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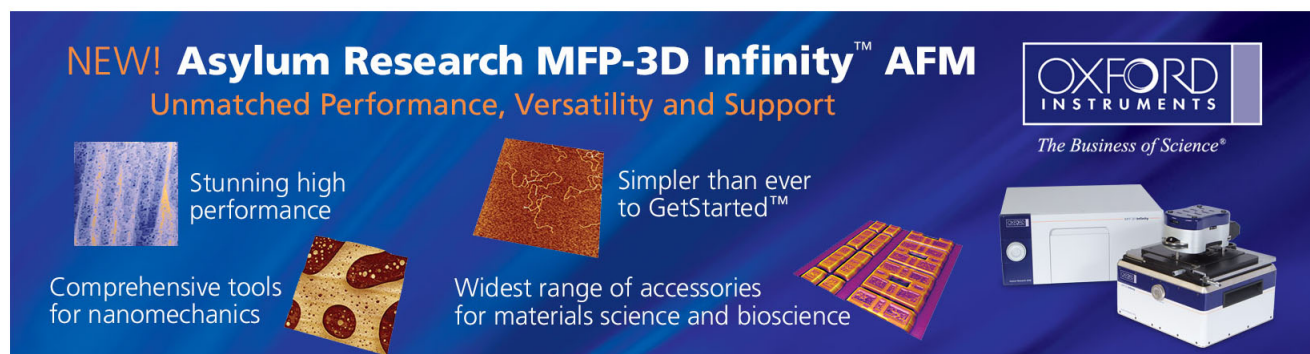J. Laser Appl. **18**, 320 (2006); 10.2351/1.2355525

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Ultrafast laser inscribed waveguide lattice in glass for direct observation of transverse localization of light

Somnath Ghosh,[1] Nicholas D. Psaila,[2] R. R. Thomson,[2] Bishnu P. Pal,[1] R. K. Varshney,[1] and Ajoy K. Kar[2,a)]
[1]Physics Department, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India
[2]School of Engineering and Physical Sciences, David Brewster Building, Heriot-Watt University, Edinburgh, EH14 4AS, Scotland

We present initial results of the direct observation of the signature of localized light in an ultrafast laser-inscribed (ULI) disordered lattice that contains an array of evanescently coupled, one-dimensional optical waveguides in glass in which certain amount of disorder in refractive index was introduced. Numerical simulations were carried out to test the feasibility of the initial experimental design. Such configurable ULI disordered waveguide lattices should open up a platform for investigating the phenomenon of transverse localization of light and its statistical nature. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.3691194]

The phenomenon of Anderson localization[1] of wave functions in disordered systems is now accepted to be ubiquitous in wave physics,[2–4] which includes possibility of localization of light in a disordered dielectric lattice.[4] Raedt et al.[5] introduced the concept of *transverse localization* of light in a semi-infinite disordered dielectric geometry. In recent years, there has been a resurgence of interest in this area from a fundamental physics point of view and for photonics applications.[2–11] The first ever experimental demonstration of light localization in a 2-D (temporally realized) disordered lattice was reported in Ref. 8. In this paper, we propose the technology of ultra-fast laser inscription (ULI) as a versatile tool for realizing waveguide lattices with attractive features such as a configurable level of disorder, as well as for studying the statistical nature of the localization phenomenon in permanently disordered lattices.

By numerically simulating the propagation dynamics of a light beam through a disordered lattice geometry[9,12] consisting of 100 unit cells (i.e., a pair of high and low index regions) of evanescently coupled 1D optical waveguides, the femto-second ULI experiment was designed, and its fabrication recipe defined. Such lattices with a specific level of disorder but of different realizations have been fabricated and investigated to account for the statistical nature of the phenomenon. All the waveguides in the lattice were embedded inside a medium of constant refractive index n_0.[12,13] The transverse refractive index variation $\Delta n(x)$ (over the uniform background n_0) profile of this 1-D waveguide lattice was assumed to follow the following expression:

