Design a random nano-laser based on ZnO nanorods

M. DAVOODI[a], K. ABBASSIAN[b], J. TIZFAHM[a,*], M. H. YOUSEFI[a]
[a]*Department of Nanophysics, Malek Ashtar University of Technology, Iran*
[b]*Faculty of Modern Technology Engineering, University of Tabriz, Iran*

Zinc oxide nanorods are used to emit light in the UV region because of their high energy band gap. In this paper, a set of ZnO nanorods is used to design a random laser in the UV spectrum region and Anderson's Localization in the environment includes these nanorods, is investigated then is modeled. The proposed model for the investigation of ZnO nanorods is two-dimensional. The role of nanorods is to create scatter and diffraction and thus produce local cavities to create coherent random laser spectra. Their other role is stimulated emission and laser because of the good optical gain. The random laser modes produced along with the laser gain are evaluated.

(Received August 19, 2019; accepted April 9, 2020)

Keywords: Random laser, Zinc oxide, Nanorods, Anderson's localization, Stimulated emission, Light scattering, Local cavities

1. Introduction

A conventional laser consists of two main components. An active laser medium that provides the optical gain needed to amplify light based on the stimulated emission phenomenon, and a cavity that traps light partially and causes coherent feedback within the medium. In such a system, the laser starts to oscillate when the rate of photons produced by the stimulated emission phenomenon is equal to the rate of loss of photons (due to the loss in the medium and the presence of the laser output). In contrast to such conventional lasers, there are open cavity scattering lasers, called random lasers. In these lasers, the feedback is achieved by the multiple scattering of photons by the random distribution of nanostructures in a substrate [1]. Such lasers do not have a clear feedback process like conventional lasers (Fig. 1).

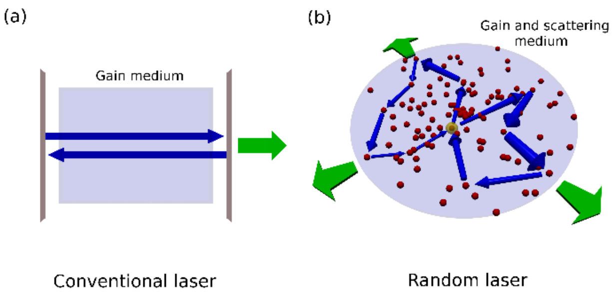

Fig. 1. Conventional lasers and random lasers (color online)

Scattering in conventional lasers is considered to be an undesirable phenomenon due to loss in system. But in random lasers, as the number of scatterers increases, the role of the cavity is done by multiple scattering in the amplification medium. In other words, the physical basis of the performance of a random laser is based on the propagation of electromagnetic waves in random medium [2]. No need for external cavity makes it easy to manufacture, low cost, and different applications of this laser versus conventional laser. From an applied perspective, random lasers of nanostructures have been considered due to their unique properties such as the angular dependence of output light, the wide spectral range, the need for no external cavity, the highly usable materials, etc. That's why, research on random nano-lasers has become increasingly important in recent years. Researches have reported that random laser phenomena are seen in various materials such as polymers, crystalline powders, semiconductors, ceramics, organic composites, nonlinear environments and even biological tissues. Investigation of the construction of screens based on random lasers, the use of soluble environments containing nanostructures as coatings, the application as temperature detector, are the latest issues about random lasers [2-4].

Random lasers have not been seriously simulated in recent years and most researches on these lasers has been reported experimentally [5]. Therefore, in this paper, we simulate ZnO nanorods with random arrangement in a suitable gain medium to create laser conditions by the Comsol software in two dimensions. We then obtain the random laser modes through plotting the emitted spectrum graph by this random medium. Finally, the substitution of the electric field in the medium including zinc oxide nano-rods, is investigated.

2. Discussion and results

In this paper, a two-dimensional structure is used for random laser modeling based on ZnO nanorods. In this two-dimensional structure, the ZnO nanorods continue in the z-axis direction to infinity and the pump beam enters the medium laterally. The actual and schematic view of the simulated structure is shown in Fig. 2. In this structure, it is assumed that ZnO nanorods are located in an air-containing medium. As mentioned earlier, in the construction of random lasers, scattering is required to create local cavities and thus produce coherent beam. On the other hand, the existence of a medium having optical gain is essential for stimulated emission. In the designed structure in this simulation, ZnO nano-rods have been used as the gain medium in the ultraviolet spectrum, and on the other hand we have used these nano-rods to create scattering and local cavities.

