Review of Open Cavity Random Lasers as Laser-Based Sensors

Atiqah Nabieha Azmi[1], Wan Zakiah Wan Ismail[2], Haslan Abu Hassan[1], Mohd Mahadi Halim[1], Norzaini Zainal[3], Otto L. Muskens[4], Wan Maryam Wan Ahmad Kamil[1*]

[1]School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia
[2]Faculty of Engineering and Built Environment, Universiti Sains Islam Malaysia, 71800, Nilai, Negeri Sembilan, Malaysia
[3]Institute of Nano Optoelectronics Research and Technology (INOR), Universiti Sains Malaysia, 11800, Penang, Malaysia.
[4]Physics and Astronomy, Faculty of Physical Sciences and Engineering, University of Southampton, SO17 1BJ, United Kingdom

**Corresponding author: wanmaryam@usm.my*

Abstract

In this review, the concept of open cavity lasing for ultrasensitive sensing is explored; specifically in driving important innovations as laser-based biosensors – a field mostly dominated by fluorescence-based sensing. Laser-based sensing exhibit higher signal amplification and lower signal-to-noise ratio due to narrow emission lines as well as high sensitivity due to non-linear components. The versatility of open cavity random lasers for probing analytes directly and ultra-sensitive to small changes in chemical composition and temperature fluctuations paves the path of utilising narrow emission lines for advanced sensing. The concept of random lasing is first explained followed by a comparison of the different lasing threshold that has been reported. This is followed by a survey of reports on laser-based sensing and more specifically as biosensors. Finally, a perspective on the way forward for open cavity laser-based sensing is put forth.

Key words: random laser, laser-based sensing, biosensor, cancer detection, Huntingtin disease detection, brain tissue detection, flexible laser, fiber random laser.

The key challenges in chemical and bio sensing relate to measuring the target molecule with maximum-signal-to-noise ratio, highest specificity, and lowest limit of detection [1]. A random laser, that relies on an open cavity system, has the advantage in probing analytes and biological substances directly whilst maintaining its lasing characteristics. Hence, a promising alternative for biomarkers, bio-sensing and biocompatible sensors [2]–[4]. For example, the sensing capabilities from random lasers, which potentially could be superior to other optical based sensors already available, arises from the capability of achieving high signal amplification and high sensitivity due to narrow emission lines which are always favorable over broad band emitters. For a random laser to be adopted into any existing technology, the lasing threshold must be small which is at present still a challenge for random lasers. As such, significant progress have been made over the years to further improve random lasers by improving the design and attributes of a random laser design that significantly lowers the lasing threshold, enhance the lasing emission and lasing intensity as well as provide lasing tuneability elements that may be of paramount importance for ultrasensitive sensing [5]–[7]. A review of current threshold values obtained for various materials is presented in the section 'Improvement of laser threshold'. This includes fundamental investigations in improving control over the random lasing threshold and scattering characteristics that can bring new opportunities of utilizing such open cavity random laser systems for a range of applications such as cancer detection, photodynamic therapy, document encoding, displays, speckle-free imaging, microscopy and sensing applications [8]–[12].

The current state of laser-based optical biosensors has mostly evolved around the use of laser dyes as a gain medium [13]–[16]. Such dye-based sensors typically result in a broad lasing spectrum (10 nm to 30 nm linewidth – which is comparable to fluorescence-based sensors) and are subject to degradation of the laser dye. As such, a lot of research on solid state gain medium for random lasers are extensively investigated to replace the need of using laser dyes to achieve lasing [17]–[21]. Certain types of random lasers employing a solid-state gain medium with high scattering provided by the gain medium itself, have been shown to provide narrow emission line [22]–[24]. Hence, degradation issues could be addressed by employing a solid-state gain medium with current laser-based biosensors. A review of random laser-based biosensors is provided in detail in section 'Random laser biosensors'. Finally, this paper concludes with a way forward for random lasers with solid state gain medium as bio compatible flexible laser-based sensors.

Concept of random laser

A random laser relies on an open cavity system whereby no physical set of mirrors like a conventional laser system is required to provide feedback. The optical feedback from a random laser is based on the trapping of light inside the gain media (that can be easily achieved by utilizing nanostructures) which results in amplified stimulated emission into the scattering modes for lasing to occur. It was first explored in 1966 by a group led by Nobel laureate N. G. Basov where one of the cavity mirrors was replaced with a scattering medium and lasing emission was observed [25]. In this 1966 experiment, one of the mirrors in the Fabry-Perot cavity was replaced with a scatterer, and lasing was observed – the first evidence of strong scattering that can produce laser emission.

This work led to Letokhov modifying the diffusion theory to include gain, in order to understand the photon's random walk in a high scattering region [26]. In a simple model description, the lasing in a random laser can be describe by the set of rate equations for the excited-state and photon populations:

$$\frac{dN_1(t)}{dt} = P(t) - \frac{\beta q(t)N_1(t)}{\tau} - \frac{N_1(t)}{\tau}$$

$$\frac{dq(t)}{dt} = \frac{\beta N_1(t)}{\tau}[q(t) + 1] - \frac{q(t)}{\tau_c} \quad (1)$$

where $N_1(t)$ is the number of excited molecules, $P(t)$ is the pump rate, $q(t)$ the number of photons in laser modes, τ the spontaneous emission lifetime of the dye, and β is the β-factor for a random laser that involves the average numbers of lasing modes. The cavity-decay time, τ_c depends on the transport of light in the medium, which in the diffusion approximation is given by the diffuse transport time $\tau_c = \frac{L^2}{8D(\lambda)}$, where $D(\lambda)$ denotes the diffusion constant of light and L is the size of the multiple scattering object (assuming equal size in all dimensions). The diffusion constant is a dynamic transport property which is related to the static transport mean free path $l_t(\lambda)$ by the relationship $D(\lambda) = \sqrt{v l_t/3}$, with v the transport (energy) velocity. By modifying $D(\lambda)$ and $l_t(\lambda)$, threshold and laser process can be controlled.

Experimentally, Migus and Markushev found that grinding a crystal into fine powder offers optical gain through stimulated emission and multiple scattering [27], [28]. Shortly after, lasing from highly scattering medium was realized in 1994 when Lawandy found a way to generate a multimode laser spectra's temporal and spectral properties without an external cavity or known as random laser [29], [30]. This was followed by seminal work by Wiersma and Lagendijk [31], [32] and by Cao and co-workers on random lasing in ZnO and GaN powders [33], [34] which set the scene for several detailed studies on different aspects of localized random lasing modes versus extended modes [35]–[37]. The effort in understanding of such random lasers was further expanded by theoretical studies addressing mode competition and lasing dynamics [38], [39]. Hence, with such versatility random laser can be tailored to suit specific application needs.

Based on equation (1), clearly random lasers require the same conditions as conventional lasers to achieve the lasing condition – a gain medium that provides optical gain through stimulated emission and partial trapping of light providing feedback. Light trapping in the case of random lasers is achieved through multiple photon scattering process; a propagation known as a random walk with as the characteristic length scale the transport mean free path (l_t). This kind of scattering is observed in nature for example in butterflies, moths and beetle [40]. Random lasers have also been inspired by the structure of butterfly wings [41]. Figure 1 shows this random walk and bio-inspired photonics from butterfly wings.

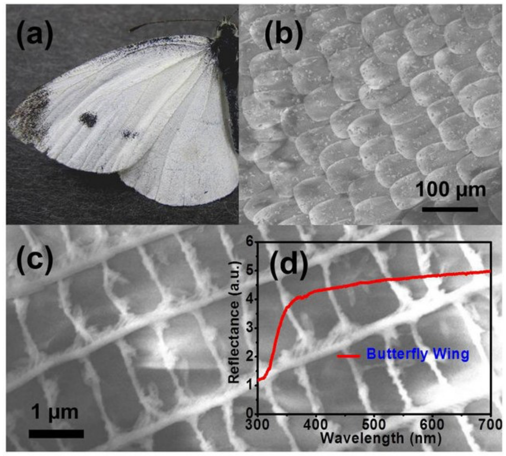

Figure 1: (a) Picture of a Pieris canidia butterfly; (b) low magnification scanning electron microscope (SEM) image of the wing scales; (c) high magnification SEM image of the wing scales; (d) reflectance spectrum of butterfly wing, (e) multiple scattering of light in a collection of microspheres with laser dye [56].

In some random lasers, the gain medium and scatterers are from the same material known as active material. Zinc oxide (ZnO) is the most common active material that has been investigated due to its high refractive index, high binding energy in room temperature (60 meV) and stability. A random laser using an active material provides several advantages such as simple experiment, only one material is required and the design can be focused on just the scatterers (e.g. population density, filling factor, thickness). The fabrication does not require a different gain material and since such material is generally solid, the issue of concentration control can be eliminated. The only drawback is that refractive index must be high so that scattering would overcome absorption losses [42]. This effect was explicitly studied in gallium arsenide (GaAs) powders whereby alumina particles were mixed with GaAs powder to increase the scattering probability for random lasing to occur [19]. Based on the results, the authors proposed that lasing was not achieved in GaAs powder alone as photons participated in the absorption much more than the scattering. Due to that, some random lasers are prepared with a separate gain material with the scatterers, where rhodamine dye is commonly used, even though the use of dyes comes with challenges of controlling concentration and degradation [43]–[45].

The gain medium of a random laser determines the emission wavelength. For rhodamine, the emission is between 550 nm to 610 nm. For ZnO random lasers, the emission is at about 380 nm and for gallium nitride (GaN) the emission is around 365 nm [46], [47]. Small changes in the emission wavelength is likely to occur in semiconductor nanostructures due to minor changes in the bandgap from small fluctuations of the size of nanostructures; mostly observed from ZnO [48]–[50]. Figure 2 shows the different random lasing emission wavelengths observed from several materials upon achieving threshold. As observed from the figure, random lasers prepared by ZnO and GaN (as well as most solid-state semiconductor random lasers) show multiple emissions. This creates a problem for utilizing random lasers as laser-based sensors. Current random lasers have been engineered towards reducing the number of lasing modes. Methods include introducing point defects, controlling absorption, and by altering the Mie resonances [50], [51], [60]–[62], [52]–[59].

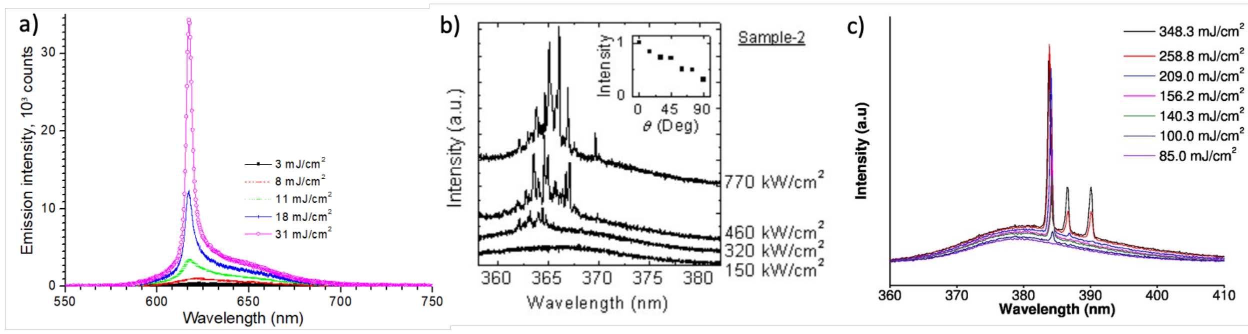

Figure 2: Emission spectra of (a) rhodamine dye mixed with TiO_2 nanoparticle at several pump powers with a concentration of 2×10^{11} cm^{-3}, (b) GaN nanocolumns and (c) ZnO nanorods [20], [49], [63].

