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Charlotte Hurot, Wan Zakiah Wan Ismail, and Judith M Dawes*

Random laser in a fiber: combined effects of guiding and scattering lead to a reduction of the emission threshold

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Abstract: Random fiber lasers incorporate scattering particles with optical gain in a fiber geometry and offer potential for sensing and biophotonics applications. In this work, the combined effects of waveguiding and scattering in random fiber lasers were investigated. A dye solution with nanoparticles was infiltrated into the hollow core of the microstructured optical fibers and the fibers were side pumped by a frequency-doubled Nd:YAG laser. The resulting emission threshold was reduced in comparison with the bulk solution. We used a Matlab model to gain a better understanding of the competing feedback mechanisms involved.

Keywords: Random laser, fiber laser, multiple scattering

1 Introduction

Unlike conventional lasers, random lasers do not need an external optical cavity to confine the light inside the gain medium. Multiple scattering provides optical feedback by increasing the path length of the emission light in the gain medium. The laser reaches a threshold, signified by a change in the emission linewidth and a change in the slope of the emission intensity with pump energy, when the amplification is sufficient to compensate for the losses [1, 2]. Random lasers are easy to construct, versatile in shape, and exhibit optical behaviors which complement those of standard lasers in terms of gain and feedback, [1–5] In particular, random lasers offer potential for applications including biomedical or biological sensing [6, 7]. Random laser emission typically exhibits a threshold and many features of regular laser light including partial coherence [8], with random lasers divided into coherent and incoherent schemes, based on the effect of field or intensity feedback [1]. Biophotonic sensing applications require a high sensitivity and very small sample volumes, for which a liquid-filled hollow core random fiber laser appears promising [4, 5, 9] since the fiber increases the emission due to light guiding.

Here, we compare the effects of guiding and scattering in influencing the emission linewidth and intensity. We modeled the photon paths in random fiber lasers, considering photons scattered by alumina nanoparticles in the hollow-core microstructured fibers, and guided in the fibers through total internal reflection. Losses were modeled when the photons leaked through the fiber core walls. Our experiments show that both guiding and scattering are needed to reduce the threshold and linewidth of the emission from incoherent random fiber lasers. We observed that the random fiber lasers are more efficient in the weakly scattering regime than in the diffusive regime, consistent with the modeling results.

2 Experimental Procedures and Modelling

To ensure guiding in the fiber, we used hollow-core microstructured optical fibers (NKT) in which the gain material was surrounded mostly by air. The gain inside the core of the microstructured fibers was provided by a solution of Rhodamine 6G (1.0 mM) in ethanol : ethylene glycol (10:90), in which Al_2O_3 nanoparticles (diameter 50 nm and concentration 5×10^{12} cm^{-3}) were suspended. The so-

*Corresponding Author: Judith M Dawes: ARC Centre of Excellence CUDOS, MQ Photonics, Department of Physics and Astronomy, Macquarie University, Sydney, Australia,
E-mail: judith.dawes@mq.edu.au
Charlotte Hurot: ARC Centre of Excellence CUDOS, MQ Photonics, Department of Physics and Astronomy, Macquarie University, Sydney, Australia
and Ecole Centrale de Lyon, 36 Avenue Guy de Collongue, 69134 Ecully Cedex, France
Wan Zakiah Wan Ismail: ARC Centre of Excellence CUDOS, MQ Photonics, Department of Physics and Astronomy, Macquarie University, Sydney, Australia
and Faculty of Engineering and Built Environment, Islamic Science University of Malaysia, Nilai 71800, Negeri Sembilan, Malaysia

lution was selectively infiltrated by capillary action into the core of the microstructured optical fiber, after first collapsing the cladding holes using a fusion splicer [10, 11]. Each sample consisted of approximately 2 cm length of microstructured fiber with dye/particle solution. The system was side-pumped by a Q-switched frequency-doubled Nd:YAG laser (wavelength 532 nm, pulse duration 5 ns, repetition rate 10 Hz) which was focussed using a cylindrical lens to produce a 5 mm pump spot on the fiber aligned with the fiber axis. The emitted light was collected from the end of the fiber by a lens and coupled to a spectrometer (Ocean Optics, ~2 nm resolution) or power meter.

