The Pennsylvania State University

The Graduate School

Department of Electrical Engineering

RANDOM LASER IN DISORDERED SOLUTIONS

A Thesis in

Electrical Engineering

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

December 2017
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Abstract

Random laser is a small laser source observed in disordered gain media, including disordered solutions, semiconductor powder, nanostructured thin films, and so on. Random laser is special because it has no optical cavity, which is different from conventional laser. Based on some advantages that random laser owns, it has been studied widely and deeply in recent couples of years.

In this thesis, it mainly describes the research history, fundamentals, applications, and experiments in our lab. Research history includes how random laser is discovered, and how it is developed. Basic theories of random laser are also explained in this thesis. Random laser can bring people great benefits owing to the low cost, multidirectional light, changeable shape, and small size. It deserves to be studied and it will change many application areas. Finally, we did some experiments in our lab and the results helps us to understand the principles of random laser.
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Chapter 1 Introduction

Lasers have been widely applied in display, medicine, industry and other areas in our daily life. As we know, there are two basic elements of a conventional laser: gain medium and cavity. Stimulated emission in the gain medium provide gain for amplification and light can be trapped by the cavity. The gain medium can be pumped electrically or by a laser source or a lamp. The Fabry-Pérot cavity is the most common laser cavity. Cavity mirrors are used to reflect and trap the light in the Fabry-Pérot cavity; a gain medium is put between these two mirrors. Light is propagating back and forth in the cavity formed by the mirrors and amplified through the gain medium.

Typically, scattering in the cavity will cause loss; so it is considered as a detrimental factor that needs to be avoided. While what will happen if the scattering is very strong? Is there any relationship between scattering and laser? From recent discoveries, it is found surprisingly that strong scattering benefits laser generation. Let us think about a gain medium including many scattering centers. When light is propagating in this scattering system, photons experience multiple scattering before they escape out of boundary of the medium. Multiple scattering increases the residence time of photon in the medium, and it increases the efficiency of light amplification. In this circumstance, it is unnecessary to add reflectors to trap light
in gain medium, because scattering traps the light. Normally, ‘random media’ is used to describe this kind of system which includes disordered medium.

This kind of system is different from a conventional laser\(^1\) as shown in figure 1. The gain medium in this system is strong scattering material such as powder but not transparent crystal. Strong scattering will supply positive feedback. Let us imagine that one photon is propagating in the medium. When it impacts a particle, it will change the direction of propagation. If the scattering is strong, the photon will take a long time to escape from the medium and it will be trapped in the medium. The longer the time the photon propagates in the gain medium, the higher gain it will get. When the gain is larger than loss, it will generate laser.
Figure 1. Comparison between a conventional laser and random laser. a) In a conventional laser, it contains two mirrors (form an optical cavity) and amplifying materials. b) In a random laser, there is no optical cavity. Multiple scattering between disordered particles traps the light in the medium.


1.1 Research History

In recent years random laser attracts more attention.

In 1968², Letokhov used a simple model called ‘photonic bomb’ to study light scattering in gain medium. The photons experience multiple scattering and
random walk before leaving gain medium. When the photon propagates in gain medium, that will cause stimulated emission. In this research, Letokhov first mentioned two parameters of length. One is generation length. It is the average distance that a photon travels before it generates a second photon. The other one is mean path length. It is the average distance that a photon propagates in the scattering medium before it leaves the medium. When the latter distance is larger than the former distance, every photon generates a second photon before leaving the medium. This is a chain reaction. One photon generates two photons, and two generate four, and so on…. The number of photon increases with time. So it is the critical point of photon generation that two distances equal to each other. Because this photon generation process is similar to neutron generation in a nuclear reactor, this model is named ‘photonic bomb’.

After Letokhov’s pioneering work, researchers observed strong stimulated emission in different kinds of crystal powder such as Nd doped glass powder, Ti doped sapphire powder, etc. When laser pulse pump these crystal powder above the threshold, the width of emission pulse sharply decreases.

In 1986, Markushev et al. studied neodymium doped laser crystal powder\(^3\). Under the strong pumping with laser pulses of 30-nsec duration, stimulated emission was observed. In 1990, Markushev et al. also did further studies about Nd-doped laser crystal powder.\(^4\) Since then, scientists did significant research on random lasing in powder.\(^5, 6, 7, 8\)
Based on the above studies, lasing in solution containing laser dye and particles is observed in early 1990s. In 1994, Lawandy reported that their group observed laser like emission in methanol solution containing rhodamine 640 perchlorate dye and TiO$_2$ particles. This case is different from the one in powder. In the solution, gain medium and scattering centers are separated. Light amplification exists out of the scattering centers. The particle size is roughly 250nm. The research work Lawandy et al did triggers a large number of experimental and theoretical studies on random lasers. Random laser is realized in many material systems such as polymer, liquid crystal and biological tissue.