To achieve open cavity lasing it is also important to trap the wavelength of light that can achieve gain. Early discussion of this phenomenon has often highlighted the close relationship to strong multiple scattering of light in disordered media also known as photon localization or Anderson localization. However, over years of study it was found that this type of lasing was found in a very wide range of systems of different scattering strength, far beyond the regime where localization conditions could possibly play a role [12]. Different particle sizes in looking into the effect of scattering in random lasing emission have been investigated with varying gain mediums [64]–[69]. Further investigations yielded the relation of random lasing with photon random walk that defines the transport mean free path of these photons – a parameter to understand how far photons can travel in a highly scattered medium of a random laser that has gain [70]–[72]. Below we briefly discuss some of the basic principles of light scattering of importance to understand the behavior of open cavity random lasers.

When light passes through particles or obstacles such as dust, mists, and powder, it caused the light to move in all directions. Rayleigh's Law as in equation (2) states that the intensity of scattered light is inversely proportional to the 4th power of wavelength.

$$I_S = \frac{1}{\lambda^4} \tag{2}$$

I_s refers to intensity of scattered light and λ refers to the respective wavelength.

There are two types of scattering: elastic scattering and inelastic scattering. Elastic scattering occurs when the direction of light propagation is changed, and the photon's energy is conserved. But for inelastic scattering, the direction of light propagation and the energy of the photon both changes. The elastic scattering can be characterized using Rayleigh scattering, Mie scattering, and geometric optics or ray optics, which depend on the size of nanoparticles.

Rayleigh scattering refers to scattering of particles when the diameter is much smaller than the wavelength of scattered light (d << λ). The Rayleigh scattering's equation is crucial to determine scattering cross section, polarization of dielectric sphere, and radiation from a driven oscillating dipole. Inversely, geometrical optics are cases where the particle's radius is larger than the wavelength of light (d >> λ). This is when light is treated as rays as they encounter big objects or optical systems generally a thousand times larger than the wavelength of light. On the other hand, Mie scattering refers to scattering from spherical nanoparticles that are almost the same size as the wavelength of light (d ~ λ). The idea of Mie scattering is to expand the incident plane wave in Fourier series using appropriate basis functions that satisfy Maxwell's equation in spherical coordinates. The derivation of the Mie scattering leads to the determination of the differential and total scattering cross sections. For random lasing, scattering must be within the Mie scattering regime for Anderson localization of photons to work [73]. The Mie scattering cross section is shown in equation (3):

$$\sigma_{Mie} = \left(\frac{2\pi}{k^2{}_{med}}\right) \sum_{n=1}^{\infty} (2n+1)(|\alpha_n|^2 + |b_n|^2) \tag{3}$$

Where $k_{med} = \frac{2\pi n_{med}}{\lambda_0}$. The coefficients a_n and b_n are given by:

$$a_n = \frac{\mu m^2 j_n(mx)[xj_n(x)]' - \mu_1 j_n(x)[mxj_n(mx)]'}{\mu m^2 j_n(mx)\left[xh_n{}^{(1)}(x)\right]' - \mu_1 h_n{}^{(1)}(x)[mxj_n(mx)]'}$$

$$b_n = \frac{\mu_1 j_n(mx)[xj_n(x)]' - \mu j_n(x)[mxj_n(mx)]'}{\mu_1 j_n(mx)\left[xh_n{}^{(1)}(x)\right]' - \mu h_n{}^{(1)}(x)[mxj_n(mx)]'}$$

Where the j_n's are the spherical Bessel functions of the first kind, h_n's are spherical Hankel functions, and μ_1 and μ_2 are the magnetic permeability of the sphere and surrounding medium, respectively.

In random nanostructures, light waves are scattered by mesoscopic variations of refractive indices to create a complex wavelength dependent grainy mode structure ('speckle') within a certain volume of material. Both scattering mean path and transport mean free path are essential to describe the scattering process. The scattering mean path is defined as the average distance a molecule travels between collisions. Meanwhile, transport mean path is the average distance a wave travels before its direction of propagation is randomized. The relationship between scattering mean path and transport mean free path is given as equation (4) [72]:

$$l_t = \frac{l_s}{1 - \langle\cos\theta\rangle} \tag{4}$$

Here $\langle\cos\theta\rangle$ is the average cosine of the scattering angle obtained from the differential scattering cross-section. Rayleigh scattering is an example of $\langle\cos\theta\rangle = 0$ or $l_t = l_s$, while Mie scattering may have $\langle\cos\theta\rangle \approx 0.5$, or $l_t \approx 2l_s$.

For an open cavity system, such as a random laser, threshold would be high compared to traditional lasers as the system is very lossy [74]. Several factors affect the lasing threshold of a random laser and the main factor is the scattering strength. Hence, many efforts have been focused on increasing the scattering strength which is determined by l_t. A quantitative analysis of several random lasers were compared with their different l_t that determines the threshold for the random lasers [75]. In the weak scattering regime, l_t is roughly the sample thickness and the role of scattering is only to redistribute the amplified spontaneous emission. Most reported random lasers have l_t much smaller than the sample size but larger than the wavelength. The scattering in this case increases the residence time of light in the gain region owing to the multiple scattering [76]. In the strong scattering regime, l_t becomes equal to or smaller than the wavelength. Then, the recurrent scattering event becomes important. This was observed in semiconductor powder and the observed discrete lasing modes were argued to arise from ring cavities in the scattering medium formed by the recurrent scattering events [65].

Incoherent and coherent random lasers

There are two types of random laser namely laser with incoherent feedback and a laser with coherent feedback. The incoherent random laser is the result of amplified spontaneous emission taking place inside a diffuse scattering volume and can be considered as the solution of an incoherent photon diffusion model with gain. Two characteristic length scales must be considered to identify incoherent feedback i.e., gain length and average path length. The gain length can be defined as the distance a photon travels before generating other photons. The average path length is the average path length of photon that travels in the gain medium. Theoretically, the gain length and average path length are mutually dependent. As the number of scattering increases, the average path increases. When the average path is equal to the gain length, the number of photons increases.

In the late 1990s, the first batch of random lasers with coherent feedback was realized with disordered semiconductors and organic materials [29]. The coherent feedback mechanism is related to gain provided by specific scattering eigenmodes of the system. These eigenmodes could be potentially closed-loop paths where light is cycled several times like in a cavity, or alternatively these can consist of a subset of non-recurrent, open pseudo modes of the scattering medium with sufficiently long dwell times and gain length [32]. Coherent random lasing gives rise to narrow spectral peaks above the emission background when lasing threshold occurs [77]. Early experiment discussed that coherent feedback in both strong and weak scattering regimes may be provided by recurrent scatterings. However, the transport mean free path of photons must be considered to produce sufficiently strong scattering for a significant number of recurring paths to occur - it must be shorter than their reciprocal wave vector, known as the Ioffe-Regel criterion [72]. This regime produces strong photon localization equivalent to Anderson localization. The localization regime is however much easier to achieve in lower dimensional systems such as 1D or 2D waveguides and therefore open cavity lasers in these lower dimensions could particularly benefit from localization effects. For such closed loop paths, the coherent feedback enables spatial resonance. Then the spontaneously emitted photons are amplified through stimulated emission with mode structures derived from the spatial resonance.

Figure 3 shows the different emissions obtained in an incoherent random laser and a coherent random laser from DCM doped PVK polymer layer. Based on Figure 3 (a), L. Sznitko and et al. [78] describe the emission from an incoherent random laser starts by a broad emission (spontaneous photons) induced by photoluminescence whereby the emission peak increases linearly with increasing pump power. Then, above the energy density value of 700µJ/cm^2, the integrated intensity grew rapidly, which confirms the onset of lasing. However, above the energy density of 2.4 mJ/cm^2, sharp spikes are observed in the emission spectra. The narrow spectrum confirms coherent lasing. However, coherent random lasers as shown in figure 3(b) indicates a clear threshold at around 450 µJ/cm^2 whereby the intensity increases exponentially with pump power. As observed, the threshold of coherent random lasers is lower by almost half (450µJ/cm^2) compared to incoherent random lasers (700µJ/cm^2). This condition of double threshold behavior has also been observed in resonance-controlled ZnO random lasers [48]. Lasing at the first threshold appeared around exciton recombination energies and the lasing threshold carrier density was comparable to the Mott density, whereas the lasing at the second threshold was induced by population inversion accompanied by electron-hole plasma recombination like conventional ZnO random lasers. However, for laser-based sensing coherent random lasers should be considered as fluctuation in the threshold can change the sensing parameters accordingly.

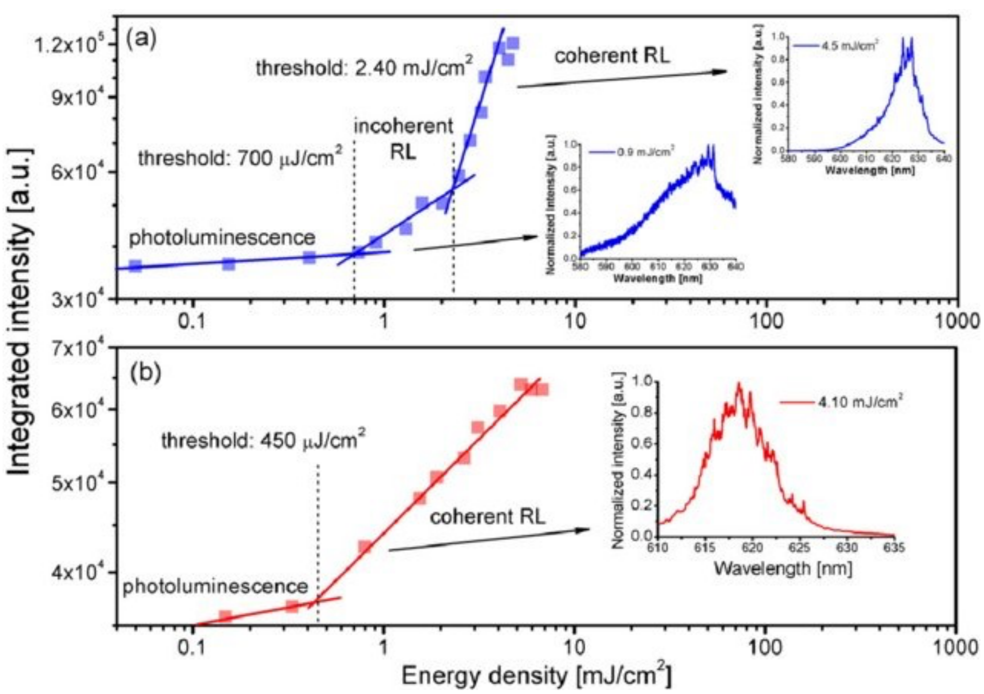

Figure 3: Integrated intensity dependences on energy density of pumping light for DCM doped PVK polymer layer before (a) and after (b) the rubbing process that explains the laser emission due to coherent and incoherent feedback. Insets contain averaged random lasing spectra observed at selected regions [78].