$$\Delta n(x) = \Delta n_p(H(x) + C\delta(x)), \qquad (1)$$

where C is a dimensionless constant whose value governs the level/strength of disorder; the periodic function $H(x)$ takes the value 1 inside the higher-index regions and is zero elsewhere; $\Delta n(x)$ consists of a deterministic periodic part Δn_p of spatial period Λ, and a spatially periodic random

component δ (uniformly distributed over a specified range varying from 0 to 1). This particular choice of randomly perturbed refractive indices in the high index, as well as low index layers, enables us to model the diagonal and off-diagonal disorders to study the localization of light.[9,14] The remaining details of modelling light localization in such a disordered waveguide lattice have been described in our earlier paper.[12] The choice of the parameter set for an optimized lattice structure for this target experiment was dictated by the ULI technology;[15] the chosen lattice consisted of N number of periodic waveguides, each of 7 μm width and spatially separated by 7 μm [see Fig. 1(a)]. The unperturbed lattice of waveguides had a periodic index modulation Δn_p of 0.001 over the bulk Er-doped bismuthate glass sample.

The lattice consisting of an array of a large number of waveguides [Fig. 1(a)] was fabricated using a Fianium® Femtopower Yb-doped fiber laser emitting 350 fs pulses at a wavelength of 1064 nm. The repetition rate of the laser was set to 500 kHz. The pulses were focused onto the erbium doped bismuthate glass through an aspheric lens of 0.4 NA [see Fig. 1(b)].

First, a 500 μm wide slab waveguide was written using a multi-scan technique employing sequential passes (each with 0.4 μm spacing) of 86 nJ pulses and an 8 mm/s writing speed. The slab waveguide yielded single-mode guidance in the vertical direction and highly multimode guidance in the horizontal direction. Second, array elements were superimposed onto the slab waveguide using the same multi-scan technique and overwriting onto the slab again with a separation of 0.4 μm
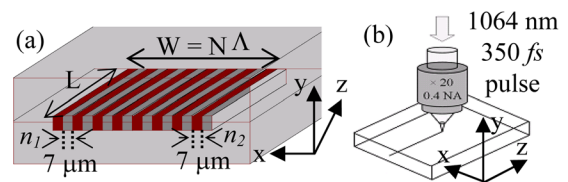

FIG. 1. (Color online) (a) Schematic of the chosen evanescently coupled waveguide lattice. (b) Schematic of the femto-second laser inscription technique.

a)Electronic mail: a.k.kar@hw.ac.uk.

between successive passes.[15] The array pitch was set at 7 μm with a duty cycle of 50%. The same pulse energy of 86 nJ was used in order to maintain the same depth of the inscribed pattern due to the self-focusing effect. The elemental inscription inside the slab was carried out at a translation speed of 10 mm/s. The insertion loss will be relatively high, as the samples used for this work were very highly doped bismuthate glass (which had an Er concentration of 4.8×10^{20} ions/cm^3), and we were propagating light in it at 980 nm. Assuming a cross section of approximate 2.5×10^{-21} cm^2, which is standard, this would result in an absorption loss alone of >5 dB/cm at 980 nm.

In order to produce randomized arrays, a pseudo-random array pattern was generated with numbers ranging between 0 and 1. This array was then multiplied by the writing speed and a scaling factor. These values were then fed to the array element writing speed to introduce a scalable randomness in the speed of inscription between each element. Changing the writing speed allows fine control of the net amount of laser energy transferred to the substrate, which essentially dictates the net modification of the refractive index. A range of arrays with varying C's as scaling factor was fabricated, using the same pseudo-random array pattern for each. Arrays with $C = 0$ to 0.6 through control of the translation speed were inscribed with a step size of 0.1 relative to the previous sample. It takes approximately two hours to fabricate a set of lattices with specific disorder levels $C = 0$, 0.1, 0.3, 0.4, 0.5, and 0.6, respectively, on the chosen glass with suitable aspect ratio.

