



Controlling the lasing modes in random lasers operating in the Anderson localization regime

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Abstract: Random lasers, which rely on random scattering events unlike traditional Fabry-Pérot cavities, are much simpler and cost-effective to fabricate. However, because of the chaotic fluctuations and instability of the lasing modes, controlling the lasing properties is challenging. In this study, we use random InP nanowire (NW) arrays that operate in the Anderson localization regime with stable modes as the random lasers. We show that by changing the design parameters of the NW arrays, such as filling factor, dimensions of the NWs, degree of randomness, and the size of the array, the properties of the lasing modes including the number of modes, lasing wavelengths, and lasing threshold can be controlled.

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1. Introduction

Unlike traditional lasers with cavities supporting Fabry-Perot or whispering gallery modes that need precise fabrication to support the lasing modes, random lasers do not require well-defined cavities and can be obtained by multiple scattering of light within a gain medium. This property has given some unique properties to random lasers including low-cost and unrestricted angular emission. On the other hand, the randomness of the scattering events results in lasing modes that cannot be easily controlled. Therefore, controlling the lasing modes in random lasers is important for the further development of sensors [1–3], speckle-free imaging [4], integrated devices [5], and spectral super-resolution spectroscopy [6].

Changing the gain material is one of the methods developed for controlling the lasing modes. For example, by mixing various laser dyes with gold nanostructures, Ziegler et al. were able to achieve random lasing throughout the visible up to the infrared range [7] or using a two-dye system with broadband plasmonic resonance scatterers, Wang et al. achieved coherent dual-color random lasing [8]. Changing the pump beam profile is another way to tune the lasing modes. It was shown by using a spatial light modulator to shape the pump beam profile, single-mode lasing at a particular wavelength can be achieved [9,10]. Using the same method, emission directionality [11], lasing threshold [12], and modal interactions [13,14] have also been controlled. Leonetti et al. have also shown by changing the pump beam shape from disc-shaped to stripe-shaped it is possible to move from a system with non-resonant feedback to a resonant one [15]. We have previously shown that by defocusing the pump beam in random lasers based on GaAs-AlGaAs core-shell NWs it is possible to suppress the resonant modes [16]. Using liquid crystal [1] and magnetic materials whose properties can be tuned by temperature [17], externally applied voltage [18], and magnetic field [19] are other ways to control the lasing threshold and emission of random lasers. Nevertheless, most studies reported that the rise in temperature or increase in applied voltage would decrease the emission intensity, which is not ideal for practical applications

[20]. Changing the geometry and structure of the scatterers are other ways to modify lasing properties. It was shown using monodisperse scatterers can create resonant feedback and by changing the scatterers diameter and refractive index it was possible to control single-mode lasing wavelength [21]. Consoli et al. have demonstrated that by controlling the randomness degree by shaping the roughness of the scattering surfaces it is possible to tune the average number of lasing modes in random lasers with spatially localized feedback [22]. Using a photonic crystal structure with a transport mean free path, l_t of 2–3 μm , which is almost five times bigger than the lasing wavelength, the random laser was reported to operate in the diffusive regime [23]. In diffusive random lasers (also known as delocalized random lasers), sharp emission peaks are usually not present, and only an overall linewidth narrowing around the peak of the gain spectrum is observed [24]. However, some theoretical works have predicted the possibility of lasing in resonant feedback mode even in diffusive systems with low-Q resonances [25,26]. Unlike the diffusive regime, in the localization regime, where $kl_t \leq 1$ (k is the wavenumber), these lasing modes are more stable and can exhibit a higher degree of controllability due to spatial confinement of the modes [27].

We have previously reported a random laser system made of random InP nanowire arrays which operated in the Anderson localization regime where stable multi-mode lasing was observed [27]. Here, we report our systematic investigation into how the various parameters of the nanowire arrays, such as average diameter, nanowire length, filling factor, degree of randomness, and system lateral size can be used to design the lasing modes of these random InP nanowire arrays.

