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Strong Light Confinement in Novel Compact Pseudo-Random Structures Designed via Evolutionary Algorithms

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Abstract: High optical confinement of 1.55 μm light is shown in a 5 μm sized high-index-contrast pseudo-random distribution of dielectric rods. This structure, designed using Evolutionary Algorithms, utilizes Anderson Localization to achieve confinement.

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In random media, when the separation distance between high-index contrast scattering sites is on the order of the wavelength, interference from multiple scattering events can result in a wave propagation phase transition [1]. Media satisfying this condition is referred to as strongly scattering. Depending on the size and arrangement of the strongly scattering media, light can cease classical diffusive propagation and form localized stationary eigenstates (Anderson Localization) [2]. For waves confined to one or two dimensions localization always occurs in the limit that the size of the disordered media reaches infinity [2]. In contrast, for finite size media, light leakage results in finite lifetimes of the eigenstates and consequently a broadening of eigenstate energy levels. According to the Thouless criterion, a localized eigenstate persists as long as the spacing between the energy levels of different eigenstates is larger than the spectral width of the state [3]. Mathematically this can be represented as a Thouless number (γ_T) less than 1 where $\gamma_T \equiv \frac{\delta\omega}{\Delta\omega} \approx \frac{\delta\lambda}{\Delta\lambda}$, $\delta\omega$ is the full width at half maximum (FWHM) spectral width of the eigenstate and $\Delta\omega$ is the average spacing between eigenstates.

Confinement and enhancement of light due to Anderson localization has been observed in active media such as metal-dielectric nanocomposits, as well as materials with optical gain [4–7]. In these works the enhancement is largely a consequence of gain or surface plasmon resonances. In random passive media, however, only indirect evidence of confinement has been shown at microwave and near infrared wavelengths [8–10].These measurements, however, rely on statistical analysis of various sizes of samples and reveal no information specific to localized eigenstates in a single sample.

To date, small modal confinement has not been directly observed in compact (finite sized) random passive media. The difficulty in observing confinement effects in such structures is the extreme sensitivity of both the coupling of an input source and degree of localization to the configuration of the scattering media [2]. For physically-realizable compact structures strong confinement is difficult to achieve due to the broadening of the eigenstate spectral widths resulting from light leakage in finite size media.

In this paper, we obtain strong intensity enhancement due to Anderson localization in a compact passive media by using an Evolutionary Algorithm (EA) to design a pseudo-random structure which achieves large intensity enhancement in a highly localized eigenstate. EAs are inspired by natural evolution, and operate by repeatedly selecting, varying, and replicating successful individuals in a population of candidate solutions [11]. These algorithms are well suited for finding solutions to problems that involve very large and complex search spaces that do not have smooth gradients leading to an optimum. In this work the algorithm optimizes the time-averaged peak intensity which is calculated by directly solving Maxwell's equations in the structure using 2D finite difference time domain (FDTD) method.

The optimized compact passive structure where light enhancement occurs is shown in Fig. 1(a). It consists of a single mode input slab waveguide operating at 1549.5 nm with a TE polarization (E points out of the plane) incident on a 5.04 μm by 5.28 μm grid. The grid is composed of 120 nm by 120 nm squares which are either a high ($n_H = 3.50$) or low index ($n_L = 1.46$) passive dielectric material. In the 2D FDTD computation these squares repre-

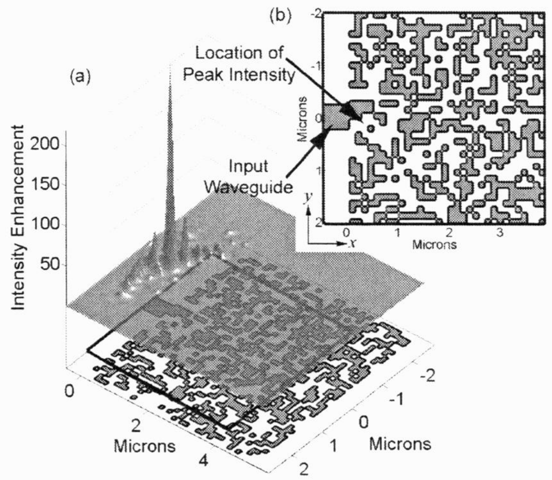

Fig. 1. (a) 2D FDTD simulation of the time-averaged intensity normalized to the input intensity in the optimized pseudo-random dielectric structure illuminated at its resonant wavelength (1549.5 nm) by an input waveguide. The intensity enhancement from the simulation is superimposed over the dielectric structure. (b) top view of the boxed portion of the dielectric structure. The gray and white boxes represent high index ($n_H = 3.50$) and low index ($n_L = 1.46$) dielectric rods, respectively.

sent infinitely long rods which extend into and out of the plane. It is important to note the configuration of the structure near the end of the input waveguide at $x = 0\ \mu\text{m}$, $y = 0\ \mu\text{m}$ (see Fig. 1(b)). The arrangement of the high index material connected to the waveguide aids in coupling the waveguide mode to the localized eigenstate. The intensity enhancement (calculated from the FDTD simulation) superimposed over the structure in Fig. 1(a) shows strong intensity enhancement due entirely to Anderson localization. The peak average intensity is over 200 times that of the input waveguide. The effective modal area defined as

$$A_{eff} \equiv \frac{\int \epsilon(\vec{r})|E(\vec{r})|^2 d^2r}{\max[\epsilon(\vec{r})|E(\vec{r})|^2]} \tag{1}$$

is $0.0465 \pm 0.0015 \mu\text{m}^2$ or $0.95 \pm 0.03(\frac{\lambda}{2n_H})^2$.

