solitons in such a discrete system. To the best of our knowledge, reports in

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the literature are rare because a discrete structure such as a waveguide array is not easy to modulate while it is being fabricated.

In this paper, we propose a new method for controlling discrete solitons in waveguide arrays by electrical field. By applying an external electrical field on periodically poled lithium niobate (PPLN), a $LiNiO_3$ waveguide array can be formed. Based on this kind of waveguide array, we study how to control discrete diffraction and spatial solitons in PPLN waveguide arrays by electrical field. Because this method provides an easy way to control solitons, it may be useful for further research on optical switching and filtering.

2. Theoretical Model

Materials that have been used to fabricate waveguide arrays usually have a large nonlinear coefficient, like AlGaAs for Kerr solitons [8] and copper-ion-doped $LiNiO_3$ for gap solitons [14]. In our method, we choose periodically poled lithium niobate (PPLN) as a waveguide array since z-cut $LiNiO_3$ has a large electro-optic coefficient as well as its large nonlinear coefficient. When an external electrical field is applied along the z axis of PPLN crystal, the extraordinary refractive indices of the positive and negative domains will change oppositely due to the linear electro-optic effect (as shown in Fig. 1). In fact, such a linear electro-optic effect affects the refractive indices along the x and y axes through γ_{13} only when the light is ordinary polarized. In our simulation, extraordinary polarized light propagating along the y axis is assumed, so only the refractive index along the z axis should be considered. As shown in Fig. 1, the PPLN waveguide array is formed by using the largest electro-optic coefficient γ_{33}. Evidence for inducing an alternative refractive index change by applying an electrical field along the z axis has been reported in realizing Bragg modulators [27], a cylindrical lens, a switching and deflection device [28], and Fresnel zone plates [29]. Consequently,

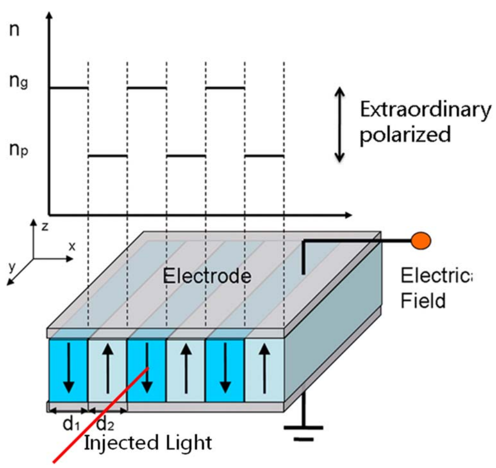

Fig. 1. (Color online) Schematic of PPLN with an electrical field applied along the z axis. The injected light beam is extraordinary polarized.

a waveguide array forms with identical periodically distributed rectangular waveguides. Compared with other waveguide arrays, such a waveguide array shows its advantages in easy controllability and flexibility.

As for the study of diffraction and discrete solitons in waveguide arrays, the coupling coefficient of the waveguides is essential, and in our simulation, it is determined by the electrical field through the refractive indices of the positive and negative domain, n_p and n_g, respectively, which are determined as follows:

$$\begin{aligned} n_p &= n_e - \tfrac{1}{2} n_e^3 \cdot r_{33} \cdot E, \\ n_g &= n_e + \tfrac{1}{2} n_e^3 \cdot r_{33} \cdot E, \end{aligned} \quad (1)$$

where n_e is the refractive index of $LiNbO_3$ for TE input light, γ_{33} is its electro-optical coefficient, and E is the applied electrical field. PPLN has a fixed period of domain distribution, so when the electrical field is applied, the identical waveguides are positioned with equal separation between each other so that all the coupling coefficients between them are equal.

When light is launched into one waveguide, it will couple to the neighboring waveguides along its propagating direction and broaden its spatial distribution, which is analogous to diffraction in continuous media. Because all the waveguides are identical, energy can be exchanged between two neighboring waveguides through the overlap of their mode. According to the coupling mode equations [30,31], the coupling coefficient of the waveguide array is

$$C = \frac{2\kappa^2\gamma^2 e^{-\gamma d_2}}{\beta(2+\gamma d_1)(\kappa^2+\gamma^2)}, \qquad \begin{cases} \kappa = (n_g^2 k_0^2 - \beta^2)^{1/2} \\ \gamma = (\beta^2 - n_p^2 k_0^2)^{1/2} \end{cases}, \quad (2)$$

where d_1 and d_2 are the width of the negative and positive domain, respectively, and k_0 is the wave vector of light in vacuum. β is the propagation constant in the waveguide and is determined by the following eigenfunction [31]:

$$\tan \kappa d_1 = \frac{2\gamma}{\kappa\left(1 - \frac{\gamma^2}{\kappa^2}\right)}, \quad (3)$$

where κ and γ are described in Eq. (2).