2. Results and discussion

For a disordered media to support cavities in the localized regime, according to Ioffe-Regel criterion, l_t should be smaller than the wavelength of light, λ ($kl_t \approx 1$, $k = 2\pi/\lambda$ is the wavenumber) and the sample dimension should be larger than the diffusive critical volume, or in other words, the sample size should be bigger than l_t [28]. In these systems, like all other types of lasers, lasing can occur if the gain is large enough to balance the loss mechanisms. There are two main loss mechanisms in random lasers: (i) out-coupling loss to the surrounding media and (ii) internal absorption loss. To quantify the first mechanism, the quality factor, QF of the system can be used. However, the second mechanism is mainly due to material loss. In the following section, it is shown that the geometrical parameters, such as filling factor (FF, filling factor is defined as the ratio between the volume of NW region and the volume of the disordered medium) and diameter of the random laser could affect the cavity's QF and the carrier generation.

Using the commercial finite-difference time-domain (FDTD) Lumerical software package, the effects of FF and NW average diameter, d_{av} on the random NW system have been shown in Fig. 1. The inset of Fig. 1(a) shows the optical carrier generation, G_{op} of a randomly distributed InP NWs ($n=3.73+i0.446$, where n is the refractive index on InP at the excitation wavelength) with $FF=0.3$, $d_{av}=125$ nm, and length, $L_{NW}=3$ μm . To calculate G_{op} , FDTD Solutions was used to solve Maxwell's equations and determine the spatial distribution of the electric field, $E(r, \lambda_{source})$, for the disordered medium. Then using

$$G_{op}(r, \lambda_{source}) = \frac{\pi}{h} |E(r, \lambda_{source})|^2 \text{Im}(\epsilon(r, \lambda_{source})), \quad (1)$$

where h is the Plank constant and ϵ is the permittivity of the medium, $G_{op}(r, \lambda_{source})$ as a function of position and excitation source wavelength was calculated [29,30]. As for the excitation source, we assume a 522 nm laser ($\lambda_{source}=522$ nm) which is the same as that used in the experimental setup. The pumping intensity of the plane wave source was chosen to be 10^4 Wcm^{-2} . Carriers are mostly generated at the top 0.3–1 μm of the NWs, depending on the diameter NWs and FF of the system as shown in Fig. 1(a). The average carrier density at different slices along the NW

axis is obtained through:

$$N_{av}(z) = \tau_c \iint G_{op}(x, y) dx dy, \quad (2)$$

where τ_c is the carrier lifetime and is assumed to be 1 ns [31]. It can be seen decreasing the FF has spread the carrier generation profile deeper into the NWs. However, decreasing the diameter decreases the maximum generation and increases the generation depth. Calculating the average carrier density over the top 1 μm of the NWs (which is around the diffusion length of the carriers in InP) for the three systems, we obtain values between 2.3×10^{17} - $2.6 \times 10^{17} \text{ cm}^{-3}$ for the three systems, indicating that the average carrier density in the three systems is almost the same over the top $\sim 1 \mu\text{m}$. However, the system with higher FF has almost three times higher carrier density inside the gain media (inside the NWs) leading to higher photon generation and lower lasing threshold. This shows that to obtain gain at a lower pumping threshold, systems with higher density NWs are preferred (i.e higher FF). In Fig. 1(b) and Fig. 1(c) the probability of finding QFs higher than a threshold value of $Q_t = 3000$ with resonance wavelength, λ_r near the NW bandgap energy of $725 \text{ nm} < \lambda_r < 775 \text{ nm}$ (Fig. 1(b)) and $800 \text{ nm} < \lambda_r < 850 \text{ nm}$ (Fig. 1(c)) are plotted as a function of FF and d_{av} . In real systems, only modes with high QFs with resonance wavelengths in the emission spectra could survive. That is to say, in our calculations, we obtain many low QF modes (Fig. 2(e) and Fig. 2(f)) and because of low photon life-time, τ_p , and high mode leakage, they cannot survive. Besides, after the formation of high QF modes, because of gain depletion and mode competition, these low QF modes would not get enough gain to survive. For analyzing each distribution of nanowires with particular d_{av} and FF, a statistical approach based on a 2D simulation has been used. For each system, 10 different distributions were analyzed. It is further assumed the 2D systems have the same lateral size of 3 μm in x and y directions ($L_x = L_y = 3 \mu\text{m}$ where L_x and L_y are lateral sizes of the system in the x- and y-direction, respectively).