Improvements in lasing threshold

An important factor for laser-based sensing, other than controlling the lasing emission, is achieving a low lasing threshold. If the photons participate on the scattering event much more than in other events such as absorption or just pass through the sample, then random lasing is easily achieved and hence the threshold would be low. Reducing the threshold is not only critical for lowering the operation costs but also for integrating as an electronically pumped laser. The current method of making random lasers rely on optical pumping, however increased efforts have been pushed towards achieving stable electrically pumped random lasers since the threshold for achieving it has gone down significantly [79]–[81].

Table 1 summarizes the thresholds from random lasers prepared from different scatterers and gain mediums. Additional factors such as concentration, size and population density of scatters, concentration of gain and choices of material (as each material has different refractive index) play a role to determine the threshold of a random laser. It is evident from the literature that the threshold is low when the gain material are semiconductors. The gain material can be tailored to nanoscale sizes that are within the Mie resonances for random lasing to occur. Increasing the scattering strength and exploiting the resonances in scattering coefficients (Mie resonances) with surface plasmon resonances are other ways of reducing the random lasing threshold [82]–[84].

Table 1: Summary of random lasing threshold in different random lasers where D is the scatter diameter, CS is the coronal section of brain tissues, L is the length of the scatterer, T is thickness of scatterer and n is the refractive index of the medium.

Year	Threshold value	Gain material	Scatterer	Size of scatterer	Ref
2021	23 kW/cm^2	Rhodamine 6G	Silver nanoparticles	D: 70 nm L: 0.7-1.2 µm	[85]
2020	43.3 MW/cm^2	Rhodamine 6G	Polydimethylsiloxane	D: 17 µm	[86]
2020	0.07 W/cm^2	Aluminum doped zinc oxide nanorods	Aluminum doped zinc oxide nanorods	D: 34 nm	[54]
2020	5 kW/cm^2	Zinc cadmium selenide /Zinc sulfide quantum dot	polymer-dispersed liquid crystals	10-15 nm	[87]
2020	160 kW/cm^2	4-(Dicyanomethylene)-2-tert-butyl-6(1,1,7,7 tetramethyljulolidyl-9-enyl)-4H-pyran	poly(dimethyl siloxane)	6 µm	[88]
2019	318 kW/cm^2	Rhodamine 6G	Brain tissues	CS: 100 µm	[89]
2019	2.75 MW/cm^2	Rhodamine 640	Titanium dioxide	D: 200 nm	[69]
2019	30.5 kW/cm^2	Luminescence polymer	Silver nanoparticles	100 - 300 nm	[90]
2018	80 W	Pyrromethene 597 dye	Nematic liquid crystals	n.p	[91]
2018	0.63 W/cm^2	Rhodamine B	Silk fibroin	D: 0.82 - 0.88 µm	[92]
2017	267 kW	Rhodamine B	Hexagonal Boron nitride	D: 388 nm	[67]
2016	1.3 MW/cm^2	Rhodamine 6G	Photonic glass	D: 1.3 µm	[93]
2015	7.75 MW/cm^2	Rhodamine 640	Gold nanoparticles	D: 20 nm	[4]

2014	9.5 MW/cm^2	Rhodamine 6G	Aluminum particles	D: 150 nm	[94]
2013	4.5 MW/cm^2	Rhodamine 6G	Latex nanoparticles	D: 51 – 380 nm	[95]
2010	0.5 kW/cm^2	Rhodamine 800	Bone tissues	T: 200 µm	[96]
2009	600 kW/cm^2	Zinc selenide	Zinc selenide	several hundred nm	[97]
2004	198 kW/cm^2	Gallium nitride	Gallium nitride	D:80 nm	[98]

To cater for high precision sensors (especially biosensors) that require wavelength tuneability, random lasers can be designed to have tuneability in the emission wavelength. This contrasts with conventional lasers whereby the emission wavelength is fixed due to a fixed cavity and tuning can only be done at either double or triple the frequency using a frequency double placed at the laser head. In a random laser however, fine-tuning of the wavelength is achieved by manipulating the gain medium or the scattering elements. Tunability can be achieved by changing the weight fraction [99], particle size [59], photonic crystal lattice [100], and adding a non-fluorescent dye to the gain medium [53]. A more recent approach to tuning a random laser is by doping the gain material with metal or inorganic elements that shifts the bandgap of the material [6], [54], [101]. The threshold for these doped random lasers varies but are much smaller (at least one order of magnitude) than the material without doping elements.

Laser-based sensing overview

Laser-based sensors have been reported to address critical challenges in creating reliable, real time and cost-effective monitoring integrated systems which are robust to changes in chemical composition over extended periods of time [102]. The sensors must be precise to make them efficient especially for monitoring greenhouse gasses for near- and long-term applications in environmental monitoring, measuring, and tracking ultrahigh precision movement particularly as a form of detecting misalignment in high precision systems [103], as a delivery rate sensor for laser-based additive manufacturing [104], as well as being integrated into laser measurement system known as LMS for preventing accidents [105].

Common detection characteristics vary according to whether the application is macroscopic or microscopic. For the automation industry (and most macroscopic applications) for example, the control engineer and software developers rely on laser-based sensing to identify if a particular target or object has arrived at a particular location. The common characteristic is detecting changes in the amount of light reflected from the object using sensors that are either diffusive, reflective or through-beam. Lasers are generally used for sensing further than 50 meters. It can also be used to detect and track moving objects [106]. For microscopic applications such as for detection of gas molecules, the characteristics investigated include side-mode suppression ratio, tuning range, spectral emission linewidth, frequency stability and wavelength modulation [107]. Combined with fiber optic, lasers can also be used to detect ulcers in the intestines. The detection characteristics rely on the distinctive spectral differences in Raman spectra [108]. Lasers are also used to study internal structure of microorganism and cells [109]. Remote sensing is another form of laser-based sensing with LIDAR (Light Detection and Ranging) being the most popular choice. The distance, height of objects from the ground and chemicals in the air is measured by light reflection [110].

Perturbation measurements for detecting explosives utilizes the amplified spontaneous emission (ASE) whereby changes in intensity at a range of emission wavelength are recorded with high sensitivity [111]. Laser-based sensing has also been used to trace hazardous gas detection [112]. The laser is combined with photoacoustic effect whereby light pulses are used to detect small concentration of trace gasses. Thus, the sensor should be highly sensitive (by obtaining narrow linewidth), tunable in wavelength, stable and reliable. Figure 4 shows some examples of laser-based sensing.

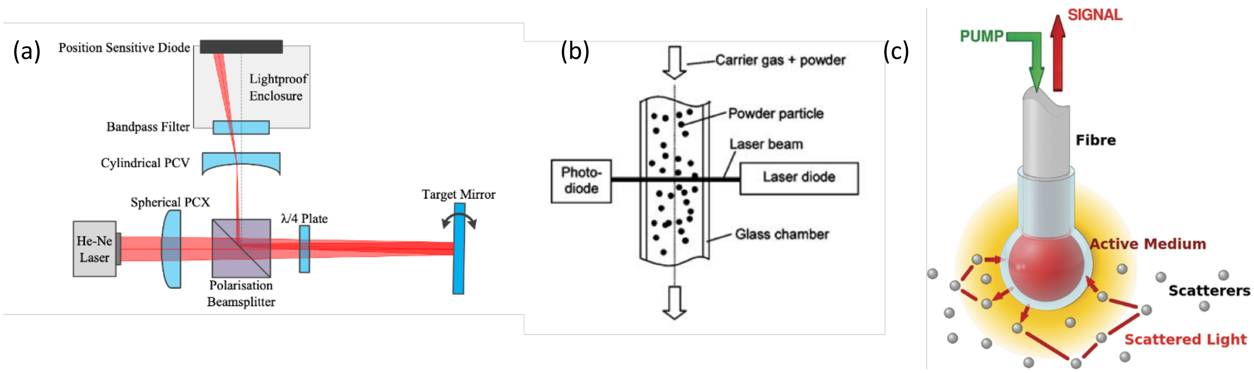

Figure 4: a) Schematic diagram of the laser-interferometry-based sensing for misalignment detection. b) Powder delivery rate sensor. c) Random laser based optical sensor [104], [113], [114].

For the detection of misalignment in high precision system, laser-interferometry-based sensing has been exploited. The detection of misalignment of position and orientation measurement beam such as robot manipulators is shown in figure 4 a). For laser-based additive manufacturing, an optoelectronic sensor is developed to sense the metal powder delivery rate in real-time. The sensor consists of a laser diode, a photo diode, and a glass window as shown in figure 4 b). The components are installed in such a way that the laser beam emitted from the laser diode passes through the powder stream flowing inside the glass chamber, and subsequently is received by the photo diode. The photo diode is characterized with a good linearity between the illumination energy received by the diode and the output current that is converted later to a voltage signal through a current signal pick-up circuit.

A laser-based vision sensor was also reported in welding; as part of an integrated system for structural health monitoring [115]. To check the quality of the welding by identifying the associated defects. As it is extremely difficult to identify the quality of the welding by human eye, laser-based vision sensor provides a solution for controlling and maintaining the quality of the welding. A special type of welding; Metal Inert Gas (MIG) welding is an arc welding process in which a continuous solid wire electrode is feeds through a welding gun and into a weld pool; joining the two base materials together [116]. Commonly, the MIG welding is applied in robots to combine each part of the robots whereby laser-based seem tracking sensor was utilized to achieve high accuracy of the MIG welding.

In surgery, random lasing has been used to differentiate tissue [117]. According to the authors, different approaches have been investigated as a feedback mechanism during laser surgery which are mainly categorized as imaging and non-imaging techniques. However, imaging techniques have the disadvantage of being too slow to provide feedback before damage is done to the tissue, making non-imaging techniques more favourable. A random laser has the added potential to provide information of a volume of the tissue on the surface and can detect the tissue type within a micro second which may stop an otherwise nerve damaging laser pulse. Moreover, a random laser has the advantage that it can be generated easily with ultra-short pulse lasers. Results reveal the possibility to use random lasing for tissue differentiation even in the case of thermal tissue damaging. However, the lasing emission is very close to the lasing threshold in some cases. In this specific case R6G dye was used whereby threshold tend to be high. A semiconductor gain medium for generating the random lasing is a potential alternative due to current reports on low lasing threshold (as shown in Table 1) however this is yet to be investigated.