In 1999, H. Cao group observed random laser in the fluorescence experiment in ZnO semiconductor powder. They utilized Laser sputter deposition method to get ZnO film. The thickness of ZnO film is between 6um and 15um. As it was shown by SEM, the size of ZnO powder particle was roughly 100nm. By coherent backscattering experiment, the scattering mean free path is measured to be 0.8 $\lambda$. Then Nd:YAG laser of 355nm or 266nm is used as a pump source, focused as a spot or strip, and normally incident on the ZnO film. The emission is gathered and guided by a bunch of fiber to a spectrometer which is equipped with a CCD. It can picture the emission spatial distribution of samples. As shown in figure 2, the emission spectrum changes with the pump power. When the pump powder is weak, emission spectrum shows a broad spontaneous emission spectrum. With the intensity of pump power increases, width of spectrum obviously narrows. When
the pump power is over the threshold, sharp peaks appear in the emission spectrum, and the width is narrower than 0.3nm. This width is 1/30 of the width under low pump power (lower than threshold). Narrower sharp peaks appear when pump power intensity further increases.

In recent years, many different nano-scattering centers are prepared and studied, including semiconductors\textsuperscript{11}, biological tissues\textsuperscript{12}, cold atoms\textsuperscript{13}, quantum dots\textsuperscript{14}, rare earth doped nano-powders\textsuperscript{15}, and photonic crystals\textsuperscript{16}.

As mentioned above, this kind of laser can be observed in particle solutions or semiconductor powder. The difference between the conventional laser and random laser is the optical cavity. According what we discussed above, there is a well-defined and stationary optical cavity to trap the light inside in conventional laser. While in random laser, light is scattered by different particles, and it can form a random path or a loop. So we can say the random laser has a ‘random’ optical cavity. The light path is different from one to another because of the random distribution of particles.

1.2 Fundamentals

So far, random laser theories mainly include several basic theories: Scattering in random gain medium theory\textsuperscript{17}, Ring cavity theory\textsuperscript{18}, Ring waveguide theory\textsuperscript{19}, and so on.
In random gain medium theory, light diffusion equation incorporates a gain term\textsuperscript{17}. This theory studied the effect of gain and multiple scattering of light propagation. It essentially explained the amplification of spontaneous emission (ASE) phenomenon. This theory is suitable to explain the case when scattering particle size and mean free path are larger than wavelength of light in the medium. And it cannot account the interference of light. So this theory cannot explain the photon localization phenomenon in random medium.

Ring Cavity Theory is proposed by Balachandran and Lawandyde to quantitatively explain random laser experiment in 1997. And it is utilized by H. Cao group to study the optical properties of high gain and strong scattering medium. It takes the interference of light wave into account. Light wave propagates in the closed ring cavity and interfere with each other. There are many ring cavities in the random medium. The emission output is the superposition of the output in these ring cavities. Ring cavity theory explain the formation of random laser and characteristics of emission spectrum. And it also illustrates the difference with ASE. But this theory also has limitation as it uses geometrical optics. Based on the ring cavity theory, in the high gain and strong scattering medium, ring cavities distribute randomly in the medium because of the randomness of medium structure. Every single ring cavity has its own resonant frequency, threshold, luminous direction etc. They are all random. This ring cavity theory cannot quantitatively explain these characteristics.
Ring Waveguide Theory deems that the probability of ring cavity formation in the random medium is very low. The reason is that high losses exist in ring cavity scattering. So high gain in random medium is necessary. On the other hand, the formation of ring waveguide doesn’t need strong scattering and high gain random medium. Ring waveguide can also be formed in weakly scattering medium. Consequently, in the same random medium, the probability of high-Q ring waveguide formation is much higher than that of ring cavity formation. This theory reveals the relationship between ring waveguide formation and structure of medium. The formation of ring waveguide in random medium is closely related to the dielectric constant. High-Q waveguide can be achieved by changing the dielectric constant of the medium. It elaborates the micro cavity structure and conditions of formation, supplementing the deficiency of ring cavity theory.