In our numerical simulation for designing the experiment, we distributed the refractive index over different unit cells of the waveguide lattice following the prescription contained in Eq. (1), while retaining the same spatial periodicity. We introduced disorder over and above the perfectly ordered waveguide arrays as shown in Fig. 1(a) of uniform refractive index contrast. To simulate the after-effect of different levels of deliberately introduced refractive index disorder on the propagation dynamics of light through this geometry, we considered launching a probe light beam at an operating wavelength of 980 nm around the central unit cell of the lattice at its input plane. The input beam, whose spot size (w_0) was 10 μm, covered more than one unit cell around the central unit cell. In the absence of any disorder, numerically simulated propagation dynamics of an input Gaussian beam of wavelength 980 nm through the lattice indicated the ballistic mode of light propagation (Fig. 2(a)) due to discrete linear diffraction. When we introduce a 20% disorder into the refractive index distribution, the afore-mentioned ballistic expansion of the beam is significantly reduced as shown in Fig. 2(b) due to the localization effect. Recently, we had shown the behavior of effective beam width (ω_{eff}) variation (chosen as a characteristic parameter to represent localized state) with the disorder parameter C to quantify the degree of light localization.[12] For values of C above a threshold value, ω_{eff} remains almost unaltered beyond a certain propagation distance (except for the nominal statistical fluctuations). This invariance in ω_{eff} with propagation is recognized as the signature of localized light.

The ensemble-averaged (over 100 realizations, i.e., 100 different δ's) output intensity profiles from the lattice after a
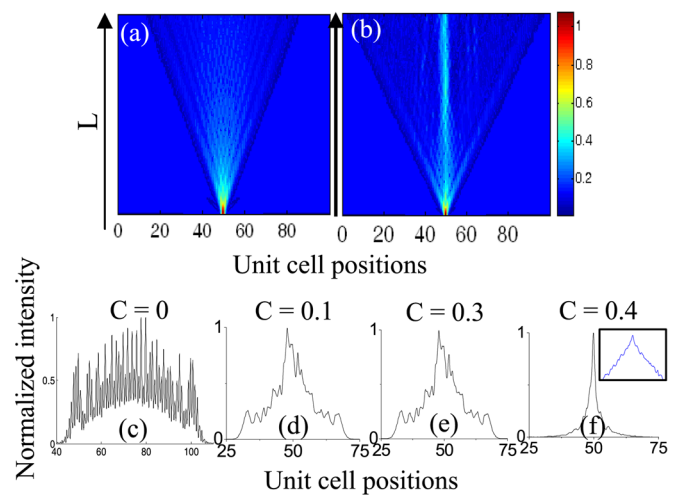

FIG. 2. (Color online) Simulation results for beam propagation through the chosen disordered lattices: (a) Simulation result indicating ballistic mode of propagation through a perfectly ordered lattice; (b) transition to a localized state in a 20% disordered lattice; (c) to (f) show the evolution of the building up of a central peak in intensity as an indicator of transition from ballistic mode to a localized state with increasing disorder from 0% to 40%; the inset in (f) indicates the localized intensity profile on a semi-log scale.

propagation of 15 mm, as obtained through detailed numerical simulations, are plotted in Figs. 2(c)–2(f) for strengths of disorder, i.e., C as 0%, 10%, 30%, and 40%, respectively; this sample length of 15 mm was chosen as simulations have indicated that for $C = 0.4$, this length is sufficient to achieve localization. A clear evolution from the ballistic mode of expansion (see Fig. 2(c)) to a characteristic localized state (see Fig. 2(f)) via intermediate states, with gradual suppression of side-lobes (characteristic of ballistic mode of propagation) and a corresponding building up of exponential tails (characteristic of localized state), is evident from Figs. 2(c)–2(f). The inset in Fig. 2(f) clearly manifests the linear tails of a localized state when plotted on a semi-log scale, which is well reported in the literature as a signature of the localization of light.