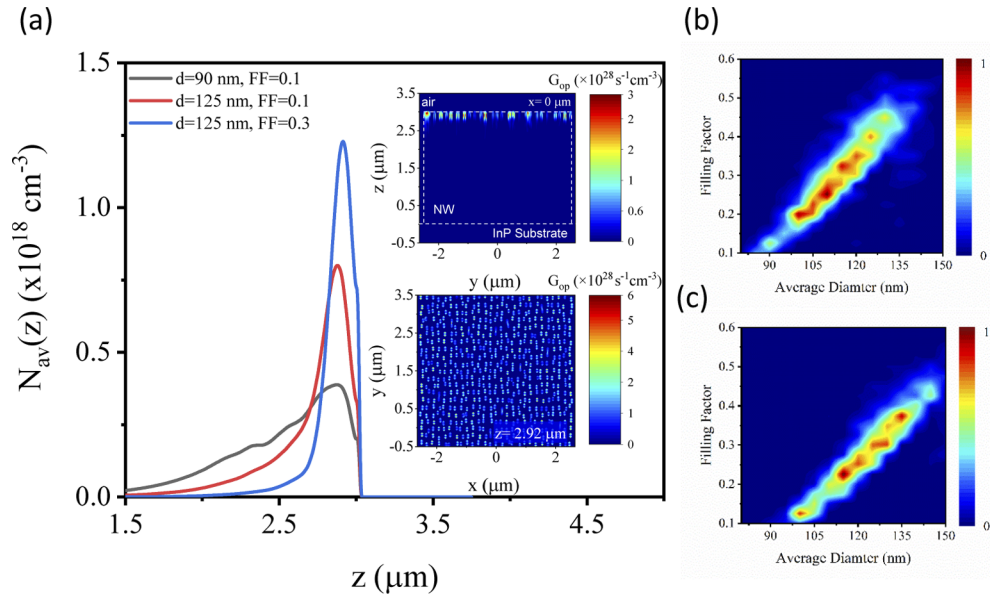


Fig. 1. The effects of d_{av} and FF on carrier generation and resonant modes. (a) Carrier generation profile along the nanowire length for arrays with different average diameters and FFs. The insets show the optical carrier generation on the z - y (top) and x - y (bottom) planes. (b,c) Probability of finding high QF (QF > 3000) arrays systems with different FFs and average diameters, in the wavelength range of $725 \text{ nm} < \lambda_r < 775 \text{ nm}$ (b) and $800 \text{ nm} < \lambda_r < 850 \text{ nm}$ (c) using 2D simulation setups.

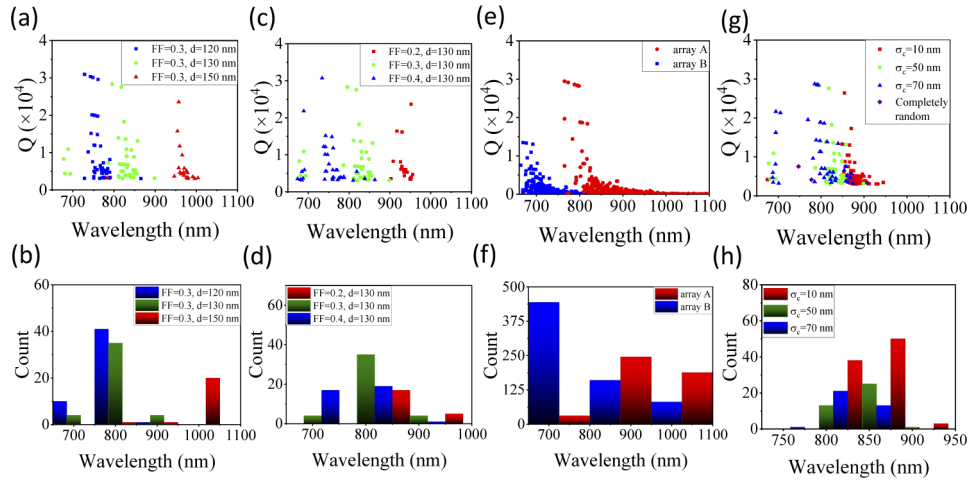


Fig. 2. The effect of d_{av} , FF, and σ_c on the statistical distribution of QF and λ_r using 2D simulation setups. (a,b) The effect of d_{av} at FF = 0.3 and $\sigma_c = 50$ nm on Q and λ_r of the cavity mode. (c,d) The effect of FF at $d_{av} = 130$ nm and $\sigma_c = 50$ nm on QF and λ_r of the cavity mode. (e,f) The effect of FF and d_{av} at a fixed σ_c value for two arrays, A and B (array A: FF = 0.25, $d_{av} = 125$ nm; array B: FF = 0.15, $d_{av} = 90$ nm). (g,h) The effect of σ_c at $d_{av} = 130$ nm and FF = 0.3 on QF and λ_r of the cavity mode.