1.3 Incoherent and coherent random lasers

Let’s imagine that photon propagates in powder. It will change the propagation direction when it is scattered by a particle. If the scattering is strong, there are two cases as following: first, photons experience a random walk, then escape from the random medium. Second, In case of the scattering is stronger, photons walk a long journey then go back to the original point; so photons are trapped in the random medium. These two cases correspond to two random laser mechanisms: incoherent random laser and coherent feedback random laser.
Figure 2. Illustration of spectral output of random laser. Upper figure is incoherent feedback with a relatively smooth peak. Bottom figure is coherent feedback with sharp spikes on top. (Source from: Feng Luan, Bobo Gu, Anderson S.L. Gomes, Ken-Tye Yong, Shuangchun Wen, Paras N. Prasad, “Lasing in nanocomposite random media”, Nano Today, vol.10, pp.168-192, Apr. 2015.)

As shown in figure 2, there are two different spectral outputs for incoherent and coherent feedback random lasers. The top spectrum shows a smooth curve. It corresponds to incoherent lasing. The photon travels in scattering medium, and experiences a relatively long life time. Then it escapes the medium. There is
enough time to get amplification, but no loop formed in this process. So we can only observe a curve without sharp spikes. While from the bottom figure, some sharp spikes are shown. This means that photons generate some closed loop among different scattering centers when they propagate in scattering medium. As discussed above, the different signature between incoherent and coherent random laser is sharp spike which is caused by close-loop light path in random media.

H. Cao’s et al investigated incoherent and coherent feedback and transition between these two cases\textsuperscript{21}. In one experiment, ZnO particles of 100 nm diameter are prepared. Rhodamine 640 perchlorate dye is the gain medium and the concentration is 5mM. Particles ZnO are scattering centers and it is easy to change the amount of scattering centers by changing the density of ZnO particles. As shown in figure 3, the left figure illustrates the spectra at different pump power when the particle density is 2.5×10\textsuperscript{11}/cm\textsuperscript{3}. The pump power is from 0.68µJ to 5.6 µJ (from bottom to top). With the increase of pump power, a narrower peak appears. It is roughly 5nm. When the particle density is increased to 6×10\textsuperscript{11}/cm\textsuperscript{3}, with the pump power from lower to higher (0.74-3.9 µJ), some discrete peaks occurs. The width is nearly 1nm (Curves in the middle). Continuing to increase the particle density to 1×10\textsuperscript{12}/cm\textsuperscript{3}, many sharp spikes are shown with the increase of pump power (0.68-2.9 µJ). The width is less than 0.2nm (Curves on the right).

From the figures shown, incoherent random laser, coherent random laser, and the transition between these two cases are all characterized. When the scattering is
weak, under the same circumstance of dye concentration, photons propagate in scattering media, but difficult to form a closed loop. One photon generates another photon, and the number of photon increases. Thus the intensity of emission spectra is increasing suddenly. While the scattering is strong, path of photon can generate a closed loop. This closed loop is like a resonant cavity in a conventional laser. Consequently some sharp spikes are shown in the spectra.
Figure 3. Spectra of emission from rhodamine 640 dye solution containing ZnO nanoparticles. The particles densities are $3 \times 10^{11}/\text{cm}^3$, $6 \times 10^{11}/\text{cm}^3$, and $1 \times 10^{12}/\text{cm}^3$ separately (From left to right). From bottom to top, the pump power increases gradually. This figure shows incoherent and coherent random laser, and the transition between them. (Source from: Hui Cao, J. Y. Xu, Yong Ling, A. L. Burin, E.W. Seeling, Xiang Liu, R.P.H. Chang, “Random Lasers with Coherent Feedback”, IEEE J. of Selected Topics in Quantum Electronics, vol.9, pp.111-119, Jan. 2003.)
1.4 Applications

Random lasers have been studied for many years since the first study by Le-tokhov\textsuperscript{2}. Researchers observed random laser phenomenon in several different kinds of gain media, including laser crystals powders, liquid laser dye with particles, particle colloidal solutions, ZnO powder, and polymeric film.\textsuperscript{22,23,24,25} Because random laser has its own special properties, there are a lot of applications. So, random lasers attract researchers’ interests recently. Not only is powder random laser studied, but also have various solutions with particles been developed in recent years\textsuperscript{26}.

