# Guiding light in optically induced ring lattices with a low-refractive-index core

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We demonstrate a ring-shaped Bessel-like photonic lattice akin to a photonic bandgap fiber with a low-index core. While the ring lattice is optically induced in a bulk crystal with a self-defocusing nonlinearity, guidance of a probe beam propagating linearly through the core is clearly observed. The possible mechanism for such guidance is also discussed. 

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One of the most intriguing properties of photonic bandgap (PBG) structures lies in a fundamentally different way of guiding light, as in a hollow-core photonic crystal fiber (PCF).[1–3] By using the bandgap properties in frequency domain, a beam with selected wavelengths can be guided in the low-index region, as has been proposed and demonstrated in air-core PCFs, Bragg fibers, or OmniGuide fibers[2–5] and recently in all-solid PCFs with a low-index core.[6,7] Such PBG materials or fibers often require sophisticated fabrication technology, as the period in photonic crystals is usually in the range of the wavelength, and the desired refractive index contrast is typically higher than 1%.[7] On the other hand, in waveguide lattices the analyses of how a light field distributes itself focuses on the PBG of spatial frequency modes (propagation constant versus transverse wave vector).[8–11] Recent work has predicted the possibility of spatial confinement of light in optically induced 1D waveguide lattices as defect modes,[11] and, indeed, such defect modes have been observed in 2D square lattices with a single-site defect.[12] However, it remains a challenge to optically induce a PCF-like lattice structure with a negative defect (a low-index core) to demonstrate PBG guidance. Although in the nonlinear region a light beam can induce a defect via nonlinearity in waveguide lattices, and thereby localize itself in the induced defect such as with discrete solitons,[13–16] these localizations via nonlinear self-action are fundamentally different from the PBG guidance in which a light beam undergoes linear propagation.

In this Letter we demonstrate the formation of Bessel-like photonic lattices by optical induction in a self-defocusing photorefractive nonlinear crystal. When propagating through the crystal, a spatially modulated lattice beam induces a set of concentric rings of index change with a low-index core. Such an index structure is similar to those of Bragg fibers and OmniGuide fibers, but it is reconfigurable with a low-index change of the order of $10^{-3}-10^{-4}$ and a lattice period (pitch) of the order of tens of micrometers. A transition of the probe beam from linear discrete diffraction to the guidance into the low-index core is clearly observed by fine-tuning the lattice potential. We show theoretically that this guidance persists when the outer rings of the lattice are removed, and we discuss the possible mechanism for the observed guidance in the experiment.

The crystal used in our experiment is a 10 mm long strontium barium niobate (SBN:61). The experiment setup is similar to those used for generating solitonic square lattices[17] and for demonstrating lattice solitons,[16,18] except now an amplitude mask with an equally spaced concentric ring pattern is used for creating nearly periodic ring lattices instead of square lattices. The lattice-forming beam passing through the mask is ordinarily polarized at a 532 nm wavelength. When the mask is imaged onto the input face of the SBN crystal, a spatial bandpass filter is introduced into the Fourier plane. With proper filtering, the mask gives rise to a Bessel-like intensity pattern at the crystal input [Fig. 1(a)], which remains nearly invariant during the propagation throughout the 10 mm long crystal even under a negative bias field of 2 kV/cm [Fig. 1(b)]. Starting from the first ring, the measured spacing between adjacent rings in Fig. 1 is about 20 $\mu$m even far away from the center. We note that the ring pattern created this way is somewhat different from the true Bessel pattern, since the intensity of rings does not decrease as dramatically in the radial direction as in a true Bessel pattern. (In fact, the true Bessel pattern has intensities normalized to the central peak intensity of 1.00, 0.16, 0.09,

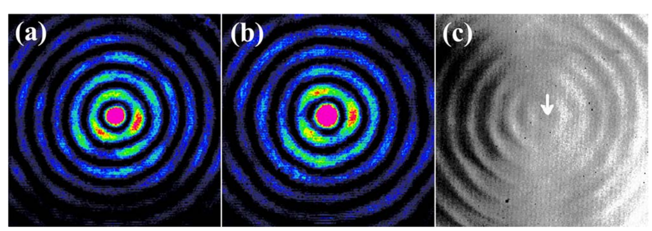


Fig. 1. (Color online) Intensity pattern of a ring lattice at crystal (a) input and (b) output after 10 mm of propagation. (c) A broad incoherent beam probing through the lattice shows a reversed contrast respective to (b). The arrow in (c) marks the center of the lattice (i.e., the low-index core).

 

and 0.06 for the first four maxima, while our measured intensities are 1.00, 0.25, 0.14, and 0.10.)