When light power increases, the Kerr effect occurs to reduce the broadening of linear coupling. If the power is high enough, light can be focused back to the central waveguide to form a discrete soliton. These two processes can be described by the well-known discrete nonlinear Schrödinger equation, which gives the evolution of E_n, the light wave in the nth waveguide:

$$i\frac{\mathrm{d}E_n}{\mathrm{d}z} + \beta E_n + C(E_{n-1} + E_{n+1}) + r|E_n|^2 E_n = 0, \quad (4)$$

where β is the linear propagation constant and C is the coupling coefficient. The last term of the equation describes the nonlinear effect, and the coefficient is

$$r = \frac{\omega_0 n_2}{c A_{\mathrm{eff}}}, \tag{5}$$

where ω_0 is the optical angular frequency of input light, n_2 is the nonlinear coefficient, A_{eff} is the common effective area of the waveguide modes, and r is calculated to be $0.413\,(\mathrm{W\ m})^{-1}$ in our simulations.

Using all the parameters calculated above, we can exactly simulate the light propagation under different external electrical fields in our PPLN waveguide array. To solve the discrete nonlinear Schrödinger equation, we use the split-step fast Fourier transform method [32]. The period of the PPLN is set to be $6.5\,\mu\mathrm{m}$ with duty ratio 1:1, the length of the waveguide is 10 mm, and the light source is at the wavelength of 800 nm with a pulse width of 100 fs. We also consider the influence of dispersion, and the dispersion coefficient β_2 is about $1.575 \times 10^{-3}\ \mathrm{ps}^2/\mathrm{m}$ for $LiNbO_3$.

3. Simulation Results and Discussion

The rule of the coupling coefficient of the PPLN waveguide array changing with electrical field is important for controlling the light propagation. As shown in Fig. 2, the coupling coefficient increases with electrical field, increasing until reaching a peak, and then starts to decrease. It can be explained that at the very beginning when the electrical field is applied, the refractive index difference between the positive and negative domains increases, and a waveguide array starts to form, making a positive contribution to the coupling coefficient. In the meantime, the guide mode confinement of the waveguide becomes stronger and stronger, preventing light from coupling to adjacent waveguides. Thus, the coupling coefficient climbs to a peak and then starts to roll down as the applied electrical field increases.

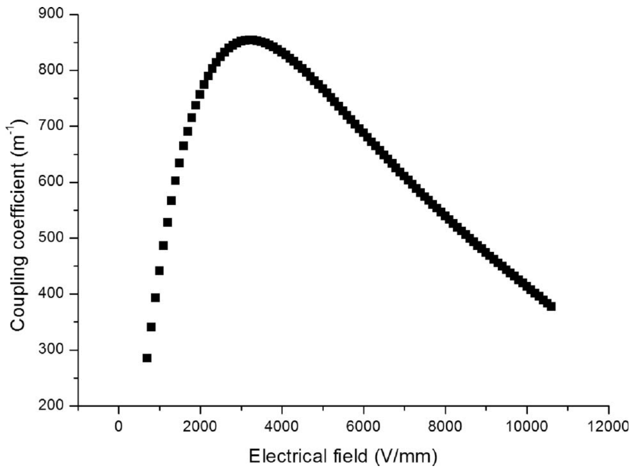

Fig. 2. Diagram of coupling coefficient as a function of applied electrical field.

