Enhanced spontaneous emission in Anderson localized cavities

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ABSTRACT
In our work, transverse Anderson localization is introduced for the first time in a simple wedge-type optical waveguide, which is formed by a triangular air hole imbedded into a fused silica material via a conventional fiber drawing technique. The micro tube is filled with a polymeric medium consisting of fluorescent dye molecules and naturally formed air inclusions caused by the capillary effect to offer a scattering medium for photons to localize the interfered electromagnetic waves. Anderson localization is explored through various single modes at different emission wavelengths within the photoluminescence spectral bandwidth of dye molecules. The photonic design of the optical waveguide allows the guidance of a single Anderson localized mode and suppression of the other modes to enable investigation of the spontaneous emission rate of the emitters, which are principally coupled into a single Anderson localized mode. The physical mechanism behind the changes in the emission dynamics of the fluorescent emitters is investigated by the time-resolved spectroscopy, which is found to be on resonance dependent with a particular cavity mode. The fastest decay rate of the light emission from the excited dye molecules is attributed to be due to the photons that couple into the localized optical modes without any spectral detuning. The enhancement of the spontaneous emission rate by a factor of 2.2 is achieved as the majority of the photons are coupled into an Anderson localized mode. Thus, a simple wedge-type optical waveguide is demonstrated to provide an opportunity to enhance light-matter interaction and opens new avenues to understand the nature of the spontaneous emission dynamics of the fluorescent emitters that are trapped in quasi optical cavities.

Keywords: Nanophotonics, nanostructure, Anderson localization, spontaneous emission, optical mode, quasi-cavity.

1. INTRODUCTION

Anderson localization is a wave phenomenon, which originates from the interference of electromagnetic waves in an anisotropic photonic medium to constitute standing waves in quasi optical cavities. In such kind of photonic cavities, photons are trapped at random frequencies by multiple elastic light scatterings. Thus, each Anderson localized mode has a distinctive spatial and spectral profile; nevertheless, the physical nature of such kind of optical modes is similar to that of well-structured optical cavity modes [1, 2].

Photonic structures, which generate Anderson localized modes from structural imperfections, have been achieved by advanced engineering processes. The behavior of the electromagnetic waves in such kind of photonic structures has also been thoroughly investigated through the light confinement of the individual emitters in both strong and weak coupling regimes [3-8]. Our photonic design, which allows generation of the Anderson localized modes in a simple wedge-type optical waveguide, offers an alternative way for efficient light confinement in transverse plane.

2. EXPERIMENT

In this paper, transverse Anderson localization is explored in a wedge-type optical waveguide, which is formed inside a triangular air hole imbedded into a fused silica material via a conventional optical fiber drawing technique. The optical structure is utilized as a capillary tube in micro optical waveguide, offers generation of the Anderson localized mode from structural imperfections, has been thoroughly investigated through the light confinement of the individual emitters in both strong and weak coupling regimes [3-8]. Our photonic design, which allows generation of the Anderson localized modes in a simple wedge-type optical waveguide, offers an alternative way for efficient light confinement in transverse plane.

The micro tube is filled with a polymeric medium consisting of fluorescent dye molecules and naturally formed air inclusions caused by the capillary effect to offer a scattering medium for photons to localize the interfered electromagnetic waves.
dimensions are created during the capillary process, caused by the characteristic properties of the liquid and surface tension inside the capillary tube. The air inclusions in the polymeric medium are utilized as the scattering centers for the electromagnetic light waves, as demonstrated in Figure 1. The localization of the photons is achieved by the interference of the electromagnetic waves through multiple elastic light scatterings in a disordered medium. As the localization length is comparable to the wavelength scale, photons at particular frequencies are trapped to generate confined optical modes.

In the wedge type optical waveguide, light waves are confined in the transverse xy-plane and propagate along the z-direction. The photonic design of the optical waveguide allows the guidance of a single Anderson localized mode and suppression of the other modes to enable the investigation of the spontaneous emission rate of the emitters, which are principally coupled into a single Anderson localized cavity. The optical modes are detected as sharp spectral resonant peaks at different emission wavelengths within the photoluminescence spectral bandwidth of the dye molecules upon their excitation by a high-power laser beam. Directly coupling the emitter’s light into the specific guided optical mode causes a change in the localized density of the electromagnetic states (LDOS) of the fluorescent emitters, which results in an enhancement of the spontaneous emission rate of the Rhodamine 6G molecules. The emission dynamics of the Rhodamine 6G molecules coupled into the quasi cavities at certain frequencies are investigated by the time-resolved spectroscopy. The fastest decay rate of the light emission from the excited dye molecules is attributed to be due to the coupling of the photons into the localized optical modes without any spectral detuning.

![Figure 1](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

**Figure 1.** The schematic representation of the capillary effect and Anderson localization in wedge-type optical waveguide.

