Light localization and nonlinear beam transmission in specular amorphous photonic lattices

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Abstract: We demonstrate specular photonic "lattices" with random index variations at disordered positions of lattice sites. These amorphous lattice structures, optically induced in a bulk nonlinear crystal, remain invariant during propagation since they are constructed from random components residing on a fixed ring in momentum space. We observe linear spatial localization of a light beam when probing through different "defect" points in such specular lattices, as well as the nonlinear destruction of localized modes. In addition, we illustrate the possibility of image transmission through the disordered lattices, when a self-defocusing nonlinearity is employed.

OCIS codes: (160.5293) Photonic bandgap materials; (190.4420) Nonlinear optics, transverse effects in; (230.7370) Waveguides; (130.2790) Guided waves.

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1. Introduction

Propagation of light through disordered dielectric systems and associated phenomena have intrigued scientists for more than three decades and have provided insights into recent studies on Anderson localization [1–5], random lasing [6], and disordered photonics [7]. In optical systems, photonic lattices with periodic optical modulations have been studied intensively in the past decade for exploring discrete wave dynamics [8–10]. Recently, there has been an increasing interest in the study of amorphous photonic lattices, where a host of phenomena including Anderson localization has been demonstrated [5, 11, 12]. Surprisingly, some two-dimensional amorphous photonic structures can exhibit complete photonic energy bandgaps [13, 14] or spatial photonic bandgaps [15]. Many intriguing phenomena have been studied by introducing disordered components into periodic or quasiperiodic photonic lattice structures, including disordered lattice solitons [12], bandgap guidance [15], and self-trapping of light [16]. In most prior studies, the disorders were only introduced either in lattice spacing (on-diagonal disorder), while the amplitude of potential (index change) was uniform, or in the amplitude of potential (off-diagonal disorder) at various lattice sites, while the positions of lattice sites remain to be ordered.

In this paper, we demonstrate both experimentally and theoretically an optically induced amorphous photonic structure, which has disorder in both lattice spacing and lattice potential [17]. It is a speckle-like structure constructed from a random superposition of plane-waves residing on a ring in momentum space. We demonstrate that, in such an induced specular

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photonic lattice, localization of a light beam can be realized at various sites. We observe linear localization of a probe beam, akin to the guidance of light by defects due to total internal reflection or Anderson-type localization, as well as the nonlinear evolution of a single probe beam under the action of a self-focusing nonlinearity. Furthermore, we illustrate the possibility of image transmission through the amorphous lattices when a self-defocusing nonlinearity is employed.

Our amorphous photonic structure can be readily realized experimentally via the optical induction technique [18], i.e., by launching a non-diffracting disordered light pattern through a biased bulk nonlinear crystal. This disordered light pattern is created by sending a speckled beam through a narrow annular aperture in the Fourier plane (a spatial narrow-band-pass filter), so it is inherently a random but non-diffracting pattern, combining the features of non-diffracting Bessel or conical beams with disorder due to random superposition of the spatial frequency components. Similar methods were used previously to induce the disorder for observing Anderson localization [5] and disorder-enhanced transport in quasicrystals [19]. However in this study, we examine the propagation dynamics of this disordered lattice itself rather than use it as a seeding amplitude modulation as used previously. To our knowledge, the physical properties of specular potentials without applying any underlying crystal or quasicrystal lattice have not been investigated thoroughly. Although recent work showed that similar disordered lattices can be generated by randomizing the phase of the spatial spectrum with a spatial light modulator (SLM), as used for analyzing Anderson localization by successively increasing the disorder strength of the random potential [20], we focus our work on different aspects of the amorphous lattices, and our lattice generation technique, which utilizes a diffused laser source and a ring filter, is much more convenient. The momentum space distribution of our structure is, in essence, a non-diffracting random superposition of Bessel's beams, which means that this lattice is invariant in the propagation direction. In such lattices, positive defect modes are highly pronounced and reside significantly above the "amorphous band" (dense populated region associated with Anderson localization modes).

