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Image transport quality can be improved in disordered waveguides ☆

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ABSTRACT

We show that the quality of image transport can be improved in disordered waveguides compared with periodic waveguides such as coherent fiber optic bundles that are commonly used for imaging applications. The improvement is due to the transverse Anderson localization phenomenon that creates localized transport channels with finite radii through the disordered imaging waveguide.

Multicore optical fibers have been used extensively in high resolution optical imaging, especially in biological and medical imaging applications [1–4]. The transmitted images are inherently pixelated due to the discrete nature of the light-guiding array of cores [3,4]. The pixelation can be reduced by increasing the number density of cores per unit area; however, care must be taken to ensure that the cores remain optically uncoupled to minimize power leakage to neighboring cores, avoiding image degradation. Detailed analyses of imaging fibers have been performed in the published literature and identify the best practices and trade-offs in selecting the geometrical and optical characteristics of imaging fibers (see, e.g., [5]).

Inter-core coupling can negatively affect the performance of imaging fibers. Certain structural non-uniformities such as variations in the size of the cores have been shown to improve the image quality by reducing the core-to-core coupling efficiency due to the mismatch in the effective index of the neighboring cores [5]. However, for the common levels of core-size variations, such as in Fujikura FIGH-10-350S, the inter-core coupling remains large enough to lower the image transport quality; therefore, high numerical aperture cores are suggested to reduce the core-to-core coupling [4].

In this paper, it is argued that with a sufficient amount of random variations in the transverse structure of the imaging fiber, it is possible to transport images without considerable degradations, even if the cores are coupled either because they are too close or their numerical aperture is not sufficiently high. In disordered optical fibers, transverse Anderson localization results in localized transport channels (localized modes) that can transport the image through the fiber with a point spread function radius comparable to the localization length (effective localization radius) [6–9]. A recent report of the simultaneous transport of multiple beams in a disordered optical fiber highlights the possibility for imaging through disordered waveguides [10].

In order to examine the impact of disorder on the quality of image transport, we consider a reduced model in the form of a one-dimensional (1D) disordered slab waveguide [11]. The 1D waveguide provides the necessary physical landscape to assess the proposed idea, having to resort to heavy numerical computations that are required for the propagation and transverse localization of light in a disordered optical fiber. Moreover, it is easier to visualize the effect of the disorder on the image transport in one dimension. The waveguide studied here is similar to the one recently introduced in Ref. [9]. The advantage of this waveguide is that it is possible to introduce disorder in a controlled fashion and to quantify the impact of a gradual transition from an ordered to a fully disordered waveguide.

The waveguide considered here is constructed by perturbing a 1D periodic slab waveguide sketched in Fig. 1 (left), consisting of 100 slabs of equal thickness $\bar{t} = 20\Lambda$. λ is the optical wavelength and $\Lambda = \lambda/20$ is assumed. The slabs have alternating refractive index values of $n_t = 1.50$ and $n_b = n_t - \delta n$, and a periodic boundary condition is assumed for the slab waveguide. In order to construct the refractive index profile of the 1D disordered optical waveguide that is shown in Fig. 1 (right), the thickness of each slab is perturbed around a mean value of $\bar{t} = 20\Lambda$ by $\delta t = \eta\Lambda$. η is chosen from a zero-mean uniform integer-valued distribution in the

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interval $[-\Delta, \Delta]$, where Δ is referred to as the disorder level. For example, by choosing $\Delta = 2$, we assume that δt can be selected with equal probability to be 0, $\pm\Lambda$, or $\pm 2\Lambda$.

In Fig. 2, we consider the propagation of a Gaussian beam with a transverse electric field profile of the form $\exp(-x^2/2w_0^2)$, where x is the transverse coordinate along which the refractive index varies, and $w_0 = 5\lambda$ characterizes the beam width. TE polarization is implicitly assumed in the simulations without any effect on the general conclusions presented in this paper. The propagation along the waveguide is implemented by numerically solving the wave propagation equation (1), using the Fast-fourier transform beam-propagation method (FFT-BPM):

$$i\frac{\partial A}{\partial z} + \frac{1}{2n_0k_0}[\nabla_T^2 A + k_0^2(n^2 - n_0^2)A] = 0. \quad (1)$$

Eq. (1) is the paraxial approximation to the Helmholtz equation, where $A(\mathbf{r})$ is the slowly varying envelope of the primarily transverse electric field, where $k_0 = 2\pi/\lambda$ and $n(x,y)$ is the (random) refractive index of the optical waveguide which is a function of the transverse coordinate, while n_0 is the average refractive index of the waveguide [12].