However, all the sensors mentioned above look into macroscopic elements or are observable by the naked eye. Open cavity laser-based sensing has the added advantage of analyzing analytes directly, which may not be the case with conventional laser systems that relies on a physical cavity. Therefore, random lasing is most suitable as optical sensors-which are largely dominated by fluorescence-based sensors due to its simplified architecture. Optical sensor systems in several applications such as cellular temperature probe, fluorescence bio imaging or anticancer therapies have been recently implemented [118]–[120]. However, a comparison of random lasing-based sensor with conventional fluorescence sensor shows the sensitivity of random laser-based sensor exceeds two orders of magnitude [93]. The sensing mechanism was attributed to the modified gain and lasing threshold. No complex alignment was required, and the sensitivity was high. The mechanism of an open cavity laser-based sensor is shown in Figure 4 c). Slight changes in scattering would change the threshold for lasing and shift the lasing wavelength. This makes it possible as a promising candidate for future biosensing and disease detection, which will be discussed in more detail as follows.

Remote sensing

Lasers in general have been used for remote sensing applications. The mostly used laser based remote sensing application is in conjunction with LIDAR and DIALEX instrument [121].

DIALEX instrument is based on differential absorption spectroscopy and optical detection measured by the change in Doppler shift. This is commonly used to detect atmospheric species and natural target reflectivity [122]. LIDAR on the other hand is based on the principle of backscattering whereby a light pulse is transmitted, and the backscattered light is detected and analyzed. The scattered light is detected earlier for closer objects compared to objects located much further away. The return signal will not be the same length as the transmitted pulse but extended in time. For a more accurate measurement of the concentrations of atmospheric gasses, especially gasses at low concentrations, strong absorption features must be accessed. Since each molecular species or constituent has mid-infrared absorption characteristics, choosing the right laser source is also a crucial factor. Therefore, for assessing these characteristics, specific mid infrared lasers has been considered for remote sensing applications [123]. According to the author, among other vital consideration in choosing a laser source for specific remote sensing related to assessing molecular species is that (1) no cryogenic cooling is required to maintain lasing, (2) beam is not divergent and astigmatic, (3) uses high gain material (high power/energy output), (4) simple design (for example optical parametric oscillator (OPO) and difference frequency generation (DFG) have complex design), (5) low laser induced damage, (6) narrow spectral bandwidth and (7) broad tunability.

Apart from this, sensitivity may also be provided from scattering feedback. For example, a laser with external feedback is analogous to non-linear Fabry-Perot resonators whereby the dynamic properties of injection lasers are significantly affected by external feedback [124]. The self-mixing effect has been applied for sensing applications whereby the interferometric system was built around the laser under optical feedback and results in many signals arising from laser feedback interferometry [125]. The signals detected by photodetectors can be easily collected and modulated, simplifying the structure and reducing disturbance noise and cost as the laser itself can be used as the detector and does not need a reference beam, and the optical paths do not need additional optical components such as isolators, beam splitters, or target mirrors [126]. Another interesting innovation related to self-mixing interferometry is by integrating with random laser resonators that are operating at terahertz (THz) frequencies [127]. According to the authors, the emitted light reflects onto a surface with random holes pattern, and by varying the external cavity length, the temporal dependence of the laser voltage is detected by a sequence of interference fringes that follow the bias-dependent spectral emission of the laser structure - a visible signature of the random laser sensitivity to the self-mixing effect. Results show possibilities of detector-less speckle-free nano-imaging and quantum sensing applications across the far-infrared.

Wideband remote sensing has been investigated using random fibre lasers [128]. Random fibre laser have been used in combination with remote fibre sensors over ultra-long-distance fibre link. Very recently the authors claim observation of instantaneous and linear response to remote feedback disturbances using Raman-gain-modulated power-balance model from the random fibre laser intensity, suitable for ultra-high-bandwidth sensing. On the other hand, random fibre lasers that does not have point reflectors have been shown to achieve thermal stability which is beneficial for long distance remote sensing using fibre optics [129]. This novel idea of utilising such random lasers provides high fidelity and long distance transmission for the sensing signal. The authors claim >20dB optical signal-to-noise ratio (OSNR) over 100km distance. Intriguingly, the authors also found that the second order random lasing emission has much better OSNR due to enhanced lasing efficiency by incorporating a 1455 nm fibre grating. The setup of such device is shown in figure 5.

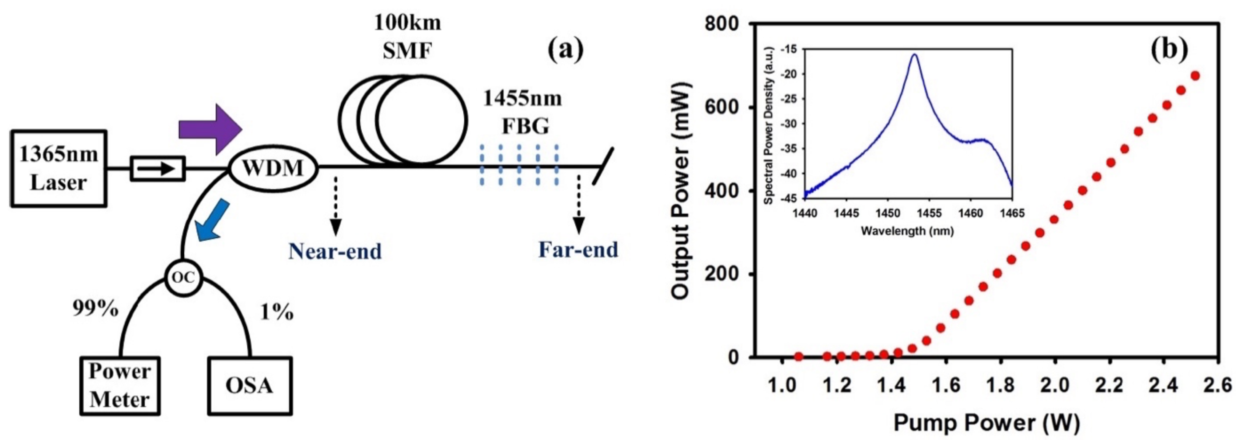

Figure 5: (a) The setup of the random fibre laser; (b) the output power as a function of the input pump power (inset: the output spectral shape corresponding to 2.3W pump power) [129].

Random laser biosensors

Random lasers have the added advantage of manipulating scattering to induce lasing. Therefore, changes in the scattering properties for example changes in cell structure will change the lasing characteristics. As such, changes in biological analyte such as microorganism, cells, biomolecule, and other biological structure can correspondingly be detected [130]. This makes random lasers as promising candidates for biosensor applications. The simplicity in its architecture is another compelling feature compared to other lasers whereby no physical cavity is required making them a very versatile type of laser well suited for such applications.

There are many types of biosensors such as piezoelectric, thermal, enzyme-based, tissue-based and immunosensors which are used for different applications. In food industry, biosensors can be used to detect bacteria and pathogens such as Escherichia coli (E. coli) [131]. One of the methods is by using redox potential measurements. When the analyzed solution reacts with the biosensor, it will immobilize on a particular semiconductor structure and the response is recorded through changes in the modulated pulsed LED source, embedded within the system. Biosensor has also been developed for healthcare monitoring with the combination of microfluidic sampling, multiplexed biosensing and transport systems. To improve the wearability and ease of operation, all components are integrated, miniaturized, and combined with flexible materials. These systems rely on fluorescence/spontaneous emission sources, hence the amount of bacteria/substance required are high. However, to detect low concentrations or for early detection and diagnosis, laser-based sensing is required.

For laser-based biosensors, different types of lasers have been proposed and investigated. Intracellular micro laser is a good example whereby optical micro resonators (small resonators) are used to confine light inside biological cells to measure internal stress and dynamic fluctuations at a sensitivity of 20 Pa, an order of magnitude better than direct image-based analysis [132]. The authors noticed that cells under uniaxial stress gives rise to splitting of the laser line and small deformation of the cells supports laser oscillation. To excite and collect the light emitted from the tissues, optical fibre was punctured into the tissue. No clear cavity was defined in the experiment however a gain medium was inserted in the cells and excitation of the gain medium was done by optical pumping from an external source – a very similar principle to random lasing generation that utilizes an open cavity and relies on the scattering between the cells to confine the light for lasing to occur. However, based on the size of the droplet, authors claim the lasing mechanism to be due to whispering gallery modes. Whispering gallery mode lasing has also been utilized to observe contractility of cardiac cells [133]. Fluorescent polystyrene microspheres with diameters ranging from 10 and 20μm was used as the gain medium. The authors showed that changes in cardiac contraction induces shifts in the laser emission wavelength. These investigations show the high sensitivity that laser-based sensing can achieve especially when it relates to microscopic biological events.

Conventional lasers with a Fabry-Perot cavity have also been investigated to explore cell parameters such as the size, shape, and refractive index. For instance, Song *et al* discovered the effective refractive index of a kidney cancer cell is 1.399 with 0.1% accuracy and an average cell size of 17.8 μm [134]. The experiment was carried out by capturing a single kidney cancer cell into the laser cavity, which resulted in a spectrum shift. Recently, a similar principle was also applied to detect concentration of cells in yeast with a sensitivity of 0.121 nm/(amo/mL) (2×10^{-7} nm/(cells/mL)) and a resolution of 3.65 × 105 cells/mL [135]. To improve the sensitivity, authors applied dielectrophoresis to make the final concentration of aggregation 50 times the initial state. Monitoring changes in refractive index in a Fabry-Perot cavity was also investigated in red and white blood cells [136]. The authors were able to distinguish the type of cells on a correlation coefficient threshold of 0.8. Identifying spectral properties of cancerous cell was also reported from investigating the mode confinement resulting from wavelength shifts [137].

For random lasers, utilizing it as biosensors is mostly due to its ability in achieving lasing with smaller gain material diameters compared to that of whispering gallery mode and conventional Fabry-Perot lasers. One particular example is to use random lasing to detect dopamine [4]. A set of different dopamine concentrations were added to a solution consisting of gold nanoparticles, copper (II) chloride and Rhodamine 640. In the detection process, dopamine triggers the aggregation of gold nanoparticles, where higher dopamine concentration can result in faster and larger aggregation of gold nanoparticles. The sensing parameters consist of the emission peak shift, emission peak linewidth, signal-to-noise ratio, and lasing threshold. The emission profile is shown in Figure 6. All these parameters contribute to just 250 SNR at 35 mJ/cm^2 of the lasing threshold. The detection limit of the system is ~1 × 10−7 M.