2. Methods and results

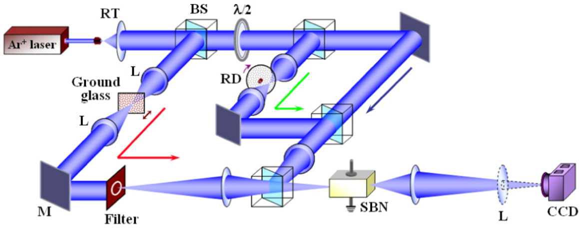

Fig. 1. A Sketch of the experimental setup. The red (left-side) route is for generating the non-diffracting disordered photonic lattice. The green (middle) route is for Brillouin zone spectroscopy, which can be added or blocked. The navy-blue (right-side) route is the probe beam. RT: reversed telescope; BS: beam splitter; RD: rotating diffuser; SBN: strontium barium niobate crystal.

As shown in Fig. 1, an Argon ion laser beam at 488 nm wavelength is split into two beams for both lattice induction and probing the lattice. Following the red (left-side) path, the speckle pattern is created by passing the beam through a ground-glass rotating diffuser, and then through a narrow ring aperture as a bandpass filter to create the random ring spectrum depicted in Fig. 2(b1). This beam subsequently passes through a Fourier transform lens to generate the desired non-diffracting disordered pattern as shown in Fig. 2(b2). The amorphous photonic lattice is established by launching the ordinarily polarized speckle pattern into a strontium barium niobate (iron-doped SBN:60) photorefractive crystal [17, 18]. Note that this induced amorphous lattice structure is disordered in both the lattice amplitude modulation and lattice spacing. As seen in Fig. 2(b3), such disordered patterns are kept

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invariant after 1cm propagation through the biased nonlinear crystal. The Brillouin zone spectrum of the induced disordered lattice is obtained by following the method described in [21].

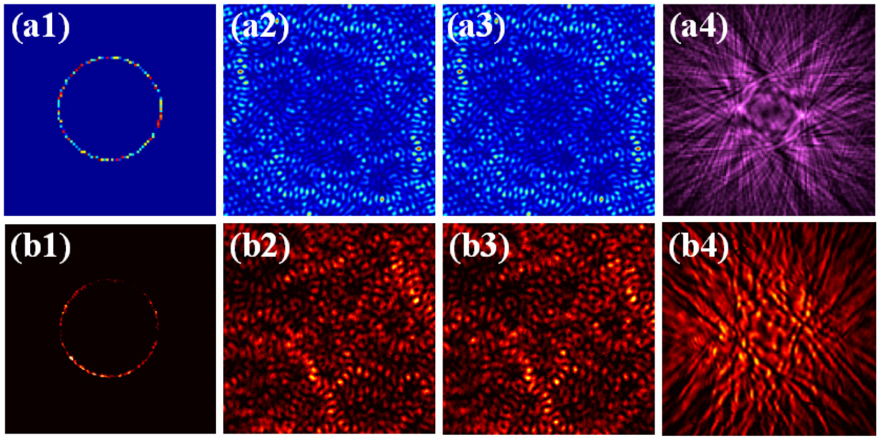

Fig. 2. Simulation (a, top) and experimental results (b, bottom) of a non-diffracting amorphous lattice and its Brillouin zone spectroscopy. (a1, b1) Spectrum of a diffused light beam after a ring-shaped spatial filter, (a2, b2) lattice input, (a3, b3) lattice output after 1cm of propagation, and (a4, b4) corresponding Brillouin zone spectrum.

We perform beam-propagation simulations similar to the method used in [5, 15, 22]. The disordered lattice is created by Fourier transform of a ring spectrum (i.e., in momentum space) shown in Fig. 2(a1), populated by a random (both amplitude and phase) superposition of plane waves. Since all the spectral components are on a single ring in momentum space, the generated lattice-inducing amorpous beam [Fig. 2(a2)] propagates invariantly. No diffraction or deformation is noticed even after 1 cm of propagation [Fig. 2(a3)]. The experimental results shown in Fig. 2(b1-4) resemble the corresponding simulation results shown in Fig. 2(a1-4). Figures 2(a4,b4) show the simulated and experimentally-measured Brillouin zone spectrum [23] of the induced disordered lattice structure, where the Bragg reflection "lines" in the amorphous photonic lattice are clearly noticeable and randomly oriented as expected.