The total propagation distance is taken to be $L = 1000\lambda$ and the index difference is $\delta n = 0.02$. Fig. 2(a) shows the optical intensity of the beam at the input. The output intensity after propagation through a periodic waveguide ($\Delta = 0$) is shown in Fig. 2(b), in which considerable pixelation and coherent inter-core coupling can be observed. The inter-core coupling is responsible for the spreading of the optical power; such a spreading is proportional to the propagation distance. Similar to Fig. 2(b), subfigures (c) and (d) show the output intensity of the beam, except that the waveguides are disordered with the disorder levels of $\Delta = 10$ and $\Delta = 20$, respectively. Transverse Anderson localization limits the spreading of the beam in the case of disordered waveguides; unlike the case of a periodic array, the beams remain confined in the transverse direction to a region whose size is determined by the localization radius. The pixelation in the periodic array is also replaced with the random intensity variations, which result from the beatings of the transverse Anderson localized modes [9].

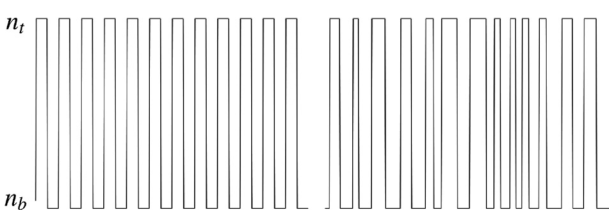

Fig. 1. Sample refractive index profiles of ordered (left) and disordered (right) slab waveguides are shown.

While the images presented in Fig. 2 show the beneficial impact of the disorder in keeping the beam localized, which is essential in image transport, the improvement must be quantified by a proper metric. Moreover, the inherent variations due to the randomness in disordered structures imply that the imaging performance can vary from device-to-device and even at different positions across the device. Therefore, it is important to quantify such inevitable variations and ensure that they remain at an acceptable level.

We use a metric that quantifies the confinement of the optical power near the peak of the launched Gaussian beam: the beam confinement factor is defined as

$$\tilde{C} = 10 \log (P_s/P_n), \quad (2)$$

where P_s is the total optical power in the central region $|x| \le w_0$ and P_n is the total power outside this region.

In Fig. 3, we plot the beam confinement factor as a function of the disorder level for propagation in the disordered 1D waveguide. The propagation distance is $L = 1000\lambda$, $\delta n = 0.05$, and $w_0 = 5\lambda$. For each value of disorder level, $\tilde{C}$ is averaged over 100 independent realizations of the disordered waveguide, where the error bars indicate one standard deviation around the mean. The case of $\Delta = 0$ indicates the propagation of the Gaussian beam in an ordered periodic waveguide, where the power leakage caused by the efficient inter-core coupling results in a low value of confinement. Increasing the disorder level improves the confinement to levels not far from that of an ideal Gaussian beam at the input; $\tilde{C}$ saturates to approximately 4.5 dB for $\Delta > 13$. For an ideal Gaussian beam (such as in Fig. 2(a)), $\tilde{C} \approx 7.3$ dB. The reduction in the value of the standard deviation when the disorder is increased is notable; it indicates that the improvement in the confinement factor can be reliably expected for different random realizations of the waveguide, as well as different positions across each waveguide.

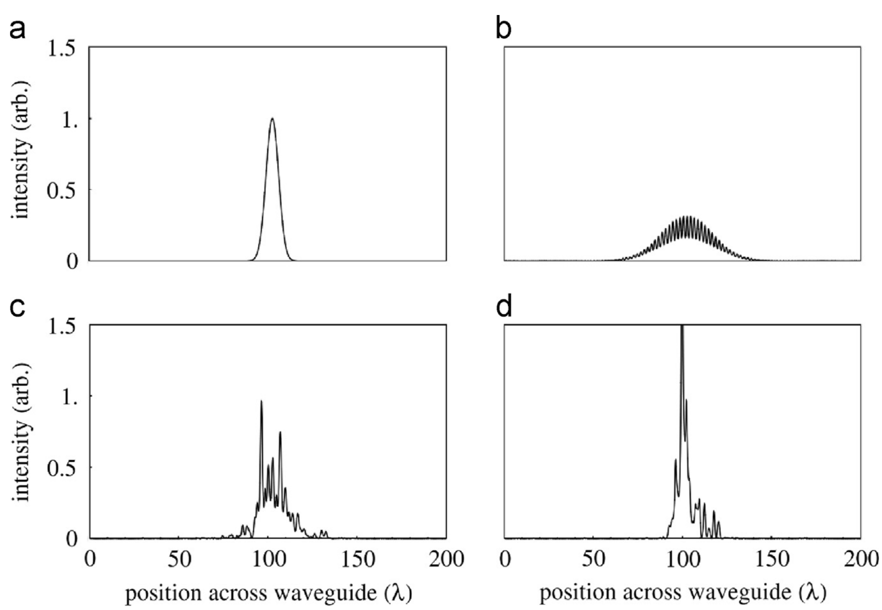

Fig. 2. Intensity plots of the beam from the slab waveguides at the (a) input, (b) output in a periodic waveguides, (c) disordered waveguide with $\Delta = 10$, and (d) disordered waveguide with $\Delta = 20$. (c) and (d) are for a single realization of the disordered waveguide.