Another example is a plasmonic random laser that is used to detect Immunoglobulin (IgG) through specific binding to protein. The silver nanoparticles were self-assembled on a fiber facet by polyvinylpyrrolidone (PVP) assisted reaction. The detection limit was as low as 0.68 nM [138]. There are also other plasmonic nanolasers that does not rely on scattering feedback but rather on localized surface plasmons that are utilized as biosensors. Galanzha *et al* have shown the capabilities of utilizing plasmonic nanolasers for biomedical imaging and a potential for photothermal disruption of cancer cells – a very novel approach in targeted cancer therapies [139]. The authors use gold nanoparticles surrounded by silica shell doped with a fluorescent dye as the gain medium. Plasmonic random lasers generally requires longer pathways to achieve lasing and, in the past, requires high concentration of the gain medium in the cells which limits the use of plasmonic random lasers in biomolecules and cells investigations. However, current advancement in the gain medium used for random lasers, the low threshold that it can achieve, and very good detection limit as mentioned by Gather *et al* shows that plasmonic random lasers are very promising candidates for future biosensors.

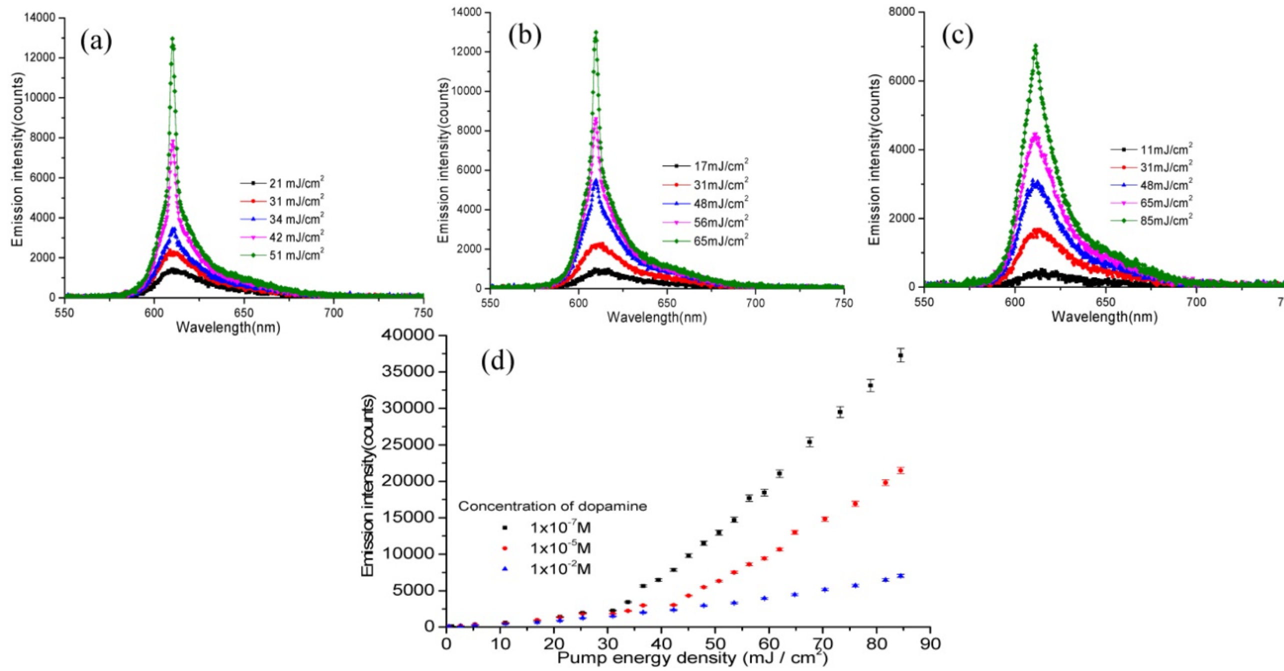

Figure 6: Emission spectra of Rh640 / gold random lasers with copper (II) chloride (0.15 mM) with different concentrations of dopamine for different pump energy densities [4].

Random lasers for disease detection

Random lasing has the advantage of sensitive detection for changes in biological cells. This discovery has led to using random lasers as detectors for diseases that involves changes in cells, most of them cancer related. For example, to study marked PLCD1 gene therapy effect on human breast cancer. The different breast cancer gives rise to either coherent or incoherent random lasers, hence making them as unique identifiers of specific breast cancer [140]. For observing the actin cyto-skeleton of AdHu5-PLCD1-infected cells, cells with or without AdHu5-PLCD1 were cultured on coverslips, soaked for 10 min in 4% paraformaldehyde, permeabilized in 0.1% Triton X-100 for 4 min, blocked with 1% bovine serum albumin for 1 h, and incubated for 1h with rhodamine-conjugated phalloidin at room temperature. 4-(dicyanomethylene)-2-tert-butyl-6-(1,1,7,7–tetramethyljulolidyl-9-enyl)-4H-pyran was selected as the gain media. The light emitted by the dyes is scattered in the biological tissues, which act as scatter centers. Coherent random lasing was associated with the human breast cancer tissues that do not receive PLCD1 gene therapy, while incoherent random lasing was related to the tumour tissues that receive PLCD1 gene therapy. HE staining images attest to the fact that the distribution pattern of the breast tumour tissues that received PLCD1 therapy (AdHu5-PLCD1) exhibits less disorderliness and the organizational structure of these tissues exhibits much less irregularity than that of the AdHu5-EGFP breast tumour tissues. This shows remarkably possible application of random laser in marking the process of gene therapy.

Most recently, random lasing has been utilized to detect mutant Huntingtin expression in cells related to Huntingtin disease [141]. According to the authors, the morphological/structural changes induced by mHTT expression can modify the scattering strength and the optical behavior of an environment when light propagates through it, resulting in differences in the random lasing signal compared to the signals arising from cells that express the wild-type *HTT* form. Random lasing emissions were obtained from transfected (EGFP-HTT-Q23 or EGFP-HTT-Q74) and un-transfected cells resulting in a high-dimensional spectral dataset. This dataset was analyzed by using a multivariate statistical analysis based on principal component analysis and linear discriminant analysis. Lasing emission from this experiment is shown in figure 7.

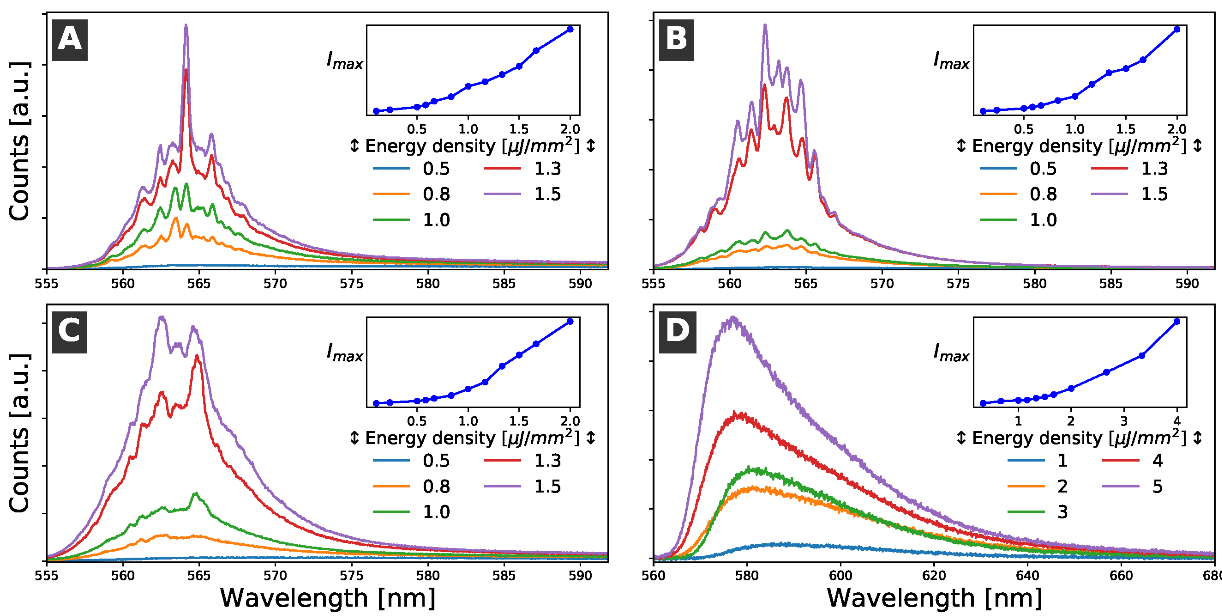

*Figure 7: Evolution of the emission of the sample with increases in the pumping power density. The blueshift of the spectra, the emergence of narrow (FWHM < 1 nm) lines, and the dramatic increase in emission intensity were all due to the coherent RL. (**A**) NT (non-transfected N2A cells). (**B**) HTT-Q23 (N2A cells transfected with the non-pathogenic pEGFP-Q23). (**C**) HTT-Q74 (N2A transfected with the pathogenic pEGFP-Q74). (**D**) Petri dish without cells. In this case, amplified spontaneous emission instead of random lasing was detected* [141].

The high response at low concentration makes random lasers like these as very promising candidates for biosensing and disease detection. However, the gain material utilized were fluorescent dyes which has problems related with dye degradation, self-absorption (can overcome by careful consideration of volume required) and the need to replace and dispose the dyes for each measurement [142]. To overcome these issues, semiconductors can be replaced as the gain medium however no implementation of random lasers prepared with semiconductors (as scatterer and gain medium) as biosensors or disease detection and monitoring have been achieved to date – a very promising avenue especially for advancement in early detection of deadly diseases.

Sensitivity of laser-based sensing

Increased interest in laser-based sensors comes from providing two main advantages: increased sensitivity and accuracy. The commonly used optical sensor is fluorescence-based has low signal amplification due to the broad emission line, high signal-to-noise ratio, the absence of nonlinearity, and low sensitivity compared to the laser-based sensor. These weaknesses from fluorescence-based sensor can be solved using a random laser.

For random laser as a pH sensor, various parameters are measured to identify the sensitivity of the sensor [93]. The sensitivity of a pH sensor is determined by value of relative absorption cross-section, quantum efficiency, excited-state lifetimes, and gain cross-section. The optimal sensing conditions and a maximal sensitivity 200 times higher compared to the fluorescence-based sensor was recorded by the authors.

Another example of sensitivity measurement from a random laser-based sensor is obtained from a random laser temperature sensor [143]. Its thermal sensitivity, S was defined as $\frac{1}{R_o}\frac{dR}{dT}$, where R_o is the intensity ratio at room temperature from the graph of the linear function intensity ratio of the signals against temperature. Thermal sensitivity up to $0.020^{\circ}C^{-1}$ have been recorded by the authors, which is at least one order of magnitude larger sensitivity than that reported for fluorescence-based temperature sensor [144].

The brain is the most complex part of the human body. The brain has uneven surfaces which makes it a good candidate for random lasing if light can be scattered efficiently. Studies have shown that a random laser can detect changes in brain tissues' structure and composition [89]. Four different regions of the brain were investigated: the corpus callosum region, cortex, corpus striatum and amygdala cortex. It was done by slicing the brain and soaked in different concentration of Rhodamine 6G. The sensitivity was then measured by the emission spectra (at 565nm), the value of full width at half maximum of the spectrum and the threshold value. Results show the brain provides enough scattering for random lasing to occur. This work can be developed further by incorporating the advantage of a random laser as a speckle-free imaging technique whereby images of the brain can be improved.