Why random lasers attract scientists’ great attention? The reason is that random laser has its own special characteristics, and it can be widely applied in different fields. For example, random laser is a micro-sized structure, and this micro structure has advantages in some areas. It can be embedded into photonic crystal as a light source. It can also be distributed into fluid. Besides, it can play an important role in light source of flat display.

In 2004, Randal et al reported that random laser is used in medical area. They picked human tissues both the malignant and healthy part as their testing samples. Laser dye is infiltrated into sample tissues. From figure 4 we can see, the spectrum collected from of healthy tissue shows a narrower and fewer peaks. Random laser emission spectra of the cancerous tissue sample has more lines. Based on random laser theory, the malignant tissue is more disordered than healthy tissue.
because of the tumor. Consequently, there are more resonators in malignant tissue, and more lines are captured in the spectra. It may be envisioned that this technique of separating cancerous tissues from healthy tissues could lead the diagnosis of cancer.\textsuperscript{27}

Random lasers can also be used to provide optical tags in biological and medical studies. When the nanoparticle clusters are attached to biological targets, the position of the targets can be traced by detecting the lasing emission from the clusters. We can differentiate the targets because each nanoparticle cluster has its own unique set of lasing frequencies\textsuperscript{28}. Besides, in 2012, H. Cao group utilized random laser to get speckle-free imaging\textsuperscript{29}.

Moreover, by virtue of the broad angular distribution which is different from conventional laser, random laser is a perfect light source in principle to be applied in display\textsuperscript{30}. A thin layer of a random medium doped with emitters can be used to coat an arbitrarily shaped display panel. Random lasers can be switched on and off much faster than light-emitting diodes and can be used to create high speed displays.\textsuperscript{31} Because of the precision and uniqueness, it can also be used in encryption.
Chapter 2 Experimental background

2.1 Motivation

As we mentioned above, random laser owns great value of application in diverse fields, such as medical domain, speckle free imaging, optical tags in biological study, display area, etc. Many researchers devoted themselves to study the random laser and investigate their fundamentals, mechanisms, applications, etc. To make random laser more useful and controllable, it is important to understand the details in random laser.

In this thesis, to study the random laser, some basic experiments are designed and performed. The goal of these experiments are to get an understanding of random laser in hands-on process. On the foundation of data we collected in the experiment, data analysis will provide me a better comprehension of random laser.

Recently researchers use different kinds of nanoparticles to study the random lasing, and the most commonly used scattering centers in the solution are TiO$_2$\textsuperscript{31}. Some researchers also tried the Al nanoparticles\textsuperscript{32}, PS nanoparticles, and polymer particles\textsuperscript{22,23,24,25}. The dye that is used in solution can be Rh6G or Rh 640\textsuperscript{31,32}. Both of them are widely used in liquid random lasers. Different solvent can be chosen to change the properties of the solution such as ethylene ethanol\textsuperscript{33}, glycol\textsuperscript{32}, and water\textsuperscript{33}.
In some other experiments, ZnO powder is chosen and this material can be both the scattering particles and gain media. While in our experiment, we pick solution to do the test, because in solution, scattering cansters and gain media are separated. We can change dye concentration to control the gain media. And it is also easy to regulate the scattering by changing the particle density. In our experiment, on the basis of reported data and conclusions, proper material are selected. This part includes how to decide the parameters we use, and how we prepare the samples.

2.2 Sample preparation

In order to control the gain and scattering more conveniently, samples of suspension are prepared. In suspension samples, gain medium and scattering centers are separated. Thus, it is easier to control the gain and scattering by changing the density of particles and concentration of dye.

There are three parts in the solution, including solvent, dye, and particles. In our experiment, two solvents are prepared. One is ethanol, the other is water. Solvent is chosen for its viscosity. Higher viscosity can prevent the particles in solution from sedimentation. Dye selected in this experiment is Rhodamine 640 which is a dark green crystal powder in appearance. The concentration is 0.1 mM to guarantee the gain and prevent quenching. Then, the particles which play the scattering centers in solution are SiO$_2$. This is a common scattering centers used in
random laser experiment. We prepared two sizes of SiO$_2$, one is 1 micron in diameter, and the other is 0.5 micron in diameter. To study the effect of density of particles to random lasing properties, three different particle densities are prepared for each particle size and each solvent. The table below summarizes the samples we made in this experiment. Sample 13 and 14 are only pure dye solvent with ethanol and DI water. We take them as comparisons.
Table 1. Fourteen solution samples prepared for random laser experiment. Two different diameters are chosen and two different solvent are used in the solution.