To design the random InP NW arrays, we took into account the limitations of the fabrication and epitaxial growth processes. The randomness of the NW position distribution was chosen in such a way that they do not significantly overlap. In our simulation, we first assumed the NWs are arranged in a square photonic lattice, and randomly deviated the NW locations from their periodic positions. The value of this deviation from the NW center, σ_c was varied between 0 and 50 nm. The smaller the σ_c value, the possibility of NWs overlapping (merging) decreases. To completely prevent any overlapping σ_c should be smaller than half of the pitch size of the non-disordered square photonic lattice. The NWs were assumed to have a 15% variation in diameter. As for the excitation source, an electrical dipole source whose electric field is along the NW axis (z-direction) was used. The system was assumed to be passive, i.e. a system without gain, and the NWs were InP with a refractive index of $n = 3.456$. It can be seen from Fig. 1(b) at the higher wavelength range, arrays with FF = 0.2–0.3 and $d_{av} = 118$ –130 nm have the highest probability of finding high QF cavities. However, for the lower wavelength range, as shown in Fig. 1(c), arrays with FF = 0.2–0.3 and $d_{av} = 105$ –120 nm have the highest probability of finding high QF cavities. The results show that to tune the emission of the random nanowire lasers to a lower wavelength, generally a smaller d_{av} is required.

Using the same 2D simulation setup used for Fig. 1(b) and Fig. 1(c), the effects of increasing d_{av} on QF and λ_r of the cavities are shown in Fig. 2(a) and Fig. 2(b), respectively. By increasing d_{av} of the NW, a redshift to the resonance wavelength is observed. Besides, in systems with a smaller NW diameter, the number of modes with QF > 3000 is higher, and as the diameter increases the number of modes decreases. As d_{av} of the NW decreases, at a constant FF, the number of scatterers increases leading to higher scattering events. Therefore the number of cavities with high QF also increases. The effects of increasing FF on QF and λ_r of the cavities are depicted in Fig. 2(c) and Fig. 2(d). It can be seen that increasing FF of the arrays would result in a blue-shift of the resonance wavelength. Besides, in arrays with lower FF, the number of modes is low, and as FF increases the number of the modes and especially the possibility of getting low QF modes decreases. Similar to the effect of decreasing d_{av} , increasing FF, increases the number

of scatterers, leading to higher scattering events, and therefore higher number of cavities with high QF.

Comparing Fig. 2(a) and Fig. 2(b) with Fig. 2(c) and Fig. 2(d), it can be seen that the effect of changing d_{av} is more pronounced than changing FF in shifting λ_r . For example, increasing d_{av} by 25% (from 120 to 150 nm) results in a redshift of 229 nm to the average λ_r . However, to obtain a redshift of 185 nm, FF needs to change by 100% (from 0.4 to 0.2). This effect is further exemplified in two different arrays (array A: $d_{av} = 120$ nm, FF = 0.25 and array B: $d_{av} = 90$ nm, FF = 0.15). As shown in Fig. 2(e) and Fig. 2(f), even though the FF of array B is slightly lower than that of array A, the effect of decreasing nanowire diameter on λ_r is significantly higher, with a blue-shift of the cavity resonance by about 60 nm.

Using the same 2D simulation setup, the effect of deviation from the NW center, σ_c which also quantifies the degree of randomness is analyzed for an array with $d_{av} = 130$ and FF = 0.3. Ten different cases for 4 different random arrays ($\sigma_c = 10, 50, 70$ nm, and completely random system) were analyzed. Note that in the completely random case, the centers of the nanowire positions were generated by a random number generator without constraining it to a certain σ_c value. The results in Fig. 2(g) and Fig. 2(h) show that in the 3 'restricted' random cases the QFs of the cavities are more than four times higher than that of the array where the NWs are completely random, indicating that even for random laser, some degree of engineering of the randomness could noticeably improve the device performance. For example, it has been shown that increasing the QF of lasing modes could make non-resonant lasing systems into resonant ones [16]. That is to say, engineering the randomness could increase the QFs of the modes and reduce the coupling and overlapping between modes which then lead to random lasers with highly localized modes [27] with resonant feedback [16]. Indeed, in the completely random array, there is a very small probability of finding cavities with high QFs. Furthermore, the results show that the amount of disorder can also significantly affect the resonance wavelengths of the modes in addition to QF of the arrays. As the amount of disorder is increased the possibility of obtaining modes with lower λ_r increases together with the bandwidth of the resonance. This is because as σ_c is increased the possibility of making NWs locally dense is increased so the possibility of getting resonances with lower wavelength resonances is increased. In other words, increasing the randomness degree would make the regional filling factor more non-uniform so according to Fig. 2(c) and Fig. 2(d) the bandwidth increases. Considering InP NWs having gain in the wavelength region of 800 to 850 nm at low temperature, the array with $\sigma_c = 50$ nm has the best overlap with the gain profile of the NWs.