According to our calculation, the largest coupling coefficient is about $860\,\mathrm{m}^{-1}$ at the electrical field of 2.8 kV/mm. If we couple a light beam with low power into the waveguide, when the applied electrical field is tuned continuously from 0 to 2.8 kV/mm, we can observe a linear coupling process, and that the beam will be coupled to more waveguides at a higher electrical field. At this point, if we still increase the applied electrical field, an inverse process will be observed that can be described as linear focusing. As shown in Fig. 3, a light beam of 500 W intensity is injected into the PPLN waveguide array, which has a total of 50 identical waveguides. Figure 3 shows the beam coupling results when the applied electrical fields are 0.6, 1.6, 2.8, and 5.0 kV/mm. Figures 3(a)–3(c) show the linear coupling process; Figs. 3(c) and 3(d) show the so-called linear focusing process. From Fig. 3, we see that the linear coupling process changes faster than the linear focusing process. This

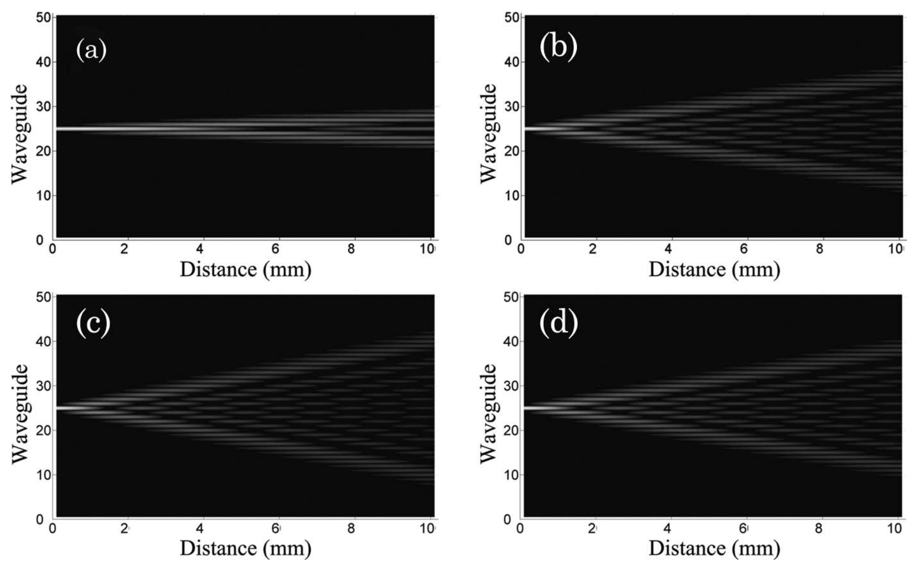

Fig. 3. Beam coupling result at the applied electrical field of (a) 0.6 kV/mm, (b) 1.6 kV/mm, (c) 2.8 kV/mm, and (d) 5.0 kV/mm.

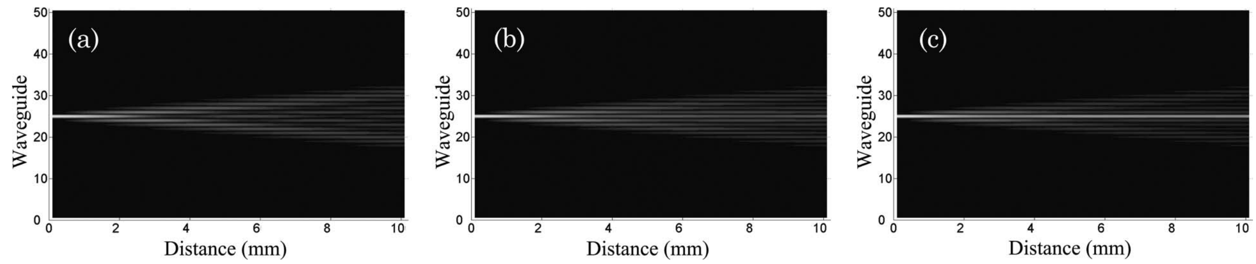

Fig. 4. Discrete spatial soliton forms in PPLN waveguide array with fixed electrical field at 800 V/mm. The light beam powers are (a) 3000 W, (b) 4000 W, and (c) 5000 W.

is because the slope of the climbing region of the curve in Fig. 2 is much larger than that of the declining region, i.e., the coupling coefficient is more sensitive to the applied electrical field in the climbing region.