In an anisotropic photorefractive crystal, the index change experienced by an optical beam depends on its polarization, intensity, and the bias field. Under appreciable conditions, i.e., when the screening nonlinearity is dominant, this index change is approximately given by $\Delta n_e=(n_e^3 r_{33}E_0/2)(1+I)^{-1}$ and $\Delta n_o=(n_o^3 r_{13}E_0/2)(1+I)^{-1}$ for extraordinarily polarized and ordinarily polarized beams, respectively.[14–18] Here $E_0$ is the applied electric field along the crystalline $c$ axis, and $I$ is the intensity of the beam normalized to the background illumination. In our SBN crystal, the electro-optic coefficient $r_{13}$ is about ten times smaller than $r_{33}$, yet the $o$-polarized lattice beam induces an appreciable index change $\Delta n_o$ necessary for forming the concentric ring waveguide lattice. Meanwhile, the width and the depth of induced waveguides depend critically on the normalized intensity as well as the bias field. With a negative bias, the crystal has a self-defocusing nonlinearity.[14] This means that the locations of the ring waveguides correspond to the dark (low intensity) areas of the lattice beam, while the center (high intensity) corresponds to an antiguide. Thus the ring pattern in Fig. 1(b) induces a periodic ring waveguide lattice with a low-index core, somewhat tested by sending a broad white-light probe beam as shown in Fig. 1(c). The guided pattern of the probe beam has a reversed contrast as compared to the intensity pattern of the lattice beam.

To further test the waveguiding property in such an induced ring lattice, a Gaussian-like probe beam [Figs. 2(a) and 2(b)] (FWHM, 14 $\mu$m) is launched directly into the core and propagates collinearly with the lattice. The probe beam is $e$ polarized but has a wavelength of 632.8 nm that is nearly photoinsensitive for our crystal, so that nonlinear self-action of the probe beam is negligible. Since the index at the center of the lattice is lower than that at its surrounding, the probe beam tends to escape from the center and couple into the surrounding ring waveguides because of evanescent coupling. As such, the peak intensity of the probe beam does not stay in the core after linear propagation and discrete diffraction. However, under appropriate conditions, guiding of the probe beam into the core is observed. Typical experimental results are presented in Figs. 2 and 3 for a ring lattice with the spacing of 37 $\mu$m. Figure 2 shows the output intensity patterns of the probe beam as a function of the lattice intensity (normalized to background illumination) at a fixed negative bias field of 1.4 kV/cm. When the intensity of the lattice is weak, the probe beam can couple to the waveguide rings far away from the center [Fig. 2(c)]. As the intensity is increased, the lattice potential increases, and the probe beam tends to be localized in the low-index core with a tail covering the adjacent rings [Figs. 2(d) and 2(e)]. But if the intensity of the lattice is further increased, the localization or waveguide confinement does not get better but rather worse [Fig. 2(f)]. This phenomenon resembles that reported for 1D defect modes in Ref. 11. Likewise, Fig. 3 shows the output patterns of the probe beam as the

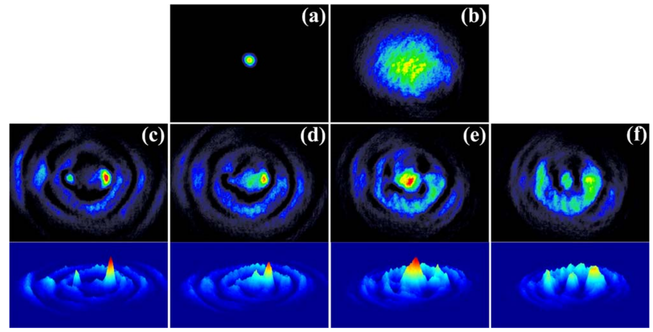


Fig. 2. (Color online) (a)–(b) Input and linear diffraction output of the probe beam without lattice. (c)–(f) 2D output patterns (top) and 3D intensity plots (bottom) of the probe at a fixed bias field of −1.4 kV/cm, while the lattice intensity is increased gradually.

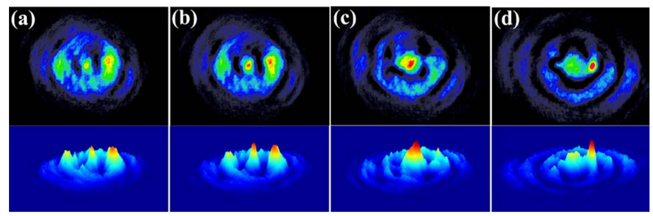


Fig. 3. (Color online) Similar to Figs. 2(c)–2(f), except that the results are obtained at a fixed lattice intensity, while the negative bias is increased gradually (0.6, 1.0, 1.4, and 2.0 kV/cm).

applied dc field is set at different levels while the lattice intensity is fixed. When the bias field is low, the probe beam tends to diffract away from the core [Fig. 3(a)], but as the bias field increases, the probe beam shows again from discrete diffraction to central guidance [Figs. 3(b) and 3(c)]. At an even higher bias field, the guidance starts to deteriorate [Fig. 3(d)].