In our system, the disorder is only in the xy-plane and just for comparative purposes (and to reduce simulation time), 2D simulation setup was used in Fig. 1(a), Fig. 1(b), and Fig. 2. The values of the QF obtained in these calculations are much higher than the QFs supported in the real device (i.e. in the 3D case). That is to say, in the 2D setup the modes are completely confined in the z-direction; however, in the real devices, which is a 3D structure, the mode can leak into the underlying substrate leading to modes with much lower Q factors. To better quantify the effects of array size on mode leakage, the number of the modes and their QFs, using Lumerical FDTD solution, 3D structures with $d_{av} = 125$, FF = 0.3, $\sigma_{c,max} = 50$, $L_{NW} = 3 \mu\text{m}$, but different lateral sizes were analyzed (Fig. 3). For each array size, 10 different cases were analyzed. The selected resonance modes have two criteria: (I) $QF > 100$ and (II) $750 \text{ nm} < \lambda_r < 900 \text{ nm}$. A single dipole source was placed at the center of the random array, so only the modes located in the middle of the systems were excited. Similar to our reported work, the top $1.1 \mu\text{m}$ of the NWs was assumed to have a higher refractive index in comparison to the rest of the NWs because of carrier generation and increased temperature [27]. It can be seen from Fig. 3 when the size of the array (L_x, L_y) is less than $1 \mu\text{m}$, the system cannot support a mode due to the size of the mode being larger than the array size that results in mode leakage. In other words, the lateral size of the array should be much bigger than l_l to be in the localization regime and not the diffusive

regime [32]. It can also be seen that at lateral sizes of around $L_x, L_y = 2 \mu\text{m}$ the system has the highest confinement property. The lateral area of the mode in this system for modes with $QF > 100$ is between $\sim 0.05\text{--}3.75 \mu\text{m}^2$, therefore the lateral size of $L_x, L_y = 2 \mu\text{m}$ (area size of $4 \mu\text{m}^2$) is big enough to support a maximum number of the modes. At a larger array size, the number of supported modes begins to decrease. This trend can be understood from the fact that the surrounding region (air) of the array acts as an optical ‘cladding’ layer for the modes. At $2 \mu\text{m}$ array size, the size of the modes is of the order of the array size and hence the surrounding region provides a good optical contrast to confine the modes. However, with increasing array size, the modes are now further away from the surrounding region, and because of the presence of other NWs the effect of optical contrast is now diminished, leading to reduced lateral confinement strength. Figure 3(a) and Fig. 3(b) show the statistical distribution of λ_r and QF of the modes in an array of size $L_x, L_y = 1 \mu\text{m}$, where there are only a few modes that are supported. Due to the small size, out of the 10 cases studied, only five of them can support any modes with $QF > 100$. Furthermore, each system only supports a single-mode, implying that single-mode lasing is possible from small systems.