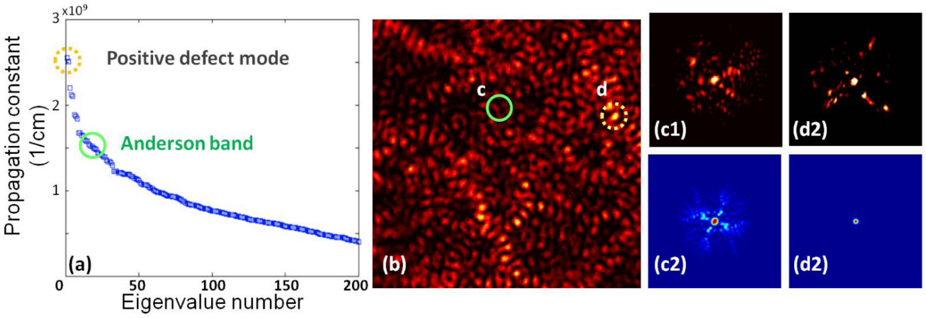

Fig. 3. (a) Calculated eigenvalue spectrum of the amouphous specular lattice and (b) observation of localized modes by launching the probe beam at different locations of the lattice with random spacing and amplitude modulation. (c) Output of the probe beam launched at a weak spot (solid circle) shows a long tail for Anderson-type localization. (d) Output of the probe beam launched at a strong positive defect point (dotted circle) shows a well-confined and much tighter localization. (c1 and d1 are from experiment while c2 and d2 are from simulation.)

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Figure 3 depicts the calculated eigenvalue spectrum of the speckle-induced disordered lattice shown in Fig. 1(a2), which has an average lattice spacing of about 20 μm and an index modulation of 5 × 10^{-4}. In both simulations and experiments, a focused Gaussian beam is launched into the induced lattice at different positions as a probe. We observed distinct linear localization of the light beam at two different regions of the spectrum marked in Fig. 3(a), corresponding to a positive defect mode (dotted circle) residing significantly above the amorphous band and an Anderson-localized mode (solid circle) residing within the amorphous band.

When the probe beam is launched at these two selected spots (see Fig. 3(b)), the corresponding output beam profiles are shown in Figs. 3(c) and 3(d), respectively. As can be seen from Fig. 3(c), when the Gaussian beam is probed at the center of the solid circle, the localized wave packet is accompanied with noticeable tails, representing a typical Anderson localization distribution. On the other hand, when the input beam is launched at the center of the dotted circle (higher index region), which can be considered as a positive defect away above the Anderson bands, the localizations are indeed much better than the Anderson-type localized mode. As shown in Figs. 3(c) and 3(d), our experimental observations (top panels) of the output beam profile agree well with our numerical simulation results (bottom panels).

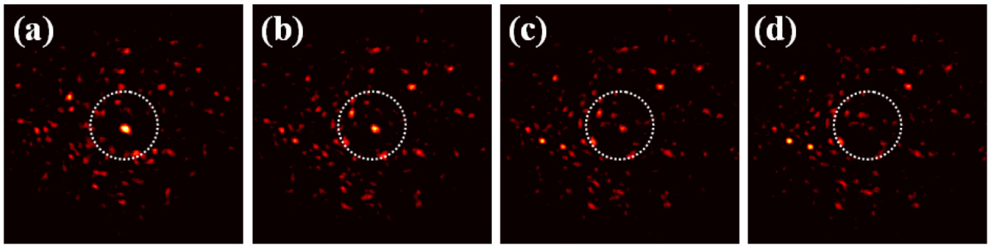

Fig. 4. Experimental results of the probe beam's output intensity pattern showing a linear localized mode (a) and its nonlinear evolution (b, c, d) in the presence of a gradually increasing nonlinearity. The disordered lattice is optically induced with a self-focusing nonlinearity, which increases in a photorefractive crystal under a positive bias electric field. The probe beam itself is initially localized as a linear defect mode. With the increasing nonlinearity, the localized defect mode is gradually destroyed from (a) to (d), and the bright spot at the center of the dashed circle disappears.

Next, we demonstrate the nonlinear evolution of such localized states in the disordered lattices by employing a self-focusing nonlinearity through appropriately adding a positive bias field across the SBN crystal [18]. To do so, we launch a narrow Gaussian probe beam into the disordered lattice at a relatively high index region. As shown in Fig. 4(a), an expected linear localized state with a pronounced tail is observed similar to that shown in Fig. 3(c), which is a superposition of Anderson localization modes. When the nonlinearity increases (here through increasing the bias E-field while keeping the beam intensity unchanged), the local index modulation also increases gradually, changing the shape of the localized defect mode. With increasing self-focusing nonlinearity, an initially tightly localized state [Fig. 4(a)], resulted from linear defect guidance, gradually disappears [Figs. 4(b)-4(d)] as the defect is gradually destroyed by the increasing nonlinearity. The mechanism for this nonlinearity-induced expansion can be intuitively understood as follows. We have excited a number of Anderson modes that lie within the amorphous band. The input beam has excited a superposition of Anderson modes that happens to have a small region of high power. Some of them are not at the Anderson band edge, but instead in the interior of the band. By adding the focusing nonlinearity (which changes the potential, mixes these modes, and allows them to change in time), the excited modes may now resonantly couple to modes located higher in the band. This tunneling allows light to "escape" from the bright, localized region and spread to other parts of the lattice. It should be noted that this phenomenon would not occur in a