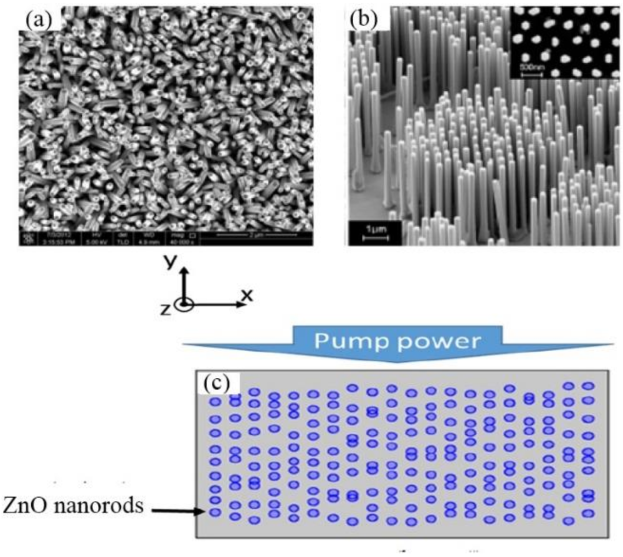

Fig. 2. (a) and (b): Real view of ZnO nanostructure, (c): simulated view of these nanostructures (color online)

To investigate the random laser in this structure, it is first assumed that the power of the pump is too low, below the threshold for detecting the candidate modes for the random laser emission. By a low power beam probe, the value of the transmission of the system in terms of the wavelength of the probe beam is calculated and shown in Fig. 3. The peaks in Fig. 3 represent the resonant frequencies generated by local cavities. Each of these resonant frequencies is caused by the trapping of light in a local cavity. Due to the different path lengths of light traveled by each local cavity, the resonance frequency of the cavity also varies. In fact, the irregularity of the zinc oxide nanoparticles causes the Anderson localization phenomenon. As a result, it results in absorbing light and resonant frequency. These resonant frequencies have a high bandwidth due to the very low power of the irradiation pump, which indicates a high loss in these local cavities. Therefore, to produce a random laser, the pumping power must be sufficiently high to compensate for this loss by stimulated emission of ZnO nano-rods and the loss equals the optical gain and the laser starts to oscillate. To observe Anderson's localization in this structure, the total electric field distribution for 380.3 nm is plotted in Fig. 4 (380.3 nm is one of the resonant wavelengths in Fig. 3). When we work with a random laser, the periodicity of the structure is no longer meaningful. But by changing the structure distribution and changing the position of the nanorods, only the local cavities created in the structure change. As the position of the cavities changes in structure, there is no change in the overall problem.

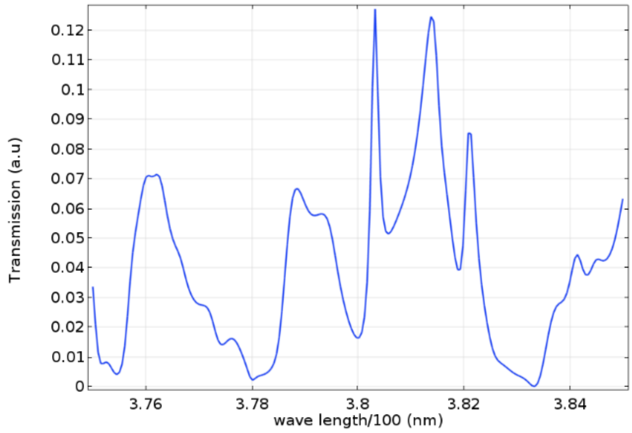

Fig. 3. Diagram of the spectrum emitted at very low pump power, below the threshold for detecting candidate modes for random laser emission

As can be seen in Fig. 4, the light is displaced within a range of structure and the intensity of the total electric field in this area is greatly increased.

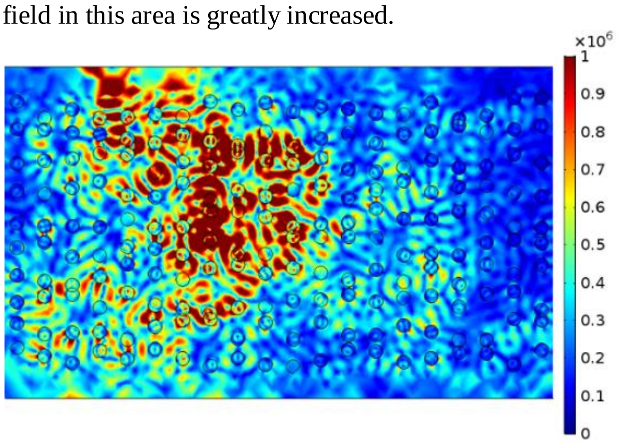

Fig. 4. Distribution of the total electric field for the wavelength of 380.3 nm in the simulated structure (color online)

By increasing the power of the irradiation pump, each of the resonant frequencies can be transformed into a random laser mode. It can be seen in Fig. 5 that with increasing irradiation pump power, one of the resonant frequencies of the wavelength of 380.3 nm has a higher transmission than the rest of the wavelengths. Therefore, the wavelength of 380.3 nm is a good candidate for random laser generation. The distribution of the total electric field for this wavelength is plotted in Fig. (6). According to Fig. (6), it can be concluded that increasing the power of the irradiation pump increases the intensity of the total electric field in the localized region. The diameter of the nanorods is 100 nm. When we change the diameter of the nanorods a few nanometers randomly, there is no significant impact on output. Because nanorods substitution leads to the formation of local cavities, the phenomenon of Anderson’s Localization and resonance frequency is created. Therefore, the change in the diameter of the nanorods and their random diameters does not make much difference to the problem.

