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Numerical Investigation of Random Laser based on "Lucky photon" model

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***Abstract*—**The spectral behavior of a random lasing system is calculated using numerical calculations. The random lasing system comprises of TiO2 powder dispersed in Rhodamine 6 G dye solution. In the present work, the random lasing action is simulated by using lucky-photon model, which does not take into account the interference effect. By tracking individual photon and repeating the same several times, we found that the intensity fluctuation at a particular wavelength shows Levy like distribution with power law parameter m = 1.62. Some exponential decay is observed at higher output intensity, which is yet need to be resolved.
Results show that with increasing particle diameter intensity decreases and intensity is higher for higher particle density. The difference between them decreases as an increase in the particle diameter.

***Keywords*—**Random laser, lucky photon model, Levy distribution, Gaussian distribution.

I. INTRODUCTION

A laser is commonly built from two fundamental elements. First is the material that provides optical gain through stimulated emission and second is an optical cavity that partially traps the photons. It may be noted that if the total gain in the cavity is greater than the losses, then the system reaches a threshold and lases. It is the cavity that regulates the modes of a laser which means it determines the directionality of the output and its frequency. Random lasers work on the same principles, but the modes are determined by multiple scattering and not by a laser cavity.

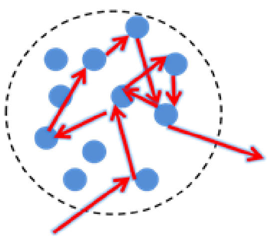

Fig.1. Multiple light scattering with gain

Figure 1. shows a random collection of microspheres which comprising laser dye. These microspheres are excited to obtain population inversion and then scatter light several times, as there is no outlet for ray. Incoming light is trapped and goes on making multiple reflections (scattering) till it is guided to leave the cavity. Hence, it amplifies it in the process. The propagation of the light waves becomes that of an amplified random walk.

Lethokov [1] in 1968 was the first in all who initiated research on strongly scattering media with optical gain, i.e. random lasers. The results show that the amplification through stimulated emission is possible in a random medium with gain. This prediction was presented in many papers. However, we refer only a few experimental [2] and theoretical [3] papers in the present study. The threshold phenomena in the power conversion and spectral narrowing have been observed in random lasers. In a few cases, sharp features like spikes in the emitted spectrum were observed. The width of these spikes indicates the width of the output of cavity lasers. Various models have been proposed to explain spikes in the emitted spectrum. These models are mainly a local cavity model with interference in a random laser [4] and the lucky-photon model without interference taken into account [5]. The local cavity model with interference in a random laser, also called as the local mode model and the lucky-photon model without interference taken into account also called as the open mode model. Monte Carlo method is a computer algorithm that uses the concept of randomness. Doma et al. [6] has performed Monte-Carlo simulation to study the effect of a strong magnetic field on the few-electron atoms.

In this work, we have simulated the intensity fluctuation by Monte-Carlo simulation. The intensity fluctuation in the random laser as a function the emission wavelength keeping the particle size fixed. We have assumed Zinc Oxide (ZnO) powder scattered in Rhodamine dye solution to achieve high gain and high scattering, simultaneously.

II. THEORY

Random laser shows turbulent characteristic in its spectral and temporal response specifically in a pulsed configuration. The laser can have a different spectrum each time in the excited state because a large number of random modes contest for the available gain. It may be noted that lasing starts from spontaneous emission which is different at every pulse. Each photon is initiating after the spontaneous emission of dye undergoes multiple scattering by the scattered ZnO powder. It travels sufficient paths to obtain adequate gain in the medium which contribute to the lasing.

A simulation has been performed by tracking specific photon from its start point to the fixed final point of collection. The spontaneous emission spectrum of the dye molecule at some position say (x, y, z) inside the pumped volume spontaneously emit a photon [7]. The emitted photon wavelength is selected randomly from a uniform distribution weighted by the measured fluorescence spectrum of the dye and the direction of travel is selected randomly from a uniform distribution over 4_ steradians. The distance (l) is the distance travels by photon before being scattered and is calculated from an exponential distribution represented as P(l)=A*exp(-l). where "A" is the scattering cross section, it is dependent on the concentration of scatterers, their size and wavelength of light.

The dimension of the system is taken as 1cm x 1cm x 1cm and the particle size is taken to be 585nm, where the emission spectrum of the dye peaks. The scattering was defined to be Mie scattering. The concentration of dye and Scattering particle was kept fixed throughout the simulation.

III. RESULTS AND DISCUSSION

Figure 2 shows the three snapshots of the spectra of the random laser. It can be easily observed that there is a considerable amount of fluctuation and each pulse looks uncorrelated. This is as a result of the fact that we have considered the pulse repetition rate to be very slow so that before the influence of the second pulse, all the excited state molecule due to the first pulse has come down to the ground state.