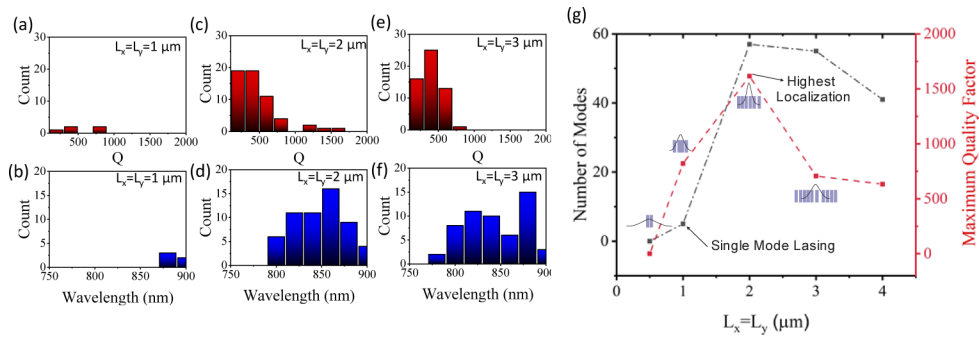


Fig. 3. Effect of array lateral size on the cavity mode using 3D simulation setups. (a-f) Statistical distributions showing the effect of L_x, L_y with $FF = 0.3$, $d_{av} = 130 \text{ nm}$, $L_{NW} = 3 \mu\text{m}$ and $\sigma_{c,max} = 50 \text{ nm}$ on QF (top row) and λ_r (bottom row). (g) Effect of L_x, L_y on the number of modes with $QF > 100$ and Q_{max} .

For optimizing the length of the NWs, L_{NW} a similar 3D simulation as the previous setup for the analysis of the effect of array size was conducted. Figures 4(a) and (b) present the statistical distribution of λ_r and QF of the modes in two arrays with $L_{NW} = 1.5$ and $3 \mu\text{m}$, respectively, for a fixed $L_x, L_y = 4 \mu\text{m}$ and $FF = 0.3$. For both systems, the same random distribution of NWs was used. It can be seen for the system with the shorter NWs the number of supported modes is very low and the QF of the modes is about one-fourth of the array with longer NWs. In Fig. 4(c-f) the electrical field intensity profiles of a mode at $\lambda_r \sim 799 \text{ nm}$ in the two systems are shown. The mode profiles along the length of the NWs (Fig. 4(d) and Fig. 4(f)) and in the x-y plane are very similar for both arrays; however, the shorter NW sample shows a slightly higher leakage into the substrate, resulting in lower QFs and number of resonant modes as shown in Fig. 4(a).

Figure 4(g) and Fig. 4(h) show the experimental emission spectra at different excitation powers from the random arrays with the shorter ($L_{NW} \sim 1.5 \mu\text{m}$) and longer ($L_{NW} \sim 3 \mu\text{m}$) NWs, respectively. The insets show the SEM images of the InP nanowires of the two arrays which were grown using selective area epitaxy growth by metal-organic chemical vapor deposition [33] similar to our previous work [27]. Using electron-beam lithography and etching processes randomly positioned holes were transferred to the SiO_x mask which was pre-deposited on the (111)A InP substrate. Then the prepared sample was transferred to the MOCVD reactor for the epitaxial growth of the NWs. Optical characterization was carried out at low temperature ($T = 6 \text{ K}$) using a frequency-doubled solid-state laser (femtoTRAIN IC-Yb2,000, $\lambda_{source} = 522 \text{ nm}$,