The type of EA used to construct the arrangement of high and low index materials is known as a Particle Swarm Optimization (PSO) [12, 13]. The PSO operates under the principles of swarm intelligence observed in nature. Swarms of bees, colonies of ants, and schools of fish behave with an overall intelligence to find food, avoid predators, and survive. This behavior is not dependent on a leader but rather the collective interaction of identical individuals operating under simple principles. This paradigm can be applied to an optimization algorithm which consists of simple individual agents working collectively to achieve a goal. Applied to the goal of achieving strong intensity enhancement, a single agent is represented as a possible configuration of high and low index materials. A configuration is stored as a binary string of 1848 bits corresponding to either a high index (1) or a low index (0) rod in a 42 by 44 bit grid. Each agent has a corresponding fitness defined as the peak intensity enhancement for 1550 nm input as calculated from 2D FDTD. During the evolutionary process, agents are attracted to combinations of other agents with high fitness. Attraction is accomplished by increasing the probability for their bits to match a highly fit individual's. After stochastically flipping bits the agents are re-evaluated with 2D FDTD. If a new configuration shows greater intensity enhancement than shown previously this individual replaces the previously attractive agent. The iterative process begins with a population of individuals with randomly selected bit strings (equally distributed with 1's and 0's), and continues until fitness remains relatively constant over many iterations.

Fig. 2(a) plots the intensity enhancement at 1550 nm versus the number of times the fitness is evaluated (i.e. FDTD simulations). Each point in the figure represents a possible structure with a given intensity enhancement which was computed after the corresponding number of fitness evaluations. A PSO with population size 20 is represented as the solid line in Fig. 2(a). A random search (Fig. 2(a) dashed line) was performed as a benchmark where a structure was defined by randomly selecting a bit string with equal probability of 1's and 0's and its fitness evaluated. Comparing the large field enhancement obtained from the evolutionary algorithm and the low values returned by the random search, it is apparent that the PSO enables the controlled design of eigenstate characteristics in compact strongly scattering structures.

Fig. 2(b) shows the spectrum of the intensity stored in the structures depicted in Fig. 1(a). This spectrum is ob-

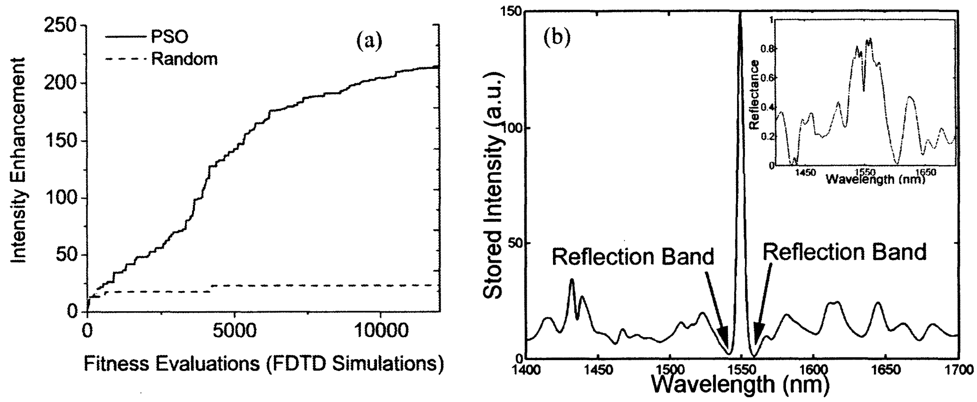

Fig. 2. (a) Best intensity enhancement versus number of trials (fitness evaluations) for a Particle Swarm Optimization (solid line) and a random search (dashed line). (b) Spectrum of the intensity stored in the structure as calculated by spatially integrating the time-averaged intensity profile over the entire structure shown in Fig. 1(a). Peaks in the stored energy spectrum correspond to eigenstates of the structure. Arrows denote reflection bands which separate the eigenstate near 1550 nm from the adjacent eigenstates. Inset shows reflectance spectrum confirming the existence of the reflection bands as well as the eigenstate near 1550 nm.

tained by spatially integrating the time-averaged intensity over the entire structure at given incident wavelengths. In the figure, a local maximum corresponds to a strong coupling of the source to an eigenstate. This coupling occurs when the wavelength of the incident light corresponds to that of an eigenstate in the structure. We see a prominent peak at 1549.5 nm in the stored intensity spectrum for the structure shown in Fig. 1(a). From the low minima adjacent to this eigenstate it is clear that this state satisfies Thouless' criterion. The deep minima correspond to gaps between eigenstates where light at these frequencies cannot propagate within the structure. This is confirmed by the Fig. 2(b) inset showing high reflectance bands on either side of the eigenstate near 1550 nm. To rigorously apply Thouless' criterion we measure the average state spectral spacing between local maxima in the range from 1400 nm to 1700 nm in Fig. 2(b). We estimate this spacing to be $\Delta\lambda = 11.7 \pm 0.5$ nm. When comparing this to the peak spectral width of $\delta\lambda = 4.2 \pm 0.6$ nm, we estimate a Thouless number of $\gamma_T = 0.36 \pm 0.05$ which is indeed well within the Anderson localization regime. The Q factor of this state given by $Q \approx \lambda/\delta\lambda$ is 370 ± 50. This is a relatively large Q compared to other structures with similar small modal areas [14, 15].

In summary, we have demonstrated an increase in localized intensity by 2 orders of magnitude due to spatial confinement of light to less than a half-wavelength squared. An Evolutionary Algorithm was shown to be an essential tool in developing these resonant structures with tightly confined modes. Similar structures can form the basis for integrated photonic devices which utilize strong intensity enhancement and sub-wavelength confinement for manipulating and controlling light at the nanoscale.

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