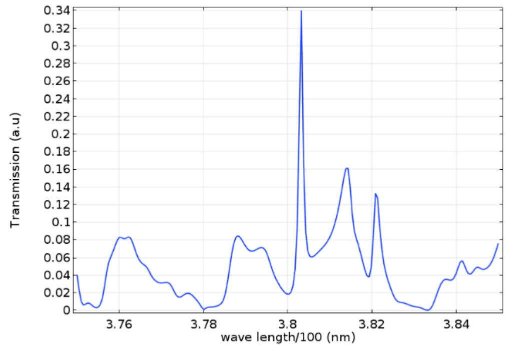

Fig. 5. Transmission spectrum (emission spectrum) of random structure with radius pump power below threshold

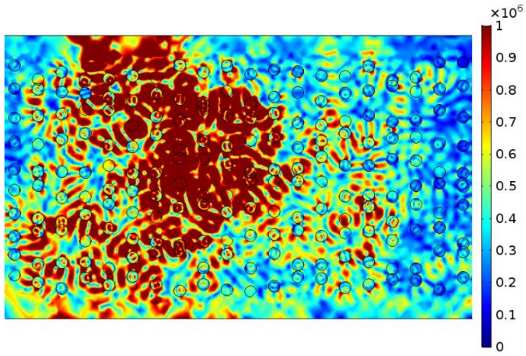

Fig. 6. Distribution of electric field for pump power below threshold (color online)

The radiation pump power is then raised to the threshold of the random laser oscillation. In this case, the gain generated overcomes the local cavity loss and the random laser starts to oscillate. The transmission diagram for the pump power when is greater than the threshold has plotted in Fig. 7. According to this diagram, the resonance frequency bandwidth at 380.3 nm is very low (less than 0.5 nm), indicating a low loss and random laser oscillation at this wavelength. It should be noted that the rest of the frequencies in Fig. 3 have not attained the required gain to overcome the loss and are therefore switched off.

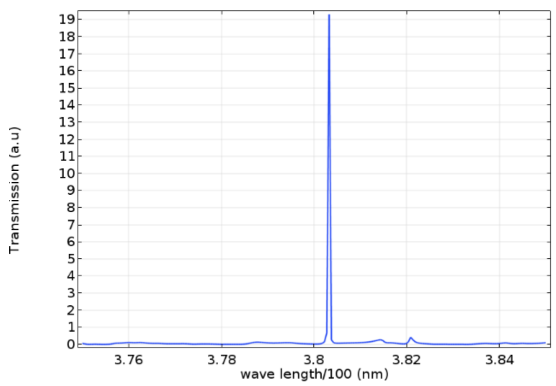

Fig. 7. Transmission spectrum (emission spectrum) of random structure with radius pump power exceeding threshold

Fig. 8 shows the distribution of the total electric field (for the pump power exceeding the threshold). According to this figure, the electric field has increased sharply due to the increase in the power of the irradiation pump and the loss compensation by stimulated emission. In this case, a random laser based on ZnO nanorods begins to oscillate.

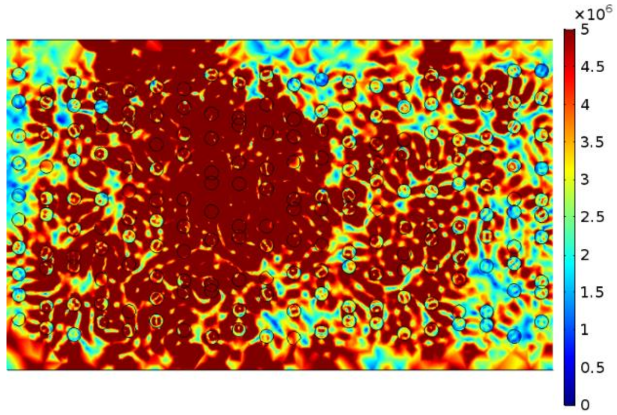

Fig. 8. Electric field distribution for pump power greater than threshold (color online)

3. Conclusion

In this paper, a two-dimensional model for the investigation of random laser based on ZnO nanorods is presented. Then by pump beam radiation and increasing the pump power, the emission spectrum of the beam was obtained. The peaks in this spectrum show random laser modes. Finally, by calculating the electric field distribution in two-dimensional structure, Anderson localization phenomenon and local laser cavities were observed. The proposed model can be used to design a random laser based on ZnO nano-rods as well as optimize the output of these lasers.

References

[1] D. S. Wiersma, Nat. Phys. **4**(5), 359 (2008)
[2] H. Cao, B. Redding, M. A. Choma, Physics and applications of random lasers, in 2014 The European Conference on Optical Communication (ECOC), 2014.
[3] J. Andreasen et al., Advances in Optics and Photonics **3**(1), 88 (2011).
[4] T. Nakamura et al., Optics Letters **40**(11), 2661 (2015).
[5] P. Rafiee, V. Ahmadi, M. H. Yavari, 3rd ICTON Mediterranean Winter Conference (ICTON-MW), 2009.

*Corresponding author: tizfahm.j@gmail.com