Observation of discrete gap solitons in binary waveguide arrays

Roberto Morandotti
Universite du Quebec, Institute National de la Recherche Scientifique, Varennes, Quebec, Canada J3X 1S2

Daniel Mandelik and Yaron Silberberg
Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel

Stewart Aitchison
Department of Electrical and Computer Engineering, University of Toronto, Canada M5S 3G4

Marc Sorel
Department of Electrical and Electronic Engineering, University of Glasgow, Glasgow G12 8QQ, Scotland

Demetrios N. Christodoulides
School of Optics/CREOL, University of Central Florida, Florida 32816-2700, USA

Andrey A. Sukhorukov and Yuri S. Kivshar
Nonlinear Physics Group and Centre for Ultra-high bandwidth Devices for Optical Systems (CUDOS), RSPhysSE, Australian National University, Canberra, ACT 0200, Australia

We report on the first experimental observation of discrete gap solitons in binary arrays of optical waveguides. We observe the soliton generation when the inclination angle of an input beam is slightly above the Bragg angle, and show that the propagation direction of the emerging gap soliton depends on the input power as a result of an inter-band momentum exchange.

© 2002 Optical Society of America
OCIS codes: 190.4390, 190.4420

Nonlinear periodic photonic structures such as arrays of optical waveguides attracted a lot of interest due to the unique ways they offer for controlling light. Periodic modulation of the refractive index breaks the translational invariance and produces effective discreteness in a continuous system, opening up many novel possibilities for manipulating light propagation, including light localization in the form of discrete optical solitons1-2. Recently, it was suggested that a novel type of discrete optical solitons, the so-called discrete gap solitons, can be generated in the binary waveguide arrays, by a single inclined beam3 or two input beams4. The binary arrays of optical waveguides are specially engineered photonic structures consisting of periodically alternating wide and narrow waveguides [see an example in Fig. 1(a)]. Discrete gap solitons in such structures can be considered as a nontrivial generalization of the spatial gap solitons recently observed in the waveguide arrays5 and optically-induced photonic lattices6. Gap solitons in binary arrays are associated with the fundamental modes strongly confined in narrow waveguides, which lowers the power threshold for the soliton excitation, and may result in reduced radiation losses compared to the gap solitons based on radiation or higher-order bound modes in the conventional arrays. In this Letter, we report on the first experimental observation of discrete gap solitons in binary arrays of optical waveguides and demonstrate a novel method of efficient steering of gap solitons based on the inter-band momentum exchange.

We investigate spatial beam self-action and soliton formation in the fabricated etched arrays of the 5 mm long AlGaAs waveguides with the effective refractive index contrast 0.0035 (see Ref. 2). The binary arrays are made of wide (4 µm) and narrow (2.5 µm) waveguides with 4 µm edge-to-edge spacing, and accordingly the full period is d=14.5 µm as illustrated in Fig. 1(a). The beam propagation in this structure can be described by the normalized nonlinear Schrödinger equation, $i\frac{\partial E}{\partial x} + D \frac{\partial^2 E}{\partial x^2} + \nu(x) E + |E|^2 E = 0$, where $E(x, z)$ is the normalized envelope of the electric field, $x$ and $z$ are the transverse and propagation coordinates normalized to the characteristic values $x_s = 1\mu m$ and $z_s = 1mm$, respectively, $D = z_s \lambda/(4\pi n_0 a_s^2)$ is the beam diffraction coefficient, $n_0 = 3.3947$ is the average medium refractive index, $\lambda = 1.5 \mu m$ is the vacuum wavelength, $\nu(x) = 2\Delta n(x)\pi n_0/\lambda$, and $\Delta n(x)$ is the effective modulation of the optical refractive index.