### 3. THEORY

The spontaneous emission rate of a fluorescent emitter surrounded by a photonic cavity is enhanced if there is a spectral and spatial matching between the fluorescent emitter and the resonant optical mode. The coupling dynamics of the resonant excited molecules modes is investigated by Purcell factor, which is given in Eq. 1 [9]:

\[
P_p = \frac{3Q(\lambda_c/n)^3}{4\pi^2V},
\]

in which \( n \) is the refractive index of the photonic medium, \( Q \) is the quality factor of the photonic cavity, which is simply defined by resonant wavelength (\( \lambda_c \)) and the spectral linewidth (\( \Delta\lambda_c \)) of the cavity mode [10]:
\[ Q = \frac{\lambda_c}{\Delta \lambda_c} \]  \hspace{1cm} (2)

\( V \) is the effective mode volume given in Eq. 3 [11]:

\[ V = \frac{\int \varepsilon(r) |E(r)|^2 dV}{\varepsilon_m(\vec{r})|E_m(\vec{r})|^2} \]  \hspace{1cm} (3)

Our disordered photonic structure induces localization of the electromagnetic waves in the subwavelength regions and enables a resonant optical mode to be trapped in a transverse plane of the wedge type optical waveguide. Since the Anderson localized modes are physically located at random positions over the cross-sectional area of the wedge-region and resonant optical modes are explored at random frequencies within the photoluminescence spectral bandwidth of dye molecules; additionally, the dye molecules are considered to display spectral and spatial mismatches with respect to the resonant optical modes, which yield a reduction in the Purcell factor. Therefore, the total enhanced spontaneous emission rate is redefined by some additional terms to Purcell factor, as given in Eq. 4 [12]:

\[ \frac{\Gamma}{\Gamma_0} = F_p \frac{\Delta \lambda_c^2}{4(\lambda - \lambda_c)^2 + \Delta \lambda_c^2} \frac{|E(\vec{r})|^2}{|E_m|^2} \eta^2 \]  \hspace{1cm} (4)

in which \( \Gamma \) and \( \Gamma_0 \) are the spontaneous emission rates of the fluorescent emitters, which are coupled into a transverse Anderson localized mode and bulk, respectively. \( E(r) \) is the electric field amplitude of the optical modes, \( \eta \) is the orientation matching of the dipole with respect to the polarization of the Anderson localized mode, which is equal to 1 for the polarized light emission of the emitters. The second and the third terms are attributed to be spectral and spatial mismatches between the dye molecules and the transverse Anderson localized mode in concern, respectively.

4. RESULTS AND DISCUSSION

The photoluminescence spectrum of the excited dye molecules coupled into the transverse Anderson localized modes in a wedge-type optical waveguide is given in Figure 2(a), which is obviously seen that the disordered photonic medium in the optical waveguide introduces Anderson localized modes as sharp spectral resonances at random positions within the photoluminescence spectral bandwidth of the dye molecules.

The total light emission from the excited dye molecules in our optical waveguide stems from both resonant and non-resonant emission parts. The resonant emission part, which is attributed to be the fastest decay rate of the total photoluminescence emission is induced by the light emission from the excited dye molecules coupled into the transverse Anderson localized mode at a specific frequency. However, a part of the light emission originates from the non-resonant portion, which is attributed to be the light emission from the non-coupled dye molecules. Thus, the fluorescence intensity distribution is expressed by multi-exponential decay fit using the following formula:

\[ I = I_1 \exp\left[-(t - t_0)/\tau_1\right] + I_2 \exp\left[-(t - t_0)/\tau_2\right] \]  \hspace{1cm} (5)
where \( \tau_1 \) and \( \tau_2 \) represent the fluorescence lifetimes of the dye molecules, which are on-resonant and off-resonant with the optical modes, respectively. The average fluorescence lifetime of the Rhodamine molecules in a bulk phenol is measured to be 3.93 ns by a single exponential decay fit. The fastest decay curve of the dye molecules coupled into the resonant optical mode shown in Figure 2(b) is measured to be 1.80 ns, obtained from the time-resolved experiments. The enhancement factor of the spontaneous emission rate \( (\Gamma/\Gamma_0) \) is also calculated by the ratio of the emission rates of the fluorescent emitters, which is on-resonant and off-resonant with the optical modes, yielding a value of about 2.2.

Figure 2. (a) Photoluminescence spectrum of excited dye molecules in a wedge-type optical waveguide. (b) Fluorescence lifetime decay curves of the excited molecules coupled into the Anderson localized mode and bulk.

A 3D finite difference time domain (FDTD) method is utilized to investigate the electric field intensity profiles of the radiating dipoles of the dye molecules, which are coupled into an Anderson localized mode in a wedge-type optical waveguide, as displayed in Figure 3. The simulation results unveil that our photonic design allows localization of the optical modes at certain physical positions over the cross-sectional area of the wedge-region and guidance of a single dominant transverse Anderson localized mode in the waveguide medium, as demonstrated in Figure 3.
The electric field intensity distribution profile of the radiating dipoles of the dye molecules coupled into a transverse Anderson localized mode in a wedge-type optical waveguide.

5. CONCLUSION

The enhancement of the spontaneous emission rate of the dye molecules that are on-resonant with the optical modes is determined by a factor of 2.2, which elucidates that the Anderson localization enables an efficient way to alter the spontaneous emission dynamics of the coupled light emitters. Thus, a simple wedge type optical waveguide is demonstrated to provide an opportunity to enhance light-matter interaction in a three-dimensional guiding medium formed by material impurities and opens new avenues to understand the nature of the spontaneous emission dynamics of the fluorescent emitters that are trapped in quasi optical cavities.

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REFERENCES