Low-power light beams experience a linear coupling process in our PPLN waveguide array when an electrical field is applied, and such a coupling process can be controlled by changing the electrical field. As $LiNbO_3$ crystal has characteristics of good nonlinearity, we want this controlling method to be available in the situation of a high-power light beam. If we fix the electrical field and increase the beam power, the nonlinear focusing process should occur and we should expect a discrete spatial soliton in the waveguide array. Figure 4 shows the light beam changing in the PPLN waveguide array with the electrical field fixed at 0.8 kV/mm, and the beam power is 3.0 kW, 4.0 kW, and 5.0 kW in Figs. 4(a)–4(c), respectively. Such beam powers are higher than that used to form solitons in AlGaAs waveguide arrays [8] because the coefficient γ in our PPLN waveguide array is much less than those in the AlGaAs waveguide arrays. Similarly, in our PPLN waveguide array, we can fix the light beam power while changing the electrical field to form a discrete spatial soliton as well. This process is shown in Fig. 5 with fixed light beam power at 5.0 kW.

In Fig. 5(a), when the electrical field is 1.2 kV/mm, the light beam is linearly coupled to other waveguides and no soliton forms. Then the electrical field is decreased to 0.8 kV/mm, and a discrete spatial soliton forms as shown in Fig. 5(b). When we keep decreasing the electrical field to 0.6 V/mm, we find that more light beams are focused to the central waveguide and the intensity of the soliton is rather high as in Fig. 5(c). This process also shows an available way to form a discrete spatial soliton in waveguide arrays.

Let us go over the principle of Kerr soliton formation and then consider the processes in Figs. 4 and 5. A Kerr solitons appears when the on-site nonlinearity exactly balances the discrete diffraction arising from linear coupling effects among the adjacent waveguides. During the process shown in Fig. 4, the dominant effect for the soliton's formation is the nonlinear effect. As the light beam power increases, the nonlinear effect gets stronger and stronger, focusing more energy to the central waveguide. During this process, the effect of linear coupling does not change, and this effect determines the spatial distribution of light beams on the output facet. So in the three parts of Fig. 4, the spatial distributions on the output facet are nearly the same, i.e., the output light beams cover nearly the same waveguides. While during the process of Fig. 5, the dominant effect for the soliton's formation is the linear effect, this linear effect is not the linear coupling effect. In our simulation, when the electrical field decreases, the coupling coefficient becomes smaller. And this effect weakens the discrete diffraction linearly, so we call it linear focusing effect. So as the electrical field decreases, the linear focusing effect increases, and the output light beams covers less waveguides on the output facet. These two different processes are shown in Fig. 6.

Figure 6(a) shows the process of nonlinear focusing as light beam power increases. When light beam power increases, a discrete spatial soliton forms, but the energy distributions of the different powers are nearly the same. Figure 6(b) shows our electrical-field-controlled linear focusing process. A soliton forms again but the energy is distributed in fewer waveguides on the output facet. In our method, three

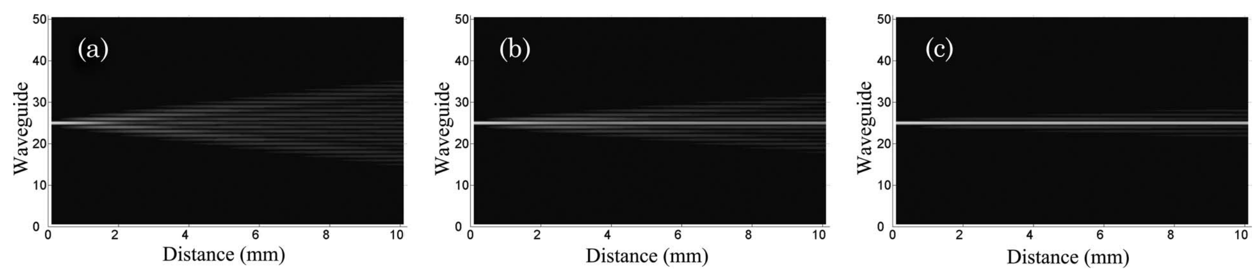

Fig. 5. Discrete spatial soliton forms in PPLN waveguide array with fixed light beam power at 5000 W. The electrical fields are (a) 1.2 kV/mm, (b) 0.8 kV/mm, and (c) 0.6 kV/mm.