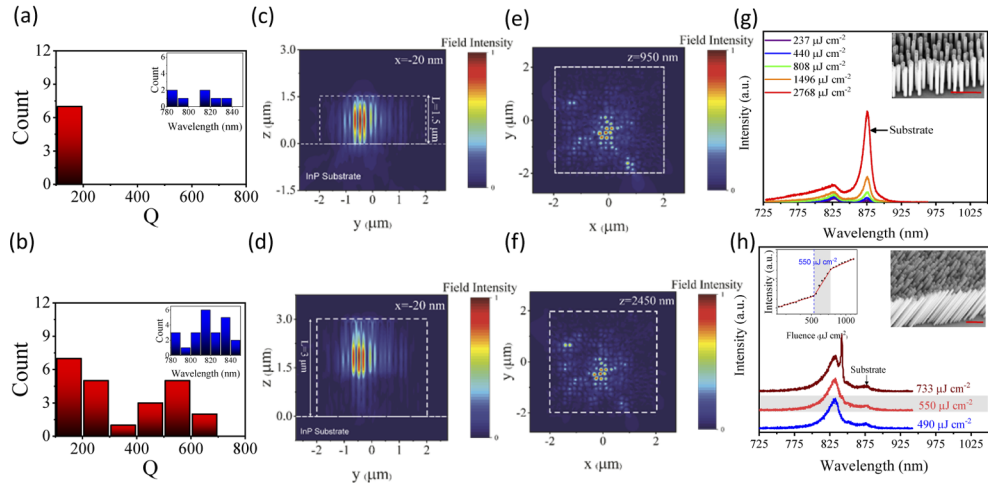


Fig. 4. Effect of NW length on the cavity modes and optical profile. Top row is for an array with NWs of length $L_{NW} = 1.5 \mu\text{m}$ whilst the bottom row is for $L_{NW} = 3 \mu\text{m}$. (a,b) Statistical distributions for QF and λ_r (inset) of the two arrays with shorter and longer NWs. (c-f) Electrical field intensity profile of a mode at $\lambda_r \sim 799 \text{ nm}$ on y-z (c,d) and x-y (e,f) planes of the two arrays with shorter and longer NWs. (g,h) Emission spectra of the two arrays with shorter and longer NWs. The inset SEM images show the tilted view of the two NW arrays grown by MOCVD (scale bars: $1 \mu\text{m}$). The upper left inset in Fig. 4(h) shows the log-log plot of light output from the random NW laser vs excitation power. The grey area is the region of amplified spontaneous emission.

repetition rate 20.8 MHz, pulse length 300 fs, Gaussian profile (FWHM = $5 \mu\text{m}$)) similar to the setup used for our previous work [27]. The sample was excited through an aberration-corrected $60 \times /0.70$ numerical aperture, a long working distance objective lens (Nikon CFI Plan Fluor), and the emission light was collected through the same lens. Spectral measurements were carried out using a grating spectrometer (Acton, SpectraPro 2750). As shown in Fig. 4(g) and Fig. 4(h), the emission spectra of the two systems have two peaks at the same wavelengths. The first peak at $\sim 830 \text{ nm}$ (FWHM $\sim 22 \text{ nm}$) is due to emission from the NWs (wurtzite crystal phase) and the second peak at $\sim 875 \text{ nm}$ (FWHM $\sim 13 \text{ nm}$) is from the substrate (zincblende phase). It can be seen in the shorter NWs the intensity of the light emitted from the substrate is much stronger than the one emitted from the nanowire. In the system with longer NWs, at the pump fluence of $\sim 550 \mu\text{J cm}^{-2}$ per pulse, we observe a small peak appearing at 843 nm , which is further amplified with increasing excitation power. Beyond lasing threshold of around $733 \mu\text{J cm}^{-2}$, a sharp lasing peak (FWHM = 2 nm) is observed at 843 nm . The light input-light output (L-L) characteristic of the laser on the log-log scale (upper left inset of Fig. 4(h)) has been obtained by integration of the emission intensities in the wavelength range of the lasing wavelength ($\lambda_{\text{lasing}} = 843 \text{ nm}$) at different pumping intensities. It can be seen that the L-L characteristic of the system shows the typical “S”-curve shape depicting all three PL regimes: spontaneous emission dominating at low excitation intensities until the onset of amplified spontaneous emission (ASE) at $\sim 550 \mu\text{J cm}^{-2}$ (grey color region) and finally, the emergence of lasing at $\sim 733 \mu\text{J cm}^{-2}$ [34–36]. In the short system, since the mode leakage to the substrate is high, the Q factor of the mode is low leading to higher out-coupling loss.

Figure 5 shows the experimental studies on the effect of the average NW diameter on the modes for two different arrays corresponding to array A and array B mentioned above. As shown by our simulation results in Fig. 1 and Fig. 2, decreasing d_{av} results in a blue-shift of the resonance wavelength. This is consistent with reports that have shown decreasing the NW diameter would

reduce the scattering cross-section [37] leading to the blue-shift of the resonance wavelength. In Fig. 5(a) the SEM images of these two arrays and their diameter distribution (inset) are shown. The fabricated lateral size of the array is around $30\ \mu\text{m}$ ($L_x=L_y\approx 30\ \mu\text{m}$). The emission spectra from an arbitrary area of these two arrays are plotted in Fig. 5(b). In both cases, lasing occurs in the range of around 725–850 nm, corresponding to the gain profile of InP NWs. The statistical distributions of the lasing wavelengths and threshold at which the ASE region starts in these two arrays are plotted in Fig. 5(c) and Fig. 5(d), respectively. For statistical analysis, for each case, several arrays with the same FF, d_{av} , L_x ($=L_y\approx 30\ \mu\text{m}$), L_{NW} , $\sigma_{\text{c,max}}$, but different NW positions (distributions) were fabricated. Then several random positions in each array were pumped (FWHM of the pumping laser is around $5\ \mu\text{m}$) to get a set of spectra. Then the lasing wavelengths and thresholds of the lasing modes in these spectra were analyzed to find sets of values for those lasing parameters for each case whose distributions are presented in Fig. 5(c) and Fig. 5(d). It can be seen, unlike Fabry-Perot mode lasing [38,39] and non-resonant random lasers [16] where the lasing wavelength is around the maximum of the gain with a narrow bandwidth of around $\Delta\lambda < 50\ \text{nm}$, in each of these two resonant random lasers the lasing bandwidth is broader ($\Delta\lambda = 100\ \text{nm}$) and most of the lasing wavelengths are at wavelengths lower than the wavelength where the gain is maximum. In array A, the minimum, maximum, and average lasing wavelengths are 742, 735, and 787 nm, respectively, and for array B where the average diameter is smaller, the corresponding lasing wavelengths are 725, 811, and 775 nm, respectively. So, decreasing the average diameter of the NW results in an overall blue-shift of the resonance wavelength, confirming the results shown in Fig. 2(e) and Fig. 2(f).