In the waveguide arrays, the wave spectrum possesses a band-gap structure with gaps separating bands of the continuous spectrum associated with the spatially extended Bloch waves of the form, $E(x, z) = \psi(x) \exp(i k x + i \beta z)$, where the propagation constant $\beta$ is proportional to the wave-vector component along the waveguides. In
When the medium nonlinearity is self-focusing, the discrete gap solitons may appear near the upper edge of the second band\(^4\). One of the distinguishing features of such solitons is their localization at narrow waveguides, as shown in Fig. 1(d). As was suggested in Ref. 3, the gap solitons can be excited by an input Gaussian beam which is inclined slightly above the Bragg angle. Each Fourier component of an incident beam excites a superposition of Bloch waves belonging to different bands, according to the values of excitation coefficients \(C_n\) plotted in Fig. 1 (see details in Ref. 7). If the input beam spans several periods of the underlying lattice (we choose the 45 \(\mu m\) FWHM beam) and its spectrum is narrow, then the excitation of the second band becomes dominant [see Fig. 1(c)], facilitating the formation of a gap soliton. Although fully controlled generation of gap solitons can be achieved only in a two-beam excitation scheme\(^4-6,8\), the single-beam approach is simpler to implement. Additionally, the simultaneously excited Bloch waves of the first band move in the opposite direction, resulting in “self-clearing” of the gap soliton, and allowing to control the soliton velocity by changing the input beam intensity\(^3\).

We note that all Bloch-wave components tend to trap together into a multi-band breather if a normally incident narrow beam is used\(^9\), and complex Bloch-wave interaction occurs for the inclined narrow beams\(^7\).

In our experiments, first we study the linear beam propagation (see Ref. 2 for description of experimental set-up). The dependence of the output field distribution on the input angle is shown in Fig. 2. We note that, in a binary waveguide array, the Bloch waves corresponding to the first and second bands can be easily distinguished, since they are primarily localized at wide and narrow waveguides, respectively. We find that the band-2 excitation becomes dominant above the Bragg angle, in full agreement with the theoretical predictions (higher bands become excited as the angle is further increased).

Next, we analyze nonlinear self-action of beams with the inclination angles below and above the Bragg angle, as marked in Fig. 2. In the former case, the Bloch waves associated with the bottom of the first band and experiencing anomalous diffraction are primarily excited. This results in beam self-defocusing as nonlinearity grows\(^10\). Indeed, we register broadening of the output beam with the increase of the laser power, see Fig. 3(a).

Strong beam self-focusing and gap-soliton formation are observed when the input inclination angle is above the Bragg angle [see Fig. 3(b)], and the gap solitons are localized at narrow waveguides. Additionally, the output soliton position depends on the input power. Numerical results for the beam propagation [Fig. 4, top] agree well with the experimental data. In Figs. 4(a-d) we show the beam dynamics inside the waveguide array structure for various input intensities. These simulations demonstrate
that the soliton velocity and, accordingly, the soliton output position are defined largely at the initial stage, where the counter-propagating Bloch waves of the first and second bands interact strongly with each other. This inter-band momentum exchange is predominantly responsible for the soliton steering, which may find applications for a simple realization of all-optical switching.

In conclusion, we have generated discrete gap solitons in binary waveguide arrays and presented an experimental evidence of the inter-band momentum exchange observed in the form of a power-dependent soliton steering.

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. A. A. Sukhorukov and Yu. S. Kivshar, Opt. Lett. 27, 2112 (2002).
4. A. A. Sukhorukov and Yu. S. Kivshar, Opt. Lett. 28, 2345 (2003).
5. D. Mandelik, R. Morandotti, J. S. Aitchison, and Y. Silberberg, Phys. Rev. Lett. 92, 093904 (2004).
6. D. Neshev, A. A. Sukhorukov, B. Hanna, W. Krolikowski, and Yu. S. Kivshar, arXiv nlin.PS/0311059 (2003).
7. A. A. Sukhorukov, D. Neshev, W. Krolikowski, and Yu. S. Kivshar, Phys. Rev. Lett. 92, 093901 (2004).
8. J. Feng, Opt. Lett. 18, 1302 (1993).
9. D. Mandelik, H. S. Eisenberg, Y. Silberberg, R. Morandotti, and J. S. Aitchison, Phys. Rev. Lett. 90, 253902 (2003).
10. R. Morandotti, H. S. Eisenberg, Y. Silberberg, M. Sorel, and J. S. Aitchison, Phys. Rev. Lett. 86, 3296 (2001).