We also developed a simple Matlab model based on Monte Carlo simulations averaging many photon paths to compare the effects of guiding and scattering. We assumed a 2D geometry with cylindrical symmetry and a mean scattering length l_{scatt} which is governed by the scattering cross-section and concentration of the nanoparticles in the gain medium. Photons are introduced into the fiber core with dimensions consistent with our microstructured fiber, where the length of the fibre gain region is L. The ratio of L with the scattering length l_{scatt} governs whether the laser is in a high scattering or low scattering regime. The photons propagate a distance dl in a direction a, and there is a probability $P_{Scatt} = dl/l_{scatt}$ for a Mie scattering event after each propagation distance dl. When the photons are scattered, the propagation direction is changed according to the Mie scattering probability calculated for the nanoparticles we used. (Mie scattering data obtained assuming spherical particles, according to the web-based calculator developed by Prof. S. Prahl [12].) Photons are coupled out of the fiber core as emission when they reach the fiber end and photons are lost from the system (not guided) if they encounter the fiber side boundaries with a propagation angle that is outside the critical angle.

3 Results and Discussion

3.1 Modelling

Results of the model comparing the fraction of photons collected from the end and the photons lost from the sides are shown in Fig. 1 as a function of the scattering length. A longer scattering length corresponds to a lower density of nanoparticles, and even very low densities of nanoparticles lead to narrower emission linewidths and lower thresholds. The length of the path of the photons before being scattered or lost from the system depends on the scattering length in an interesting way, plotted in Fig. 2. A longer path length indicates more opportunity for amplification in the gain medium, but very long or very short scattering lengths lead to reduced path length while the maximum path length appears to occur for relatively short scattering lengths within the high scattering regime. The behaviour for long scattering lengths may be due to saturation of the gain within the fiber core.

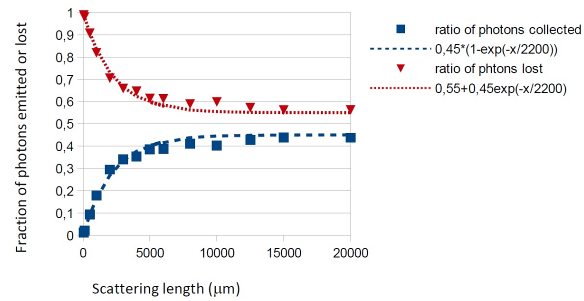

Figure 1: Monte Carlo model: Fraction of photons collected as emitted or lost, vs scattering length. Systems with scattering length > 5 mm correspond to low scattering regimes.

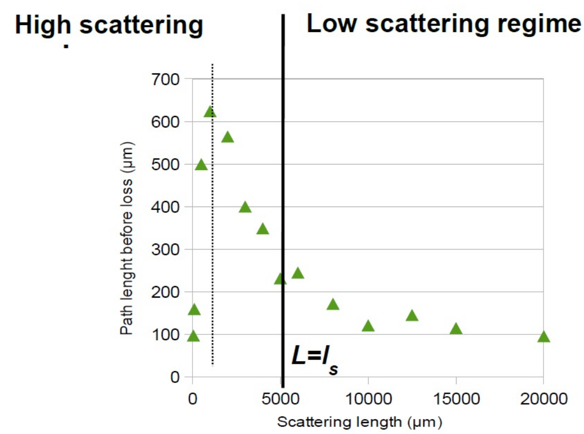

Figure 2: Modelled path length before loss as a function of scattering length: the path length has an optimum at short scattering lengths, then decreases with increasing scattering length. The division between high and low scattering regimes is placed where the size of the laser region L matches the scattering length.

3.2 Experimental results

The emission spectra below and above threshold, shown in Fig. 3, demonstrate the spectral narrowing typical of incoherent random lasing, but the spectral resolution of these measurements is limited by the pulse averaging. The threshold for emission from the random fiber laser is an order of magnitude reduced compared with the emission threshold for incoherent emission from a bulk solution of

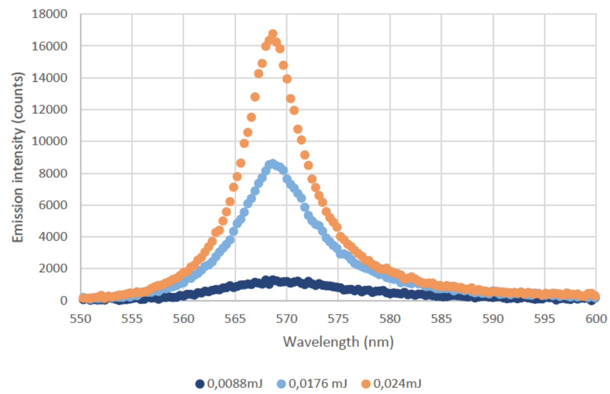

Figure 3: Emission spectra of 1 mM Rh6G/1 × 10^{12} cm^{-3} alumina in the fiber core below and above threshold.