In order to validate our afore-mentioned findings of numerical simulation in the context of transverse localization of light, we fabricated several ULI waveguide lattices having different levels of disorder (C), ranging from 10% to 60% in increments of 10%. Moreover, in order to address the important issue of the statistical nature of the phenomenon in a finite-sized lattice, we fabricated lattices of different realizations for a particular C (because just one particular realization of a specific level of disorder does not necessarily reveal seizure of the beam broadening due to disorder in a 1-D lattice of finite length). In Fig. 3(a), we have shown a microscopic view of one of the fabricated ULI disordered waveguide lattices. For better clarity, a zoomed portion of the same sample is also shown as inset in the same figure. Light from a 980 nm fiber laser at a relatively low power level (to avoid the possibility of any nonlinear effects, which may arise due to the inherent nonlinearity of the sample) was launched into the fabricated waveguide lattice around its central region through an intermediate microscope objective. A CCD camera was employed to record the intensity distribution from the image of the lattice output. From the measured output intensity distribution, it can be seen that
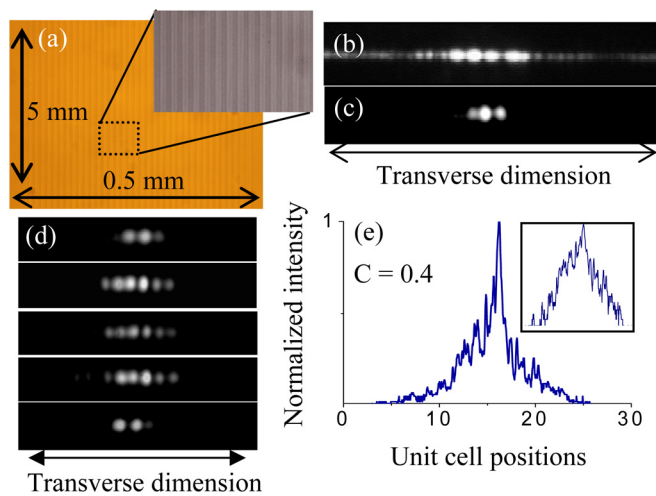
FIG. 3. (Color online) Observation of localized light in ultra-fast laser-inscribed disordered lattices: (a) Microscopic view of a ULI lattice of coupled waveguides, the inset shows the zoomed version of the marked area. (b) Measured output intensity distribution from the lattice under ballistic mode of propagation (as in Fig. 2(a)) in arbitrary units. (c) Measured output intensity distribution corresponding to a localized state for a disordered lattice having $C = 0.6$. (d) Localized states for different realizations of the same strength ($C = 0.6$) of disorder when the input beam was incident at the same location with respect to the waveguide lattice. Measured ensemble averaged output intensity profiles from waveguide lattices having $C = 0.4$, which corresponds to threshold for realization of localized light, is shown Fig. 3(e); the inset represents the localized intensity profile on a semi-log scale.

Fig. 3(b), which corresponds to propagation through an ordered lattice, that the launched beam propagates as a linearly diffracted beam (analogous to simulation results shown in Fig. 2(a)) due to the translational symmetry of the lattice. Whatever asymmetry was present in the measured output intensity profile could be attributed to insufficiently high precision in the state-of-the-art ULI technology. In this case, the chosen sample length of 5 mm is not sufficient enough to achieve the localized state with this unwanted very low level of disorder. However, this inherent scattering will lead to localization only after a length of about 210 mm, with the scattering being modeled as 5% disorder. The coupling length has been estimated from the contour image (photograph taken from the top of the sample while light beam was propagating through it) of the intensity evolution of the propagating beam through our fabricated lattices along length. The estimated coupling length is 1.42 ± 0.2 mm for a particular fabricated ordered lattice at the operating wavelength. As mentioned earlier, through adjustment in the laser writing speed we could realize lattices with different levels of disorder (i.e., of different C's). Figure 3(c), which corresponds to the measured output intensity distribution from a disordered lattice having $C = 0.6$, indicates a clear signature of a localized state of light. In order to incorporate the characteristic statistical nature of the localization phenomenon, we fabricated a set of ULI lattices of same C of 0.6 but of different δ's. In Fig. 3(d), we show a set of output intensity profiles from these lattices of different realizations. In all these cases, the input beam was focused at the same location at the input plane of these lattices, while the output intensity measurement window was kept centered with respect to the lattices, as before. To establish the fact that the experimental results