Conclusion and way forward

In this review, the advantage of laser-based sensing is put forth as future sensors in the field of precision sensing, remote sensing and mostly in the field of biosensing. A comparison between different lasers and the potential of random lasers are highlighted with emphasis on the sensitivity elements as well as the detection of biological substance, diseases, and the changes in cell structure. The elements in laser-based sensors that makes them superior to fluorescence based is the narrow linewidth that gives rise to high signal to noise ratio and sensitivity of changes within the nanometer range. For random lasers, changes in the scattering of light changes the emission spectrum and hence, small alteration of cell boundaries can be detected. In addition, detection of low concentration of substances makes it advantages for early detection of diseases which was proven for Alzheimer, different types of cancer and Huntingtin disease.

Developing a random laser with low threshold pump power is one of the main challenges in utilizing random lasers as optical sensors. However, in realizing a random laser as laser-based sensors, flexibility is also key. Hence, some recent works have been focused on flexible random lasers; electrically and optically pumped. One possibility is by constructing random lasers from optical fibers as fiber systems are well-established and readily viable. Several attempts in constructing random lasers from optical fibers have been made, involving the use of dye as the gain medium [14], [138], [145]. Figure 8 shows one example of using optical fiber as a random laser. Authors report a red shift of the wavelength due to changes in refractive index caused by the binding of the protein.

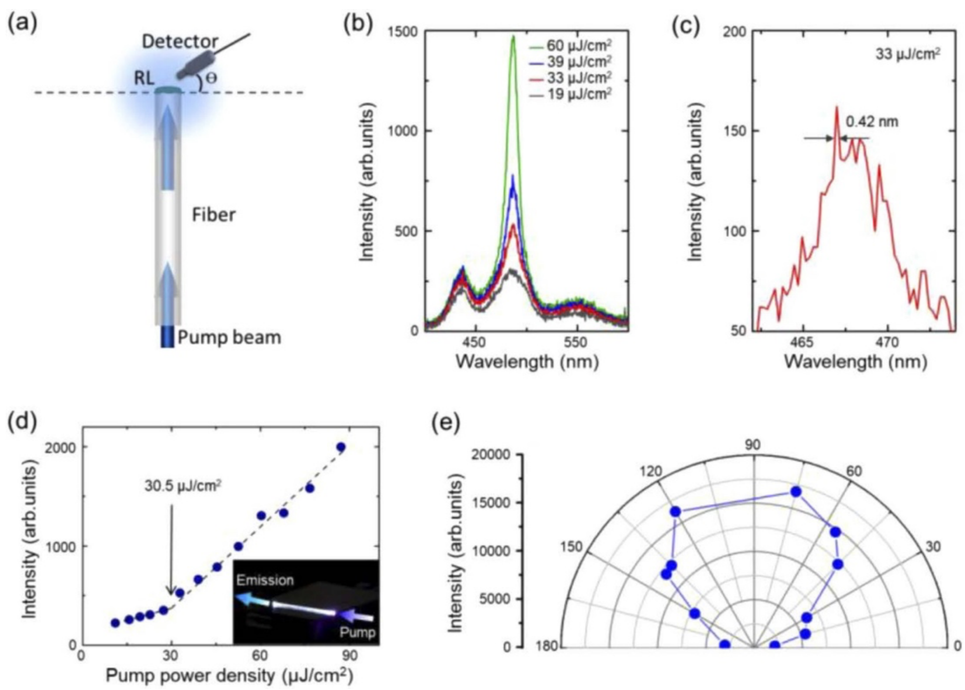

Figure 8: (a) Experimental setup of plasmonic random lasers on fiber facet. (b) Emission spectra of the plasmonic random system on fiber facet obtained under different pump power densities at a detection angle of 45°. (c) Specifics of emission spectra at pump power density of 33 μJ/cm2, recorded by a high-resolution spectrometer with a resolution of 0.1 nm. (d) Emission intensity of random lasing mode at 468 nm versus the pump energy density. Inset: corresponding images of the operating random laser on fiber facet. (e) The integrated intensity of the random laser as a function of the detection angle [138].

A more practical approach would be to embed nanostructures that can provide gain, for example ZnO, GaN and GaAs. Implementing ZnO in fiber have successfully been demonstrated for other applications; mostly for sensing [146]–[149]. Several detection mechanisms have been put forth. For instance, Bora *et al* reported average coupling efficiency of ∼2.65% that changes the sensitivity when exposed to different chemical vapors [147]. Kapoor *et al* reported the use of bi-layers of copper-zinc oxide in sensing refractive index of liquids by fibre optic SPR sensor. [148] Sensitivity increases with increasing zinc oxide layer thickness till 15 nm and reduces above this value. On the other hand, last year Wu *et al* proposed optical fibre capped with ZnO microwire whereby the tip acts as a Fabry-Perot cavity for monitoring deep UV light [149]. Changes in refractive index induced by variations in the concentration of photogenerated carriers exhibits a red shift in the lasing spectrum with a sensitivity of 0.288 $nm/(W \cdot cm^{-2})$. However, refining according to the requirements of a random laser is yet to be explored. Generally, for random lasing the size of nanorods is within the nanometer scale, much smaller than that used by Wu *et al*. However, the pumping source is the same for ZnO. Up to date, utilizing GaN or GaAs on fiber for sensing is not investigated although random lasing from these gain materials shows promising results. The most used candidate is ZnO. Hence, it would be interesting to implement this on fiber and test its sensing capabilities which may be more sensitive than Fabry-Perot.

Vocabulary section:

1. Random laser: A laser that relies on light trapping through multiple scattering process. The lasing characteristics such as onset of threshold before lasing occurs, narrow spectral width and coherent is the same as conventional lasers however the emission output directionality is random.

2. Laser threshold: A condition where laser emission just starts to occur.

3. Mie scattering: Mie scattering refers to scattering from spherical nanoparticles that are almost the same size as the wavelength of light.

4. Anderson localization: A consequence of quantum reflection in the lattice that stop the wave function. Localization in this context means the wave would decay and would not be scattered out of the lattice.

5. Scattering mean path: The average distance a wave travels between collisions.

6. Transport mean path: The average distance a wave travels before its direction of propagation is randomized.

Acknowledgement

This work was supported by Kementerian Pendidikan Malaysia through Fundamental Research Grant Scheme (FRGS) under account number: FRGS/1/2018/STG02/USM/02/6.

References

[1] C. Y. N. Nicoliche, O. N. Oliveira, and R. S. Lima, “Multidimensional sensors: Classification, nanoprobes, and microfluidics,” in *Handbook on Miniaturization in Analytical Chemistry*, Elsevier, 2020, pp. 185–219.

[2] S. Caixeiro, M. Gaio, B. Marelli, F. G. Omenetto, and R. Sapienza, “Silk-Based Biocompatible Random Lasing,” *Adv. Opt. Mater.*, vol. 4, no. 7, pp. 998–1003, Jul. 2016.

[3] H. Chen, S. Gao, M. Zhang, J. Zhang, L. Qiao, T. Wang, F. Gao, X. Hu, S. Li, and Y. Zhu, “Advances in Random Fiber Lasers and Their Sensing Application,” *Sensors*, vol. 20, no. 21, p. 6122, Oct. 2020.

[4] W. Z. Wan Ismail, G. Liu, K. Zhang, E. M. Goldys, and J. M. Dawes, “Dopamine sensing and measurement using threshold and spectral measurements in random lasers,” *Opt. Express*, vol. 24, no. 2, p. A85, 2016.

[5] A. T. Ali, W. Maryam, Y.-W. Huang, H. C. Hsu, N. M. Ahmed, N. Zainal, and M. S. Jameel, “SiO2 Capped-ZnO nanorods for enhanced random laser emission,” *Opt. Laser Technol.*, vol. 147, p. 107633, Mar. 2022.

[6] A. T. Ali, W. Maryam, Y.-W. Huang, H.-C. Hsu, N. M. Ahmed, N. Zainal, H. Abu Hassan, and M. ali Dheyab, “UV random laser in aluminum-doped ZnO nanorods,” *J. Opt. Soc. Am. B*, vol. 38, no. 9, p. C69, Sep. 2021.

[7] N. Rosli, M. M. Halim, M. R. Hashim, W. M. W. A. Kamil, G.-Y. Zhuang, S.-Y. Chan, and H.-C. Hsu, “Physical and optical effect of ZnO nanowalls to nanoflakes on random lasing emission,” *Results Phys.*, vol. 27, p. 104528, Aug. 2021.

[8] H. Cao, “Random Lasers: Development, Features and Applications,” *Opt. Photonics News*, vol. 16, no. 1, p. 24, Jan. 2005.

[9] F. Lahoz, I. R. Martín, M. Urgellés, J. Marrero-Alonso, R. Marín, C. J. Saavedra, A. Boto, and M. Díaz, “Random laser in biological tissues impregnated with a fluorescent anticancer drug,” *Laser Phys. Lett.*, vol. 12, no. 4, p. 45805, 2015.

[10] B. Redding, M. A. Choma, and H. Cao, “Speckle-free laser imaging using random laser illumination,” *Nat. Photonics*, vol. 6, no. 6, pp. 355–359, 2012.

[11] A. Boschetti, A. Taschin, P. Bartolini, A. K. Tiwari, L. Pattelli, R. Torre, and D. S. Wiersma, “Spectral super-resolution spectroscopy using a random laser,” *Nat. Photonics*, vol. 14, no. 3, pp. 177–182, 2020.

[12] D. Wiersma, “The physics and applications of random lasers,” *Nat. Phys.*, vol. 4, no. May, 2008.

[13] M. V. Santos, É. Pecoraro, S. H. Santagneli, A. L. Moura, M. Cavicchioli, V. Jerez, L. A. Rocha, L. F. C. de Oliveira, A. S. L. Gomes, C. B. de Araújo, *et al.*, “Silk fibroin as a biotemplate for hierarchical porous silica monoliths for random laser applications,” *J. Mater. Chem. C*, vol. 6, no. 11, pp. 2712–2723, 2018.

[14] X. Yang, C. Gong, Y. Liu, Y. Rao, M. Smietana, and Y. Gong, “Recent Progress in Fiber Optofluidic Lasing and Sensing,” *Photonic Sensors*, vol. 11, no. 2, pp. 262–278, Jun. 2021.

[15] N. Toropov, G. Cabello, M. P. Serrano, R. R. Gutha, M. Rafti, and F. Vollmer, “Review of biosensing with whispering-gallery mode lasers,” *Light Sci. Appl.*, vol. 10, no. 1, p. 42, Dec. 2021.

[16] W. Maryam, D. Chugh, J. M. Dawes, and H. H. Tan, “Hexagonal Boron Nitride as a Flexible Random Laser,” in *2020 IEEE 8th International Conference on Photonics (ICP)*, 2020, pp. 109–110.

[17] F. J. P. Schuurmans, “Strongly Photonic Macroporous Gallium Phosphide Networks,” *Science (80-.).*, vol. 284, no. 5411, pp. 141–143, Apr. 1999.