As it is listed above in the table, fourteen samples are prepared to be tested. We can see that different particle densities are according to different scattering mean free path. To understand random laser, there are two very important parameters: scattering mean free path and transport mean free path.
Figure 5. Illustration of scattering coefficient $\mu_s$ and efficient scattering cross section $\delta_s$.

Let’s define $N$ as the particle number per volume, and $\mu_s$ that is named scattering coefficient equals $N$ multiples $\delta_s$. The scattering mean free path (SMFP) is the reciprocal of scattering coefficient. Transport mean free path $l_t$ is defined as $l_s/(1-\langle \cos \theta \rangle)$. $\cos \theta$ is the anisotropy factor. For forward scattering, its value is between 0~1. The scattering mean free path is the average distance between scattering events. Transport mean free path can be thought of as the mean distance after a photon’s direction becomes random. Three different particle densities are chosen and six different scattering mean free path can be tested in our experiment.
\begin{align*}
l_s &= \frac{1}{N\delta_s} \\
l_t &= \frac{l_s}{1-\langle \cos \theta \rangle} \\
l_s &= \text{scattering MFP} \\
l_t &= \text{transport MFP} \\
N &= \text{particle number density} \\
\delta_s &= \text{scattering cross section}
\end{align*}

Particle densities are $1.82 \times 10^{12}/\text{cm}^3$, $7.18 \times 10^{12}/\text{cm}^3$, $2.87 \times 10^{13}/\text{cm}^3$ separately. When the particle size is 1 micron, the corresponding scattering mean free path are 119 micron, 30 micron, and 7.5 micron. When the particle size is 0.5 micron, we get the scattering mean free path 30 micron, 121 micron, and 476 micron separately.

2.3 Optical setup

The optical setup is illustrated as following. The pump power is 532nm, 5ns, 10Hz. The original beam size is 9mm in diameter. An attenuator is put after the laser to decrease the pump power. One thing need to take care is beam dump should be used after beam sampler to keep safe. After the attenuator, we use an iris to reduce the beam size to 4mm in diameter. Then the light beam propagate
through a beam splitter and focused on the cuvette sample by a 20cm-focal length lens. Then the emitted signal is collected by the same 20cm-focal-length lens. This collected signal is reflected by the beam splitter and transmitted to spectrometer by a fiber. A 550nm long pass filter is put before the fiber to filter the pump light. The spot size of pump light source on sample is calculated as 33 micron. The pump power is tested just at the position where we put samples.

The physical optical setup is shown below too.

**Figure 6.** Optical setup to test random laser in disordered solutions.
Figure 7. Physical view of optical setup for testing random laser in disordered solutions.
2.4 Measurement process

During our experiment, the pump power is changed from low to high to observe the phenomenon in samples. We started with sample 1 of particle density $1.82 \times 10^{12}/\text{cm}^3$ and dye concentration 0.1mM. Different pump power increases from very low like 2mW to very high nearly 11.5mW. The pump pulse energy is from 0.2mJ to 1.15mJ. If the signal we collected is very weak, we increase the integration time from 90ms to 2s. We only compare the spectra under the same integration time.

The samples are put in the cuvettes which is 1cm*1cm*4.5cm (length*width*height). And an ultrasonic machine is used before the measurement to prevent particles from precipitation.
Chapter 3 Results and Analysis

Random laser effect has been observed under various solution conditions, consisting of different solvents, laser dyes, and scattering centers. We have tested some solutions in our lab. The solutions are made with ethanol, Rhodamine 640 perchlorate and SiO$_2$. Based on previously published experimental parameters, we have performed preliminary experimentation in order to verify our ability to observe the random lasing phenomena. We fixed the concentration of laser dye rhodamine 640 perchlorate (R640) at 0.1mM, 1 µm diameter SiO$_2$ at 2.87×10$^{13}$/cm$^3$, and varied the pump power (mW) of a pulsed 532 laser (Figure 8).
Figure 8. Spectra of emission at different pump powers (mW), R640 concentration (0.1 mM), and particle density (2.87×10^{12}/cm^3) in ethanol. Figure on the right is the spectra of emission, showing significant amplification of emission intensity; Figure on the left is the normalized spectra, showing line width narrowing. These trends indicate lasing emission. The integration time for each spectrum is 90ms.