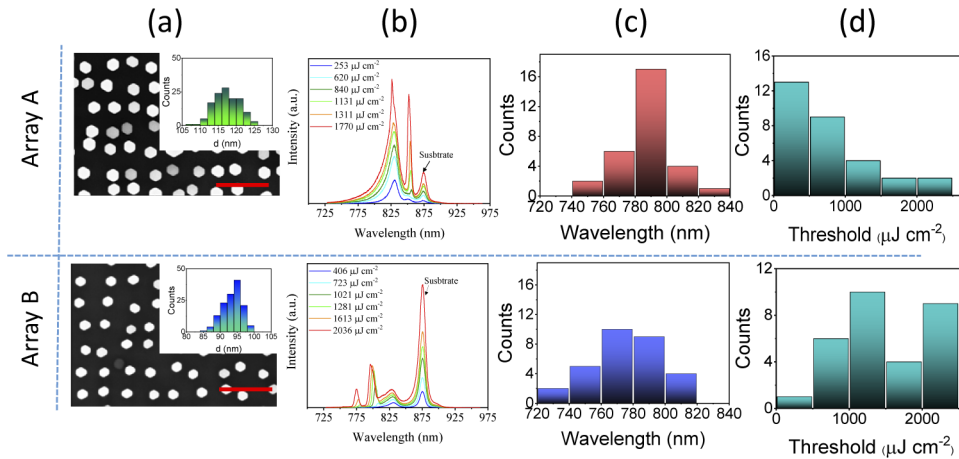


Fig. 5. Experimental results showing the effect of average NW diameter on the emission and threshold of two different arrays, corresponding to array A (top row) and array B (bottom row). (a) Top-view SEM images (scale bars are 500 nm). The insets show the diameter distributions of the two arrays. (b) Emission spectra with increasing pump fluence around the threshold. (c,d) Statistical distributions of the emission wavelength (c) and lasing threshold (d).

As shown in Fig. 5(d), the lasing threshold in array B has generally increased, which could be due to two reasons. First, there is a lower probability of finding high QF modes in array B in comparison to array A (see Fig. 2(e)) (higher loss due to out-coupling loss to the surrounding media). Secondly, the emission intensity of the wurtzite NWs in array A is higher than from the zincblende substrate (Fig. 5(b)); however, in array B the emission of the substrate is higher than the emission of the NW array. As discussed in relation to Fig. 1(a), this is because in array B the FF is lower so the carrier generation inside the gain medium is lower leading to lower gain.

Additionally, the smaller diameter can lead to a higher surface recombination rate which results in lower carrier lifetime and higher optical loss. Higher emission in array A means a higher number of photons could be created with lower excitation power, so the lasing threshold would decrease.

3. Conclusion

In this study, we have shown the controllability of the lasing properties in random NW lasers in the localization regime. By changing the design parameters of this random laser, it is possible to change the lasing threshold, the number of lasing modes, the Q factor, and the wavelength resonances of the modes. For example, changing the lateral size of the array would lead to a change from multi-mode to single-mode lasing. It was also shown by changing the density and diameter of the NWs, and the degree of randomness could change the resonance wavelength of the modes. This could expand the application of random lasers in photonic devices where controlling and managing the lasing properties are required.

Funding. Australian Research Council (Discovery Project (DP170102530)).

Acknowledgments. We acknowledge the Australian Research Council for the financial support. Access to the epitaxial growth and fabrication facilities is made possible through the Australian National Fabrication Facility, ACT Node.

Disclosures. The authors declare no conflicts of interest.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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