We emphasize that in the above experiments that the probe beam has no self-action itself because of its photoinsensitive wavelength. Should the probe beam be at a photosensitive wavelength (e.g., 488 nm), it would experience the self-defocusing nonlinearity that in turn would make the beam spread more. If a positive bias is used to turn the crystal into a self-focusing medium, the induced ring lattice will have a high-index core, where a probe beam can be either guided (by total internal reflection) or self-trapped to form a discrete soliton.[19] (Discrete solitons in a true Bessel lattice with Kerr-type nonlinearity have been predicted by Kartashov *et al.*[20,21]) Since our observed guidance differs from total internal reflection and nonlinear self-induced waveguiding, its mechanism merits further investigation.

Our motivation is to optically induce in a bulk crystal a waveguide structure akin to a PBG fiber or Bragg fiber. In this case, if the propagation constant of the probe beam is within the bandgap of the ring lattice, the probe beam cannot propagate in the radial (transverse) direction but rather must be localized in the low-index core and must propagate along the longitudinal direction. One could also view the low-index core as a repulsive defect in the center of the ring lattice and find a localized defect mode.[11] Such guidance by defect arises from the Bragg effect in a periodic structure. However, in our induced ring lattice the core diameter is not much larger than the pitch, and we do not have a perfect periodic lattice (as the index decreases along the radial direction); the guidance here may not be dominated by the Bragg effect as it is in a true Bragg fiber. Another possible mechanism for the observed guidance is the antiresonance effect as discussed for photonic crystal waveguides,[6,7,22] for which even the first high-index ring and the central low-index core can contribute to the guidance.

To better understand the experimental results in Figs. 2 and 3, we use the model equation $iU_z+U_{xx}+U_{yy}-E_0/[1+I_0|J_0(r)|^{3/2}]U=0$,[9,11] where $J_0(r)$ is the Bessel function and $r=\sqrt{x^2+y^2}$. Here $x$ and $y$ are normalized by the spacing (pitch) of the lattice far away from the center, and normalizations for $I_0$, $E_0$, and $z$ are the same as in Ref. 11. The Bessel function $|J_0(r)|^{3/2}$ was chosen for the ring lattice, since the first four peaks of this function decay in a ratio of 1.00, 0.25, 0.16, 0.12 [Fig. 4(a)], closely resembling those in the experiments. Numerical simulations under experimental conditions produce results qualitatively similar to those in Figs. 2 and 3. Furthermore, we have also searched for guided modes of the above model as $U(x,y,z)=e^{-i\mu z}u(r)$ and found solutions $u(r)$, which have a high peak in the center with weak oscillatory tails. One such solution is shown in Fig. 4(b), which resembles those observed in Figs. 2(e) and 3(c). The structure of tails in such solutions depends on $E_0$, $I_0$, and $\mu$. Note that in our ring lattice, the intensity decays along the radial direction, and thus the bandgaps do not really open in the above model. Thus the solution in Fig. 4(b) cannot be a truly localized defect mode. In fact, if we keep only the central beam and the first ring of the lattice [see Fig. 4(c)], we find that quasi-localized modes as in Fig. 4(b) persist [see Fig. 4(d)]. This finding indicates that the guidance observed above may not be attributed to the repeated Bragg reflections of outer rings, but rather it is dominated by the first high-index ring in our lattice. This guidance seems analogous to that in antiresonant reflecting optical waveguides.[6,7,22]

In summary, we have demonstrated guiding light in optically induced Bessel-like photonic lattices with a low-index core. The results presented here may be of interest for creating a new type of reconfigurable PBG structure.

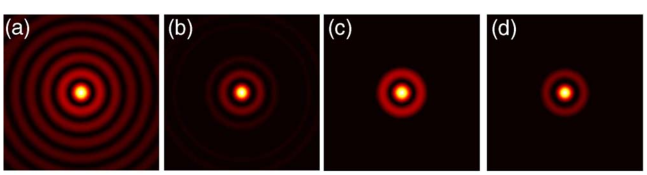


Fig. 4. (Color online) Ring waveguides and their quasi-localized modes: (a) Bessel-like ring lattice, (b) guided mode in (a), (c) lattice of (a) with outer rings removed, (d) a guided mode in (c). Normalized parameters are $E_0=-15$, $I_0=750$, and $\mu=0.97$ ($E_0=-15$ corresponds to $-1.4$ kV/cm). See color figures online for central peaks.

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