could demonstrate the transition from an initial regime of ballistic expansion to the localized regime in our ULI samples as a function of the imposed disorder, we also studied light propagation through five different realizations of disordered ULI waveguide lattices with intermediate disorder levels of $C = 0.1$, 0.3, 0.4, and 0.5, in addition to the above mentioned case of $C = 0.6$. We determined the ensemble average of the measured output profiles from those lattices whilst keeping the input excitation constant. A sample result of such measurements from our 5 mm long lattice is shown in Fig. 3(e) for a disordered ULI lattice having $C = 0.4$, which was sufficient to attain localization. To get a better appreciation of the linearly decaying tail displayed in the inset in Fig. 3(e), we need to take the ensemble average over more numbers of measured output profiles from different realizations of the disorder. The estimated localization length in one of the fabricated disordered lattice (particular realization) is ($83 \, \mu m \pm 3.5 \, \mu m$). Since the actual refractive index modifications in the laser inscribed disordered lattices could not be precisely estimated due to the limited scope of the state-of-the-art facilities for this relatively high refractive index glass, it was difficult to carry out precise simulation of the experimental data.

Nevertheless, initial simulations to design the ULI experiment were indeed verified as the ULI waveguide lattice with deliberately introduced sufficient disorder in refractive index demonstrated direct observation of the evolution of a light beam from its initial ballistic mode of propagation to a localized state in a disordered waveguide lattice. In our fabricated finite 1-D waveguide lattice, we have shown the occurrence of ballistic mode of wave expansion in the spatial domain, where lattice length plays the role of time coordinate in the original Anderson model.[1,8] These 1-D lattice structures in the form of coupled waveguides could be written with targeted transverse disorder with a fair degree of control. This fabrication technology also facilitates the process of achieving different realizations of same level of disorder in a permanent structure in order to study the important aspect of the phenomenon's inherently statistical nature. This experimental route thus affords an extra degree of freedom for studying the phenomenon of transverse localization of light in disordered structures. We anticipate that this methodology could be an efficient tool to study the role of a prominent photonic bandgap and the transverse localization of light,[16] along with various other fundamental aspects of the phenomenon in permanently disordered 1-D lattices. Such a detailed study may be undertaken in the near future. One of the main reasons for using the chosen glass was due to the relatively large green up-conversion present upon pumping the glass with 980 nm. This allows the viewing of the light from above the sample and observing the evolution of the localised state. We have reported the results on light localization at low input power level (only few mW) of the beam. The chosen glass sample could be potentially used as a gain medium once the localized state of light is achieved; a step further to realize random laser in 1D in disordered waveguide lattices. Also, there would have been 1550 nm ASE present when pumping at 980 nm; however, with the present experimental conditions, the pump level was not been sufficient enough to make ASE significant. We may

like to mention that localisation at 1550 nm ASE band of the sample would be very interesting and would play a key role while designing experiments to realize random laser. In that case, we need to choose a high pump power at the absorption bands, and at the same time, we need spectral selectivity of the output localized state to achieve the localization effect of around the signal at 1550 nm in ASE band. A suitably designed waveguide lattice with underlying photonic bandgap and with right disorder should be useful for this study. The underlying PBG helps to control the spectral selectivity of the localized state in the presence of disorder.

In conclusion, this paper reports the implementation of the ULI technique as a platform for investigating the phenomenon of light localization. The experimental results have demonstrated the signature of the localization of light taking place in sufficiently disordered lattices. Moreover, we believe that this fabrication technique can be exploited as a platform for studying transverse localization of light in a variety of situations, in addition to the perturbation studies of refractive index discussed in this paper; for example, in the simultaneous presence of diagonal (randomly changing waveguide widths) and off-diagonal disorders (randomly changing separations between two successive waveguides)[14] or in the case of pure diagonal disorder as considered in the original localization model.[1] These studies would however require more extensive experimentation. Further, this method could be extended to study the localization of light in higher dimensions of disordered photonic lattices[17] and in lattices with a controlled level of refractive index modulation depth, from very low to higher values[18] (which may not be achievable in typical photorefractive crystals by using the optical induction technique).

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