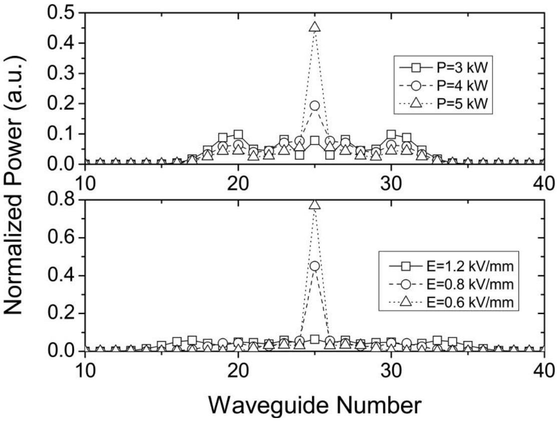

Fig. 6. Light beam distribution on the output facet of PPLN waveguide array when (a) applied electrical field E is fixed at $0.8\,\mathrm{kV/mm}$ and (b) light beam power P is fixed at $5.0\,\mathrm{kW}$.

determinant factors, the normal waveguide coupling effect, the power-dependent nonlinear focusing effect, and the electrical-field-controlled linear focusing effect, decide the discrete diffraction and spatial soliton together.

4. Conclusion

In this paper, we propose a new method to control discrete diffraction and spatial solitons in PPLN waveguide arrays by electrical field. Besides the linear coupling effect and the nonlinear focusing effect, we employ a linear focusing effect by changing the electrical field applied on the PPLN waveguide arrays. This method allows us to precisely control the light beam propagation in the PPLN waveguide arrays to form discrete diffraction and spatial solitons, which has a potential application in optical signal processing such as switching and routing by electrical field.