[18] W. Maryam, N. Fazrina, M. R. R. Hashim, H. C. C. Hsu, and M. M. Halim, “Optically driven random lasing in ZnO nanorods prepared by chemical bath deposition,” *Photonics Nanostructures - Fundam. Appl.*, vol. 26, pp. 52–55, Sep. 2017.

[19] M. A. Noginov, G. Zhu, I. Fowlkes, and M. Bahoura, “GaAs random laser,” *Laser Phys. Lett.*, vol. 1, no. 6, pp. 291–293, Jun. 2004.

[20] M. Sakai, Y. Inose, K. Ema, T. Ohtsuki, H. Sekiguchi, A. Kikuchi, and K. Kishino, “Random laser action in GaN nanocolumns,” *Appl. Phys. Lett.*, vol. 97, no. 15, p. 151109, Oct. 2010.

[21] A. Safdar, Y. Wang, and T. F. Krauss, “Random lasing in uniform perovskite thin films,” *Opt. Express*, vol. 26, no. 2, p. A75, 2018.

[22] M. N. Nordin, M. M. Halim, M. R. Hashim, M. K. Shakfa, and W. Maryam, “Influence of annealing time on random lasing from ZnO nanorods,” *Results Phys.*, vol. 16, no. October 2019, p. 102955, 2020.

[23] H.-C. Hsu, C.-Y. Wu, and W.-F. Hsieh, “Stimulated emission and lasing of random-growth oriented ZnO nanowires,” *J. Appl. Phys.*, vol. 97, no. 6, p. 064315, Mar. 2005.

[24] W. M. Wan Ahmad Kamil, M. K. Shakfa, M. N. Nordin, and D. Priante, “Lasing from ZnO nanorods on ITO-coated substrates,” in *Semiconductor Lasers and Laser Dynamics VIII*, 2018, no. May, p. 27.

[25] R. Ambartsumyan, N. Basov, P. Kryukov, and V. Letokhov, “A laser with a nonresonant feedback,” *IEEE J. Quantum Electron.*, vol. 2, no. 9, pp. 442–446, Sep. 1966.

[26] V. Letokhov, “Generation of Light by a Scattering Medium with Negative Resonance Absorption,” *Sov. J. Exp. Theor. Phys.*, vol. 26, no. 4, p. 835, 1968.

[27] V. M. Markushev, V. F. Zolin, and C. M. Briskina, “Luminescence and stimulated emission of neodymium in sodium lanthanum molybdate powders,” *Sov. J. Quantum Electron.*, vol. 16, no. 2, pp. 281–283, 1986.

[28] C. Gouedard, F. Auzel, A. Migus, D. Husson, and C. Sauteret, “Generation of spatially incoherent short pulses in laser-pumped neodymium stoichiometric crystals and powders,” *J. Opt. Soc. Am. B*, vol. 10, no. 12, p. 2358, 1993.

[29] R. M. Balachandran and N. M. Lawandy, “Laser action in strongly scattering media,” *Proc. Int. Quantum Electron. Conf.*, vol. 368, no. March, pp. 239–240, 1994.

[30] N. M. Lawandy, “Disordered media: Coherent random lasing,” *Nat. Phys.*, vol. 6, no. 4, pp. 246–248, 2010.

[31] D. Wiersma, “Light Transport in Opaque Liquid Crystal Structures,” *Mol. Cryst. Liq. Cryst.*, vol. 375, pp. 15–31, 2002.

[32] D. S. Wiersma and A. Lagendijk, “Light diffusion with gain and random lasers,” *Phys. Rev. E*, vol. 54, no. 4, pp. 4256–4265, Oct. 1996.

[33] H. Cao, Y. G. Zhao, S. T. Ho, E. W. Seelig, Q. H. Wang, and R. P. H. Chang, “Random Laser Action in Semiconductor Powder,” *Phys. Rev. Lett.*, vol. 82, no. 11, pp. 2278–2281, Mar. 1999.

[34] H. Cao, Y. G. Zhao, X. Liu, E. W. Seelig, and R. P. H. Chang, “Effect of external feedback on lasing in random media,” *Appl. Phys. Lett.*, vol. 75, no. 9, p. 1213, 1999.

[35] S. Mujumdar, S. Cavalieri, and D. S. Wiersma, “Temperature-tunable random lasing: numerical

calculations and experiments," *J. Opt. Soc. Am. B*, vol. 21, no. 1, p. 201, Jan. 2004.

[36] K. L. van der Molen, R. W. Tjerkstra, A. P. Mosk, and A. Lagendijk, "Spatial Extent of Random Laser Modes," *Phys. Rev. Lett.*, vol. 98, no. 14, p. 143901, Apr. 2007.

[37] J. Fallert, R. J. B. Dietz, J. Sartor, D. Schneider, C. Klingshirn, and H. Kalt, "Co-existence of strongly and weakly localized random laser modes," *Nat. Photonics*, vol. 3, no. 5, pp. 279–282, May 2009.

[38] C. Conti and A. Fratalocchi, "Dynamic light diffusion, three-dimensional Anderson localization and lasing in inverted opals," *Nat. Phys.*, vol. 4, no. 10, pp. 794–798, Oct. 2008.

[39] H. E. Türeci, L. Ge, S. Rotter, and A. D. Stone, "Strong Interactions in Multimode Random Lasers," *Science (80-.).*, vol. 320, no. 5876, pp. 643–646, May 2008.

[40] H. D. Wolpert, "Optical Filters in Nature," *Opt. Photonics News*, vol. 20, no. 2, p. 22, 2009.

[41] C.-S. Wang, T.-Y. Chang, T.-Y. Lin, and Y.-F. Chen, "Biologically inspired flexible quasi-single-mode random laser: An integration of Pieris canidia butterfly wing and semiconductors," *Sci. Rep.*, vol. 4, no. 1, p. 6736, May 2015.

[42] M. A. Noginov, S. U. Egarievwe, N. Noginova, H. J. Caulfield, and J. C. Wang, "Interferometric studies of coherence in a powder laser," *Opt. Mater. (Amst).*, vol. 12, no. 1, pp. 127–134, 1999.

[43] B. Kumar, S. K. S. Patel, N. S. Gajbhiye, and R. K. Thareja, "Random laser action with nanostructures in a dye solution," *J. Laser Appl.*, vol. 25, no. 4, p. 042012, Aug. 2013.

[44] L. Yang, G. Feng, J. Yi, K. Yao, G. Deng, and S. Zhou, "Effective random laser action in Rhodamine 6G solution with Al nanoparticles," *Appl. Opt.*, vol. 50, no. 13, p. 1816, May 2011.

[45] N. M. H. Duong, B. Regan, M. Toth, I. Aharonovich, and J. Dawes, "A Random Laser Based on Hybrid Fluorescent Dye and Diamond Nanoneedles," *Phys. status solidi - Rapid Res. Lett.*, vol. 13, no. 2, p. 1800513, Feb. 2019.

[46] H. Fujiwara, T. Suzuki, R. Niyuki, and K. Sasaki, "ZnO nanorod array random lasers fabricated by a laser-induced hydrothermal synthesis ZnO nanorod array random lasers fabricated by a laser-induced hydrothermal synthesis," 2016.

[47] X. H. Yang, T. J. Schmidt, W. Shan, J. J. Song, and B. Goldenberg, "Above room temperature near ultraviolet lasing from an optically pumped GaN film grown on sapphire," *Appl. Phys. Lett.*, vol. 66, no. 1, pp. 1–3, Jan. 1995.

[48] R. Niyuki, H. Fujiwara, T. Nakamura, Y. Ishikawa, N. Koshizaki, T. Tsuji, and K. Sasaki, "Double threshold behavior in a resonance-controlled ZnO random laser," *APL Photonics*, vol. 2, no. 3, p. 036101, 2017.

[49] W. M. Wan Ahmad Kamil, M. K. Shakfa, M. N. Nordin, and D. Priante, "Lasing from ZnO nanorods on ITO-coated substrates," in *Semiconductor Lasers and Laser Dynamics VIII*, 2018, p. 27.

[50] T.-C. Chiang, C.-Y. Chiu, T.-F. Dai, Y.-J. Hung, and H.-C. Hsu, "Surface-plasmon-enhanced band-edge emission and lasing behaviors of Au-decorated ZnO microstructures," *Opt. Mater. Express*, vol. 7, no. 2, p. 313, Feb. 2017.

[51] S. Xiao, T. Li, D. Huang, M. Xu, H. Hu, S. Liu, C. Wang, and T. Yi, "Random laser action from ceramic-doped polymer films," *J. Mod. Opt.*, pp. 1–9, Jan. 2017.

[52] X. Meng, K. Fujita, Y. Zong, S. Murai, and K. Tanaka, "Random lasers with coherent feedback from highly transparent polymer films embedded with silver nanoparticles," *Appl. Phys. Lett.*, vol. 92, no. 20, p. 201112, May 2008.

[53] R. G. S. El-Dardiry and A. Lagendijk, "Tuning random lasers by engineered absorption," *Appl. Phys. Lett.*, vol. 98, no. 16, p. 161106, Apr. 2011.

[54] N. Fadzliana, S. A. M. Samsuri, S. Y. Chan, H. C. Hsu, and W. Maryam, "Influence of Al doping on random lasing in ZnO nanorods," *Opt. Laser Technol.*, vol. 124, p. 106004, Apr. 2020.

[55] H.-C. Hsu, C.-Y. Wu, H.-M. Cheng, and W.-F. Hsieh, "Band gap engineering and stimulated emission of ZnMgO nanowires," *Appl. Phys. Lett.*, vol. 89, no. 1, p. 013101, Jul. 2006.

[56] C.-H. Lu, T.-Y. Chao, Y.-F. Chiu, S.-Y. Tseng, and H.-C. Hsu, "Enhanced optical confinement and lasing characteristics of individual urchin-like ZnO microstructures prepared by oxidation of metallic Zn," *Nanoscale Res. Lett.*, vol. 9, no. 1, p. 178, 2014.

[57] M. A. Noginov, G. Zhu, A. A. Frantz, J. Novak, S. N. Williams, and I. Fowlkes, "Dependence of NdSc_3(BO_3)_4 random laser parameters on particle size," *J. Opt. Soc. Am. B*, vol. 21, no. 1, p. 191, Jan. 2004.

[58] O. Popov, A. Zilbershtein, and D. Davidov, "Random lasing from dye-gold nanoparticles in polymer films: Enhanced gain at the surface-plasmon-resonance wavelength," *Appl. Phys. Lett.*, vol. 89, no. 19, p. 191116, Nov. 2006.

[59] S. Gottardo, R. Sapienza, P. D. García, A. Blanco, D. S. Wiersma, and C. López, "Resonance-driven random lasing," *Nat. Photonics*, vol. 2, no. 7, pp. 429–432, Jul. 2008.

[60] T.-F. Dai, W.-C. Hsu, and H.-C. Hsu, "Improvement of photoluminescence and lasing properties in ZnO submicron spheres by elimination of surface-trapped state," *Opt. Express*, vol. 22, no. 22, p. 27169, Nov. 2014.