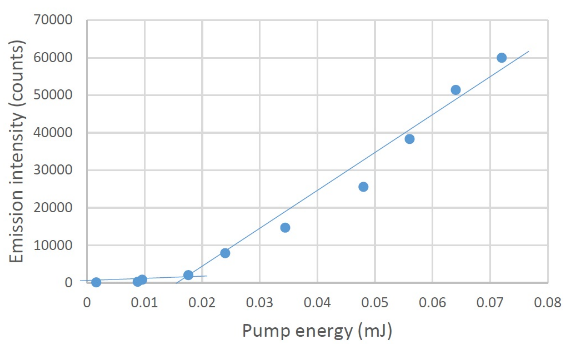

Figure 4: Emission peak intensity as a function of pump energy for 1 mM Rh6G/ 1 × 10^{12} cm^{-3} alumina in the fiber core.

the same dye and nanoparticles at similar concentrations as observed in Ref. [8]. The dye-filled microstructured optical fiber exhibits a lower threshold for solutions with nanoparticles than it does without scattering nanoparticles, as demonstrated by a comparison of Figs. 4 and 5. Both guiding and scattering tend to increase the light path inside the gain medium.

3.3 Scattering

As shown by a comparison of Figs 4 and 5, light scattering improves the efficiency of the random fiber lasers. However, much increased scattering leads to an increased threshold. The lasing threshold increases 25× when the scattering mean free path reduces from 28 cm to 0.14 cm, and no lasing threshold is observed for smaller scattering mean paths, ~0.14 cm. These observations are compatible with modelling results on the ratio of the lost photons and the mean path length of photons before loss in Fig. 2. Here, guiding and scattering both contribute to lasing in the weakly scattering regime. In contrast, in bulk random

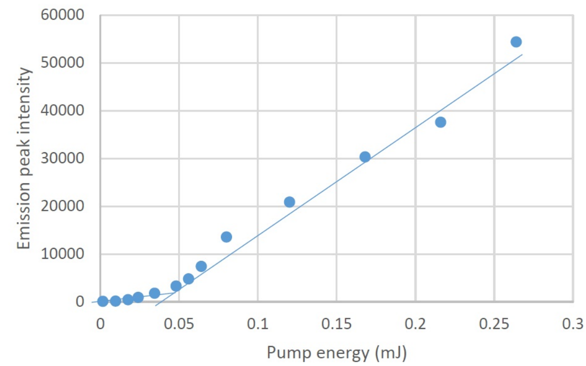

Figure 5: Emission peak intensity as a function of pump energy for 1 mM Rh6G without alumina in the fiber core.

dye lasers, the lasing threshold reduces for reduced scattering mean free path as there is no guiding [8, 9].

Scattering can increase the path length of light in the gain medium through optical feedback whereas guiding confines the light, limiting the losses through the walls and improving the directionality of the laser emission. In the weakly scattering regime, guiding is important to enhance the multiple light scattering in the fiber core. However, increasing scattering may disturb the guiding process resulting in more losses through the wall. The longer path length may lead to gain saturation with an increased lasing threshold in the diffusive regime.

3.4 Effect of guiding

To study the effect of guiding in random fiber lasers, we compared the experimental results for air-filled and filled cladding holes with fixed concentrations of Rh6G (1 mM) and alumina (1 × 10^{12} cm^{-3}) in ethylene glycol. If the cladding holes of the microstructured fiber are filled, we observe broad emission spectra, (>15 nm linewidth) and no emission threshold. Whereas, the emission spectrum narrows (5 nm) with increased pump energy and an emission threshold appears at ~0.024 mJ for a microstructured fiber with air-filled cladding holes. The emission thresholds are determined when the emission peak intensity increases nonlinearly with the pump energy [8].

For the fiber with air-filled cladding, the core is filled with the solution, which provides refractive index contrast (refractive index of cladding, n_2 ~1 due to air, and refractive index of core, n_1 ~1.43 due to ethylene glycol) to ensure light guiding through total internal reflection in the fiber core. As the scattering mean free path for this sample is l_s ~ 28 cm which is 5× larger than the sample size in our system (L~ 5 cm), the sample is considered in the weakly scattering regime. In this regime, scattering events for photons that radially cross the microstructured fiber core are rare, so the main mechanism to tranversely confine the light in the fiber core is total internal reflection [6].

In conclusion, we demonstrated enhanced performance of random lasers by incorporating gain material and scattering particles into hollow core microstructured optical fibers. We have shown that both scattering and waveguiding support a reduced threshold for the emission light, and contribute to increased path length of the emitted light within the gain medium.

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