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References

1. R. Y. Chiao, E. Garmire, and C. H. Townes, “Self-trapping of optical beams,” Phys. Rev. Lett. **13**, 479–482 (1964).
2. V. E. Zahkarov and A. B. Shabat, “Exact theory of two-dimensional self-focusing and one-dimensional self-modulation of nonlinear waves in nonlinear media,” Sov. Phys. JETP **34**, 62–69 (1972).
3. A. Barthelemy, S. Maneuf, and C. Froehly, “Propagation soliton et auto-confinement de faisceaux laser par non linearité optique de Kerr,” Opt. Commun. **55**, 201–206 (1985).
4. J. S. Aitchison, A. M. Weiner, Y. Silberberg, M. K. Oliver, J. L. Jackel, D. E. Leaird, E. M. Vogel, and P. W. E. Smith, “Observation of spatial optical solitons in a nonlinear glass waveguide,” Opt Lett. **15**, 471–473 (1990).
5. J. S. Aitchison, K. Al-Hemyari, C. N. Ironside, R. S. Grant, and W. Sibbett, “Observation of spatial solitons in AlGaAs waveguides,” Electron. Lett. **28**, 1879–1880 (1992).
6. U. Bartuch, U. Peschel, Th. Gabler, R. Waldhaus, and H.-H. Horhold, “Experimental investigations and numerical simulations of spatial solitons in planar polymer waveguides,” Opt. Commun. **134**, 49–54 (1997).
7. D. N. Christodoulides and R. I. Joseph, “Discrete self-focusing in nonlinear arrays of coupled waveguides,” Opt. Lett. **13**, 794–796 (1988).
8. H. S. Eisenberg, Y. Silberberg, R. Morandotti, A. R. Boyd, and J. S. Aitchison, “Discrete spatial optical solitons in waveguide arrays,” Phys. Rev. Lett. **81**, 3383–3386 (1998).
9. H. S. Eisenberg, Y. Silberberg, R. Morandotti, and J. S. Aitchison, “Diffraction management,” Phys. Rev. Lett. **85**, 1863–1866 (2000).
10. T. Pertsch, T. Zentgraf, U. Peschel, A. Brauer, and F. Lederer, “Anomalous refraction and diffraction in discrete optical systems,” Phys. Rev. Lett. **88**, 093901 (2002).
11. D. Mandelik, H. S. Eisenberg, Y. Silberberg, R. Morandotti, and J. S. Aitchison, “Band-gap structure of waveguide arrays and excitation of Floquet–Bloch solitons,” Phys. Rev. Lett. **90**, 053902 (2003).
12. T. Pertsch, U. Peschel, F. Lederer, J. Meier, R. Schiek, R. Iwanow, and G. Stegeman, “Discrete solitons in quadratic nonlinear waveguide arrays,” in *OSA Trends in Optics and Photonics Series* (Optical Society of America, 2002), paper NLTuA1.
13. J. W. Fleischer, M. Segev, N. K. Efremidis, and D. N. Christodoulides, “Observation of two-dimensional discrete solitons in optically-induced nonlinear photonic lattices,” Nature **422**, 147–150 (2003).
14. F. Chen, M. Stepić, C. E. Rüter, D. Runde, and D. Kip, “Discrete diffraction and spatial gap solitons in photovoltaic $LiNbO_3$ waveguide arrays,” Opt. Express **13**, 4314–4324 (2005).
15. F. Lederer and Y. Silberberg, “Discrete solitons,” Opt. Photon. News **13**, 48–53 (2002).
16. A. S. Davydov, *Solitons in Molecular Systems* (Academic, 1991).
17. A. H. Xie, L. van der Meer, V. Hoff, and R. H. Austin, “Long-lived amide I vibrational modes in myoglobin,” Phys. Rev. Lett. **84**, 5435–5438 (2000).
18. B. I. Swanson, J. A. Brozik, S. P. Love, G. F. Strouse, A. P. Shreve, A. R. Bishop W.-Z. Wang, and M. I. Salkola, “Observation of intrinsically localized modes in a discrete low-dimensional material,” Phys. Rev. Lett. **82**, 3288–3291 (1999).
19. U. T. Schwartz, L. Q. English, and A. J. Sievers, “Experimental generation and observation of intrinsic localized spin wave modes in an antiferromagnets,” Phys. Rev. Lett. **83**, 223–226 (1999).
20. E. Trias, J. J. Mazo, and T. P. Orlando, “Discrete breathers in nonlinear lattices: experimental detection in Josephson junctions,” Phys. Rev. Lett. **84**, 741–744 (2000).
21. P. Binder, D. Abraimov, A. V. Ustinov, S. Flach, and Y. Zolotaryuk, “Observation of breathers in Josephson ladders,” Phys. Rev. Lett. **84**, 745–748 (2000).
22. A. Trombettoni and A. Smerzi, “Discrete solitons and breathers with dilute Bose–Einstein condensates,” Phys. Rev. Lett. **86**, 2353–2356 (2001).
23. B. Eiermann, Th. Anker, M. Albiez, M. Taglieber, P. Treutlein, K.-P. Marzlin, and M. K. Oberthaler, “Bright Bose–Einstein gap solitons of atoms with repulsive interaction,” Phys. Rev. Lett. **92**, 230401 (2004).
24. F. Lederer, G. I. Stegeman, D. N. Christodoulides, G. Assanto, M. Segev, and Y. Silberberg, “Discrete solitons in optics,” Phys. Rep. **463**, 1–126 (2008).
25. R. A. Vicencio, M. I. Molina, and Y. S. Kivshar, “Controlled switching of discrete solitons in waveguide arrays,” Opt. Lett. **28**, 1942–1944 (2003).
26. A. A. Sukhorukov and Y. S. Kivshar, “Soliton switching and Bloch-wave filtering in periodic photonic lattices,” Opt. Lett. **30**, 18491851 (2005).

27. J. A. Abernethy, C. B. E. Gawith, R. W. Eason, and P. G. R. Smith, "Demonstration and optical characteristics of electro-optic Bragg modulators in periodically poled lithium niobate in the near-infrared," Appl. Phys. Lett. **81**, 2514–2516 (2002).
28. M. Yamada, M. Saitoh, and H. Ooki, "Electric-field induced cylindrical lens, switching and deflection devices composed of the inverted domains in $LiNbO_3$ crystals," Appl. Phys. Lett. **69**, 3659–3661 (1996).
29. R. Cudney, L. Ríos, and H. Escamilla, "Electrically controlled Fresnel zone plates made from ring-shaped 180° domains," Opt. Express **12**, 5783–5788 (2004).
30. D. Marcuse, *Light Transmission Optics* (Academic, 1972).
31. A. Yariv and P. Yeh, *Optical Waves in Crystals: Propagation and Control of Laser Radiation* (Academic, 1972).
32. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. (Academic, 1995).