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periodic lattice and is therefore a signature of the localization properties of the amorphous lattice. In a periodic lattice, by contrast, adding self-focusing nonlinearity would simply cause a localized soliton solution to emerge above the band (e.g., to appear in the semi-infinite gap) and it would tend to localize better as the nonlinearity is increased [24]. We point out that the nonlinearity we used for Fig. 4 is well below saturation and the probe or lattice beam would not form soliton or a solitonic lattice itself as shown before [25].

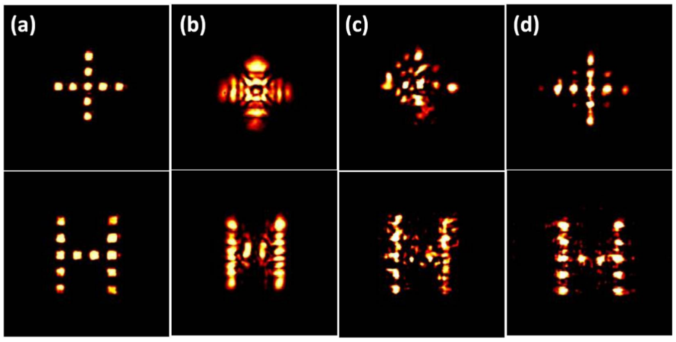

Fig. 5. Experimental demonstration of image transmission through an amorphous lattice under the action of a self-defocusing nonlinearity. (a) Input images (intensity pattern of a cross or H shape as created from an amplitude mask). (b) Output patterns after 1 cm of propagation through free space. (c, d) Output patterns after 1 cm of propagation through the disordered lattice at a (c) low and (d) high self-defocusing nonlinearity controlled by the negative bias field.

Finally, we present experimental observation of non-diffracting text or image transmission through nonlinear disordered lattices. In Fig. 5, we monitor the propagation of intensity patterns containing images, such as a cross or an H shape, under different conditions. Clearly, the image is distorted after propagation through free-space (Fig. 5(b)) or a disordered lattice induced under a weak nonlinearity (at a bias field of less than −10V/mm, Fig. 5(c)), where the index potential can be considered as linear. However, the image is restored when the input position of the image is adjusted appropriately (close to an intensity minimum in the disordered lattice) and a strong self-defocusing nonlinearity is applied (at a bias field of about −100V/mm, Fig. 5(d)). We can see that, with this self-defocusing nonlinearity, the results of image transmission are improved significantly. Since the probe beam itself has no nonlinear self-action (much weaker than the lattice-inducing beam), these restored images might arise from many defect modes with localized wavepackets of the amorphous lattices. The theoretical understanding of these experimental observations merits investigation, as it is certainly different from prior demonstrations of image transmission based on linear coherent destruction of tunneling [26, 27] or nonlinear gap solitons of arbitrary shapes [28] in ordered photonic lattices. In fact, imaging through disordered and/or nonlinear media in general is turning into an important field involving fascinating topics, including for example in situ wavefront correction [29], imaging through nonlinear media using digital holography [30], and perfect imaging through 1D disordered waveguide lattices [31]. The combined approaches mentioned in this paper, may bring forth new applications.

3. Summary

In summary, we have introduced a new amorphous photonic structure with disordered modulations in both lattice spacing and amplitude. We have experimentally created these two-dimensional non-diffracting disordered photonic lattices using an optical induction method. Localized modes due to Anderson-type localization and more tightly localized “defect” modes have been observed. In addition, we have also shown the nonlinear evolution of localized modes and illustrated the possibility of image transmission through nonlinear

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amorphous lattices. Our results bring about a convenient setting to study both linear and nonlinear wave phenomena in the presence of disordered potentials.

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