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Random nanolasing in the Anderson localized regime

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The development of nanoscale optical devices for classical and quantum photonics[1–5] is affected by unavoidable fabrication imperfections that often impose performance limitations. However, disorder may also enable new functionalities[6], for example in random lasers, where lasing relies on random multiple scattering[7–13]. The applicability of random lasers has been limited due to multidirectional emission, lack of tunability, and strong mode competition[11] with chaotic fluctuations[14] due to a weak mode confinement. The regime of Anderson localization of light[15] has been proposed for obtaining stable multimode random lasing[16], and initial work concerned macroscopic one-dimensional layered media[17]. Here, we demonstrate on-chip random nanolasers where the cavity feedback is provided by the intrinsic disorder. The strong confinement achieved by Anderson localization reduces the spatial overlap between lasing modes, thus preventing mode competition and improving stability. This enables highly efficient, stable and broadband wavelength-controlled lasers with very small mode volumes. Furthermore, the complex interplay between gain, dispersion-controlled slow light, and disorder is demonstrated experimentally for a non-conservative random medium. The statistical analysis shows a way towards optimizing random-lasing performance by reducing the localization length, a universal parameter.

In a strongly scattering random medium, light can be trapped by concurrent multiple scattering events leading to the formation of localized cavity modes that prevail after averaging over all statistical configurations of disorder. Such Anderson localization is found to occur in state-of-the-art photonic-crystal waveguides where unavoidable intrinsic fabrication disorder is sufficient to induce localized cavities in the slow-light regime of waveguide propagation[6]. (For further details see Supplementary Section 1.) Adding gain to such a waveguide enables the study of the formation of the lasing modes that were attributed to disorder in previous work[18]. Figure 1a illustrates lasing cavities, which are spatially distributed along the waveguide and appear spectrally in the slow-light regime[19]. In the present experiment, quantum wells were embedded as a gain medium in the photonic-crystal membrane and were optically pumped. In a conservative one-dimensional single-mode waveguide, the Anderson localization criterion requires that the average distance between random scattering events, the localization length ξ, is shorter than the sample length L, and their ratio universally determines the confinement of the localized modes. The presence of absorption or gain changes this simple picture, beacuse they will respectively damp or enhance the localized modes[20], and may give rise to nonlinearities[21]. In the present experiment, for low excitation pump power, the fluorescence emitted by the excited region of the quantum wells is multiply scattered along the waveguide, but is damped due to the strong absorption of the unpumped surrounding gain material, as shown in Fig. 1b. By increasing the excitation power, the light amplification compensates loss and the lasing threshold is reached. At the threshold, the system resembles a conservative waveguide. Here, we record a localization length that is more than ten times shorter than the sample length, thus confirming Anderson localization. Increasing the excitation power further leads to random lasing, as shown graphically in Fig. 1c. Figure 1d presents the emission spectrum of a single Anderson localized lasing mode below and above threshold, while Fig. 1e shows the peak output emission intensity versus input excitation power. A distinct lasing threshold is observed, accompanied by a decrease in the cavity linewidth with excitation power, both of which are signatures of laser oscillation. Two important figures of merit of a nanolaser are its β-factor (the fraction of spontaneous emission that couples to the lasing mode) and the cavity mode volume (the spatial extension of the lasing mode). These can be determined by modelling the laser input–output curves with microcavity semiconductor laser rate equations[22] (cf. Fig. 1e). The saturation observed at high excitation power is attributed to thermal effects (for details see Supplementary Section 4). For this particular lasing mode we obtain a β-factor of 0.31, which, interestingly, is significantly larger than previous values reported in photonic-crystal lasers with quantum-well gain media[23]. A mode volume of $4.53(\lambda/n)^3$ is obtained, where $\lambda = 1{,}587$ nm is the lasing wavelength and $n = 3.4$ is the refractive index of InGaAsP, which is consistent with the mode extent found for Anderson localized modes in cavity quantum electrodynamics experiments in similar structures without the gain material[24,25].

Determined by the size of the pumped area on the waveguide, multifrequency lasing can be observed (Fig. 1f,g). As shown in Fig. 1f, the onset of multimode lasing tends to be sequential; that is, with increasing excitation power the laser peaks grow one by one, each displaying the characteristic input–output lasing curve (Fig. 1g). A recent theoretical study predicted the strong suppression of interactions in multimode random lasing in the Anderson localization regime[16]. As shown in Fig. 1h, very stable lasing wavelengths are indeed observed, even for spectrally close lasing modes. This is attributed to the fact that the lasing modes overlap very weakly due to their (on average) exponential confinement[16]. In diffusive random lasers, in contrast, the extended lasing modes imply that different modes overlap spatially, inducing strong mode competition and chaotic lasing emission and therefore spectrally broad averaged emission[14]. In our case, the very narrow lasing linewidths

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with a diameter of 1.5 μm on the surface of the sample using a ×50 microscope objective lens (numerical aperture of 0.65), and aligned to the photonic-crystal waveguides using piezoelectric nanopositioners. The photoluminescence signal was collected by the same objective lens within a diffraction-limited region in a wide wavelength range of 1,500 nm $< \lambda <$ 1,600 nm, dispersed by a 300 mm grating spectrograph with a spectral resolution of 0.1 nm, and detected using a liquid-nitrogen-cooled InGaAs charge-coupled device camera.

We measured a total of 25 input–output curves by varying the excitation and collection position along the photonic-crystal waveguide. The laser threshold was obtained by extrapolating each input–output curve in a linear scale to zero power. The Q-factor was extracted by fitting the cavity mode with a Lorentzian at the threshold power. Two of the 25 input–output curves also show the cavity mode below laser threshold (Fig. 1b shows one example). For the rest of the measurements, the excitation power at which the cavity mode appeared matched the threshold power extracted from the input–output curve fitting. Based on this fact, we could increase the statistics of threshold and Q-factor distributions by gradually increasing the excitation power and recording the power at which the mode appears and its corresponding spectrum. By doing so, 25 extra data points for the laser threshold and Q-factor were added without recording the full input–output curve. The full data set is plotted in Fig. 3c,d.

The intensity probability distribution $P(\hat{I})$ was measured by collecting the intensity $I^{\lambda}_{x,y}$ while scanning the excitation and collection objective along a photonic-crystal waveguide with $r/a = 0.24$ at each spatial position (x, y) with a spatial binning size of 0.25 μm and at different wavelengths with a binning size of 1 nm. Subsequently, an average over the wavelength range 1,580–1,595 nm was performed.

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Author contributions

J.L. and M.S. carried out the optical experiments. S.E. and M.S. fabricated the sample. J.L. and P.D.G. analysed the experimental data. N.G., T.S. and J.M. developed the rate equation models. J.L., P.D.G, S.S. and P.L. wrote the manuscript. J.M., S.S. and P.L. supervised the project. All authors read and commented on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to P.L.

Competing financial interests

The authors declare no competing financial interests.