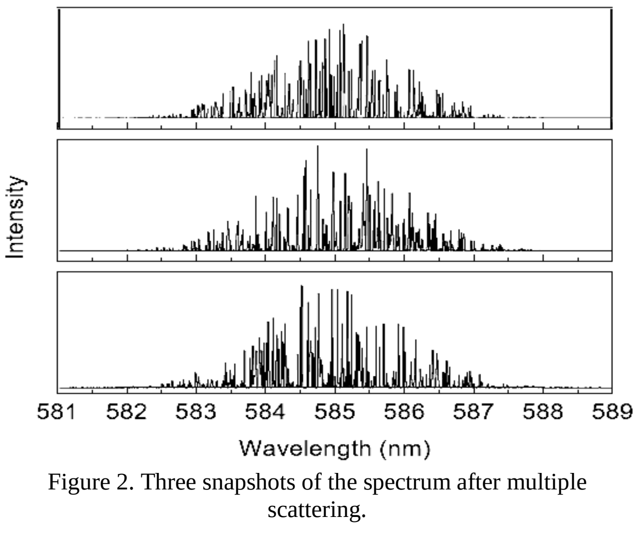

Figure 2. Three snapshots of the spectrum after multiple scattering.

However, we have observed an important correlation. This is the distribution of intensity at a single wavelength. The intensity distribution follows levy type rather regular Gaussian statistics. Levy distributions have an infinite variance due to the occurrence of rare but very large values. It characterized by a slowly decaying (power-law) tail. This type of results was also observed by Kumar and Ramachandra [8]. This particular distribution is represented by the formula $f(I)=1/I^{m}$, where I is the intensity and m is the power law parameter. We have estimated the power law parameter for a particular intensity of incident laser from the slope of output laser intensity with their probability of occurrences. It is plotted in figure 3 for the wavelength of 585 nm.

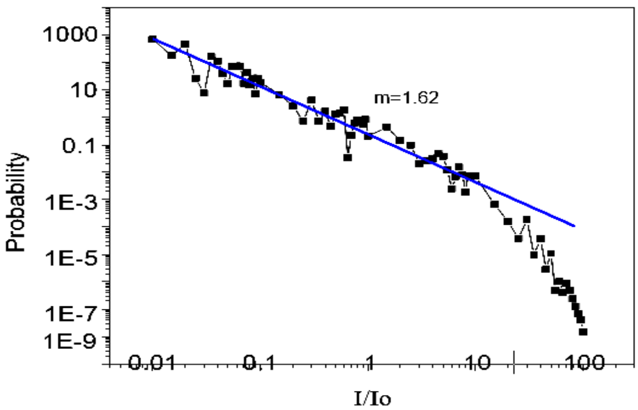

Figure 3. Distribution of Random laser Intensity

Here Io is the intensity of the incident laser. From the slope of the curve, the power law parameter was found to be 1.62(±0.02). Another, quite interesting point observed here is the exponential decay of the distribution at higher intensities. The origin is still unclear at this point of time. we have calculated the integrated total intensity and the FWHM at a pump intensity of 60mJ with a particle density of $5x10^{11}cm^{-3}$. Figure 4 illustrated the integrated total intensity as a function of particle size (diameter). Figure 5 provides FWHM as a function of the scattering particle size. It could be clearly seen that total integrated intensity decreases monotonically with an increase in scattering particle size. However, FWHM shows some valley type behavior at around 400 nm. It is surprising in the sense that, we have considered only Mie scattering, whose scattering cross-section is maximum when the light wavelength matches with that of the scattering particle size. Therefore, a peak is expected in the intensity versus particle size graph. B. Garcia-Ramiro et. al [9] calculated the location of the spectrum as a function of volume filling factors, which is the fraction of volume occupied by the scatterer. It seems reasonable because, at lower particle size, for a given number density, the volume filling factor decreases, which allow the photons to travel in high gain region. Therefore, the intensity further increases instead of going down. This is marked as a change in slope in figure 3**.** The expected behavior is shown as a dotted line in the same figure. The minimum FWHM is also expected at around 500-600 nm and shifts towards lower particle dimension, for the same reason.

This discrepancy is conspicuous, for higher particle density as expected. The repetition of figure 4 for varying particle density is shown in figure 5. This figure is normalized for relative to make a direct comparison between them. As we increase particle diameter, intensity decreases which is same as figure 4. However, it may be noted that higher density intensity is also higher but the difference between them decreases as we increase particle diameter. After 600 nm all different particle density found to be almost the same. Interestingly, though the spectrum varies randomly when any of the parameter changes as is evident from one event to next event. Figure 4-6, did not show much variation and their behavior remains the same within a certain error range. This is also true if we change the pump intensity and repeat the same calculation. This is an interesting property and needs further investigation.