Only a relatively broad fluorescence peak was observed for the lowest pump power 8.4 mW, whereas intense narrower peaks appear at higher pump powers, indicating the onset of lasing. In the left figure, we can see clearly that the bandwidth becomes 3nm when the pump power is 11.3mW. In the figure on the right, the peak intensity increases sharply as the pump power increases.
We can observe clearly in figure 9 proof of lasing occurrence by looking closely at emission peak intensity and spectral full-width-half-maximum (FWHM). The left figure plots the peak intensity corresponding to different pump powers. As the pump power is increased, we observe a change in slope in samples containing scattering particles, but not in samples without scattering centers. This slope change is indicative of a random lasing system undergoing stimulated emission. As the pump power is increased above the threshold, the intensity of emission peak further increases, accompanied by the FWHM decreasing significantly as seen in the right graph.
Figure 9. Emitted peak intensity and spectral FWHM (Full Width Half Maximum). The concentration of the Rh640 is 0.1mM and the solvent is ethanol. Figure on the left shows the peak intensity as a function of pump power: dye solution without particles (dashed blue line), particle density is $1.82 \times 10^{12}/\text{cm}^3$ (dashed green line), particle density is $7.18 \times 10^{12}/\text{cm}^3$ (dashed red line); Figure on the right shows the spectra line width as a function of pump power: Dye solution without particles (dashed black line), particle density is $1.82 \times 10^{12}/\text{cm}^3$ (dashed red line), particle density is $7.18 \times 10^{12}/\text{cm}^3$ (dashed green line), particle density is $2.87 \times 10^{12}/\text{cm}^3$ (dashed blue line).
Chapter 4 Future work and Conclusion

Future work can focus on the tunable system. In earlier work, the system is static, either in a cuvette or a dried sample. But now we can change properties of the system in real time by dynamically changing the particle density using electric field assisted assembly. If we make all particles go away, it cannot lase, and then if we bring them back, we can turn it back on. The tunability of lasing of random laser is new. If we can change the density of the particles we might be able to control which mode is stimulated beyond threshold.

We can take images while the laser was on to figure out relationship between particle packing and lasing. Then we can use that knowledge to design increasingly complex system with tunable emission.

In random lasing systems such as the ones we have studied, the concentration of scattering particles plays a large role in the ultimate profile of emission spectra. It then stands to reason that by implementing a reconfigurable dielectrophoretic assembly of scattering particles into a random lasing system, the properties of the emission can be altered in real time, and closely studied as a result. The assembly of 1 µm silica spheres has been performed between gold quadrupole electrodes and we have shown that control over the local concentration and packing density of these particles can be tuned in real time by varying alternating current field fre-
quency and intensity. We have integrated this particle assembly scheme with an optical setup capable of simultaneously exciting our R640 gain medium, imaging scattering particle assemblies, and collecting subsequent emission spectra. Having particle positional information that corresponds to optical emission will enable us to study the dependency of random laser emission on scatter structural arrays in a way that has not been done before.

In order to perform optical experiments with assembled particles, we combined an optical excitation setup with an inverted microscope. As shown in figure 10, this setup allows for the collection of data from both cuvette samples and assembly samples. The attenuator group includes a polarizer and a half wave plate. It can precisely adjust the incident laser power. Mirror 1 and 2 are used to align the laser beam. Lens group $L_1$ and $L_2$ decreases the laser beam size from 9mm to 3mm. After the 3mm laser beam passes through a $100 \times$ objective, we produce a 30 micron focus spot, which can be focused onto assembly samples of similar size.

In order to characterize the assembled samples, a coherent backscattering setup can be designed. It is shown in the following figure 11. The upper part of the setup is used to test the coherent backscattering.
**Figure 10.** Optical setup. Laser: 532nm, 5ns, 10Hz; Glass 1: reflect laser for cuvette sample testing; Glass 2: reflect laser to microscope; Polarizer and half wave plate: attenuator group to adjust the laser intensity; L1 and L2: lens group to adjust the laser beam size; BS2: beam splitter is used to collect the signal from sample; Microscope is on the left, and the laser in shining into it from the right port.
**Figure 11.** Optical setup for cuvette testing, assembled sample testing, and coherent backscattering testing.
In conclusion, there are many excellent properties of random laser. 1. The production of random laser is cheap, so the low cost can realize mass production. 2. The random laser is multidirectional. Display application is available. 3. Random laser material can be prepared in the form of suspension of particles. Thus it can be coated on surfaces of arbitrary shape and used for environment lighting. 4. The small size makes it utilized in medical diagnostics. It can characterize tissues, monitoring blood flow, etc.\textsuperscript{30}
References