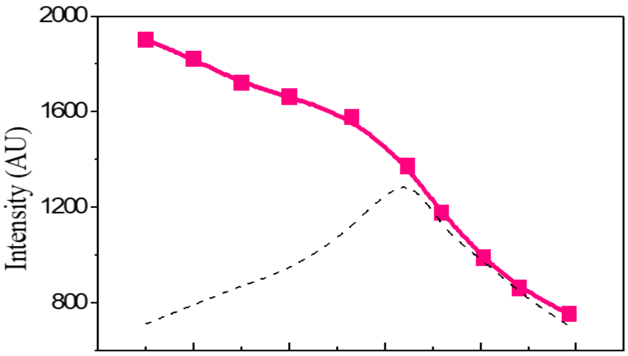

Fig. 4 Integrated Intensity of stimulated emission versus particle diameter for an input intensity of 60 mJ

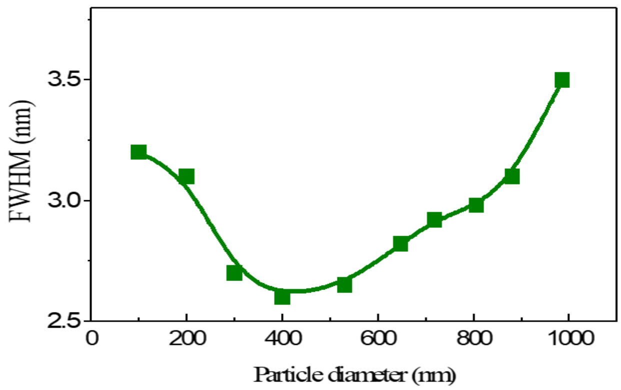

Fig. 5 FWHM of stimulated emission versus particle diameter for an input intensity of 60 mJ

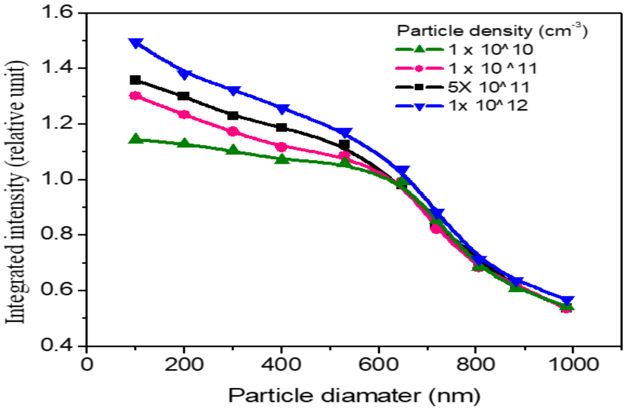

Fig. 6. Normalized Integrated intensity in relative units versus particle diameter for different particle density

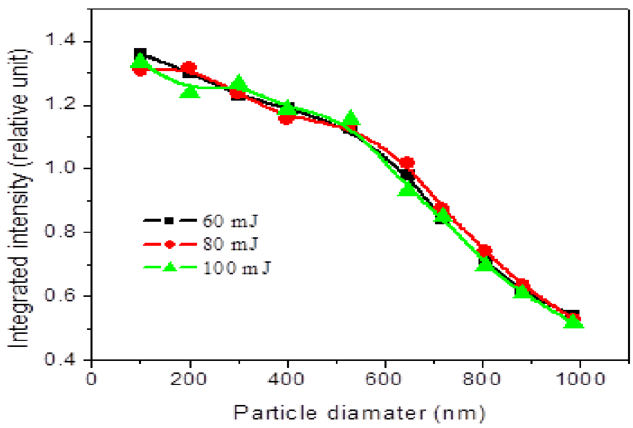

Fig. 7. Normalized Integrated intensity in relative units versus particle diameter for different pump intensity

The integrated intensity is as expressed in the relative unit a function of particle diameter. Figure 7 explicitly shows qualitatively similar behaviour for larger particle dimensions so far as the pump intensity stays above the threshold intensity.

One of the prime reasons, why we chose this simulation is to explain the power law fluctuation of the random laser. To verify reproducibility, we have performed the calculation repeatedly by fixing a set of parameters then from the spectrum we took a wavelength randomly and plot the intensity as a function of time. The slope from this plot gives power law parameter.

IV. CONCLUSION AND FUTURE SCOPE

The random fluctuation of intensity of the random laser is an outcome of Levy type random walk of the photons in the gain medium. Our results show that as we increase particle diameter intensity decreases and for higher particle density; intensity is also higher but the difference between them decreases as we increase particle diameter. After 600 nm all different particle density found to be almost same. Our calculation shows that the statistical behavior of fluctuation can be tuned by changing the particle size and particle density. We have also simulated the random laser action in randomly scattering solution. The output intensity fluctuation was found to be Levy type with power law parameter m=1.62(±0.02). We have also observed exponential decay of the distribution at higher intensities.

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