[61] H. Fujiwara, R. Niyuki, Y. Ishikawa, N. Koshizaki, T. Tsuji, and K. Sasaki, "Low-threshold and quasi-single-mode random laser within a submicrometer-sized ZnO spherical particle film," *Appl. Phys. Lett.*, vol. 102, no. 6, p. 061110, Feb. 2013.

[62] M. Gaio, M. Peruzzo, and R. Sapienza, "Tuning random lasing in photonic glasses," *Opt. Lett.*, vol. 40, no. 7, p. 1611, Apr. 2015.

[63] W. Z. W. Ismail, W. M. W. A. Kamil, and J. M. Dawes, "Enhancement of Random Laser Properties on Solid Polymer Films by Increasing Scattering Effect," *J. Russ. Laser Res.*, vol. 40, no. 4, pp. 364–369, Jul. 2019.

[64] X. H. Wu, A. Yamilov, H. Noh, H. Cao, E. W. Seelig, and R. P. H. Chang, "Random lasing in closely packed resonant scatterers," *J. Opt. Soc. Am. B*, vol. 21, no. 1, p. 159, 2004.

[65] Cao, Xu, Zhang, Chang, Ho, Seelig, Liu, and Chang, "Spatial confinement of laser light in active random media," *Phys. Rev. Lett.*, vol. 84, no. 24, pp. 5584–7, Jun. 2000.

[66] R. C. Polson and Z. V. Vardeny, "Organic random lasers in the weak-scattering regime," *Phys. Rev. B*, vol. 71, no. 4, p. 045205, Jan. 2005.

[67] S. A. O'Brien, A. Harvey, A. Griffin, T. Donnelly, D. Mulcahy, J. N. Coleman, J. F. Donegan, and D. McCloskey, "Light scattering and random lasing in aqueous suspensions of hexagonal boron nitride nanoflakes," *Nanotechnology*, vol. 28, no. 47, 2017.

[68] W. Z. W. Ismail, D. Liu, S. Clement, D. W. Coutts, E. M. Goldys, and J. M. Dawes, "Spectral and

coherence signatures of threshold in random lasers," *J. Opt.*, vol. 16, no. 10, p. 105008, Oct. 2014.

[69] W. Z. W. Ismail, W. M. W. A. Kamil, and J. M. Dawes, "Enhancement of Random Laser Properties on Solid Polymer Films by Increasing Scattering Effect," *J. Russ. Laser Res.*, vol. 40, no. 4, pp. 364–369, 2019.

[70] M. Bahoura and M. A. Noginov, "Determination of the transport mean free path in a solid-state random laser," *J. Opt. Soc. Am. B*, vol. 20, no. 11, p. 2389, 2003.

[71] T. Strudley, T. Zehender, C. Blejean, E. P. A. M. Bakkers, and O. L. Muskens, "Mesoscopic light transport by very strong collective multiple scattering in nanowire mats," *Nat. Photonics*, vol. 7, no. 5, pp. 413–418, 2013.

[72] J. Gómez Rivas, R. Sprik, A. Lagendijk, L. D. Noordam, and C. W. Rella, "Static and dynamic transport of light close to the Anderson localization transition," *Phys. Rev. E*, vol. 63, no. 4, p. 046613, Mar. 2001.

[73] P. W. Anderson, "Absence of Diffusion in Certain Random Lattices," *Phys. Rev.*, vol. 109, no. 5, pp. 1492–1505, Mar. 1958.

[74] G. van Soest, M. Tomita, and A. Lagendijk, "Amplifying volume in scattering media," *Opt. Lett.*, vol. 24, no. 5, p. 306, Mar. 1999.

[75] K. L. van der Molen, A. P. Mosk, and A. Lagendijk, "Quantitative analysis of several random lasers," *Opt. Commun.*, vol. 278, no. 1, pp. 110–113, Oct. 2007.

[76] K. Totsuka, G. van Soest, T. Ito, A. Lagendijk, and M. Tomita, "Amplification and diffusion of spontaneous emission in strongly scattering medium," *J. Appl. Phys.*, vol. 87, no. 11, pp. 7623–7628, Jun. 2000.

[77] C. Vanneste, P. Sebbah, and H. Cao, "Lasing with resonant feedback in weakly scattering random systems," *Phys. Rev. Lett.*, vol. 98, no. 14, pp. 1–4, 2007.

[78] L. Sznitko, K. Cyprych, A. Szukalski, A. Miniewicz, and J. Mysliwiec, "Coherent–incoherent random lasing based on nano-rubbing induced cavities," *Laser Phys. Lett.*, vol. 11, no. 4, p. 045801, Feb. 2014.

[79] M. L. Que, X. Di Wang, Y. Y. Peng, and C. F. Pan, "Flexible electrically pumped random lasing from ZnO nanowires based on metal-insulator-semiconductor structure," *Chinese Phys. B*, vol. 26, no. 6, 2017.

[80] Y. Zhang, D. Saxena, M. Aagesen, and H. Liu, "Toward electrically driven semiconductor nanowire lasers," *Nanotechnology*, vol. 30, no. 19, p. 192002, 2019.

[81] M. Suja, B. Debnath, S. B. Bashar, L. Su, R. Lake, and J. Liu, "Electrically driven plasmon-exciton coupled random lasing in ZnO metal-semiconductor-metal devices," *Appl. Surf. Sci.*, vol. 439, pp. 525–532, May 2018.

[82] A. Yang, D. Wang, W. Wang, and T. W. Odom, "Coherent Light Sources at the Nanoscale," *Annu. Rev. Phys. Chem.*, vol. 68, no. 1, p. annurev-physchem-052516-050730, 2017.

[83] J. M. Dawes, W. Z. Wan Ismail, E. M. Goldys, and D. W. Coutts, "Enhancing the Performance of Random Lasers - Effects of Localised Surface Plasmons and Resonance Energy Transfer," in *Proceedings of the 4th International Conference on Photonics, Optics and Laser Technology*, 2016, pp. 158–161.

[84] A. Yadav, L. Zhong, J. Sun, L. Jiang, G. J. Cheng, and L. Chi, "Tunable random lasing behavior in

plasmonic nanostructures," *Nano Converg.*, vol. 4, no. 1, p. 1, Dec. 2017.

[85] R. Gayathri, K. Monika, V. M. Murukeshan, and C. Vijayan, "Low threshold incoherent random lasing with spectral overlap optimization of size-tuned plasmonic nanorods," *Opt. Laser Technol.*, vol. 139, p. 106959, Jul. 2021.

[86] A. Sarkar, B. N. S. Bhaktha, and J. Andreasen, "Replica Symmetry Breaking in a Weakly Scattering Optofluidic Random Laser," *Sci. Rep.*, vol. 10, no. 1, p. 2628, Dec. 2020.

[87] Z. Wang, M. Cao, G. Shao, Z. Zhang, H. Yu, Y. Chen, Y. Zhang, Y. Li, B. Xu, Y. Wang, *et al.*, "Coherent Random Lasing in Colloidal Quantum Dot-Doped Polymer-Dispersed Liquid Crystal with Low Threshold and High Stability," *J. Phys. Chem. Lett.*, vol. 11, no. 3, pp. 767–774, Feb. 2020.

[88] X. Li, H. Liu, X. Xu, B. Yang, H. Yuan, J. Guo, F. Sang, and Y. Jin, "Lotus-Leaf-Inspired Flexible and Tunable Random Laser," *ACS Appl. Mater. Interfaces*, vol. 12, no. 8, pp. 10050–10057, Feb. 2020.

[89] F. Lahoz, A. Acebes, T. González-Hernández, S. de Armas-Rillo, K. Soler-Carracedo, G. Cuesto, and V. Mesa-Infante, "Random lasing in brain tissues," *Org. Electron.*, vol. 75, p. 105389, Dec. 2019.

[90] J. Tong, S. Li, C. Chen, Y. Fu, F. Cao, L. Niu, T. Zhai, and X. Zhang, "Flexible Random Laser Using Silver Nanoflowers," *Polymers (Basel).*, vol. 11, no. 4, p. 619, Apr. 2019.

[91] S. Perumbilavil, A. Piccardi, R. Barboza, O. Buchnev, M. Kauranen, G. Strangi, and G. Assanto, "Beaming random lasers with soliton control," *Nat. Commun.*, vol. 9, no. 1, p. 3863, Dec. 2018.

[92] S. Yang, S. Kim, H. Shin, S. H. Choi, Y. L. Kim, C. Joo, and W. Ryu, "Random lasing detection of structural transformation and compositions in silk fibroin scaffolds," *Nano Res.*, vol. 12, no. 2, pp. 289–297, Feb. 2019.

[93] M. Gaio, S. Caixeiro, B. Marelli, F. G. Omenetto, and R. Sapienza, "Gain-Based Mechanism for ph Sensing Based on Random Lasing," *Phys. Rev. Appl.*, vol. 7, no. 3, p. 034005, Mar. 2017.

[94] W. Z. W. Ismail, D. Liu, S. Clement, D. W. Coutts, E. M. Goldys, and J. M. Dawes, "Spectral and coherence signatures of threshold in random lasers," *J. Opt. (United Kingdom)*, vol. 16, no. 10, 2014.

[95] L. Cerdán, A. Costela, E. Enciso, and I. García-Moreno, "Random Lasing in Self-Assembled Dye-Doped Latex Nanoparticles: Packing Density Effects," *Adv. Funct. Mater.*, vol. 23, no. 31, pp. 3916–3924, Aug. 2013.

[96] Q. Song, S. Xiao, Z. Xu, J. Liu, X. Sun, V. Drachev, V. M. Shalaev, O. Akkus, and Y. L. Kim, "Random lasing in bone tissue," *Opt. Lett.*, vol. 35, no. 9, p. 1425, May 2010.

[97] T. Takahashi, T. Nakamura, and S. Adachi, "Blue-light-emitting ZnSe random laser," vol. 34, no. 24, pp. 3923–3925, 2009.

[98] A. Kikuchi, K. Yamano, M. Tada, and K. Kishino, "Stimulated emission from GaN nanocolumns," vol. 2758, no. 12, pp. 2754–2758, 2004.

[99] T. Nakamura, B. P. Tiwari, and S. Adachi, "Control of random lasing in ZnO/Al2O3 nanopowders," *Appl. Phys. Lett.*, vol. 99, no. 23, p. 231105, 2011.

[100] J. Liu, P. D. Garcia, S. Ek, N. Gregersen, T. Suhr, M. Schubert, J. Mørk, S. Stobbe, and P. Lodahl, "Random nanolasing in the Anderson localized regime," *Nat. Nanotechnol.*, vol. 9, no. 4, pp. 285–

289, Apr. 2014.

[101] N. F. Ramli, S. A. M. Samsuri, S. Y. Chan, H. C. Hsu, N. Zainal, H. A. Hassan, O. Muskens, and W. M. W. A. Kamil, “AZO nanowires as a random laser,” in *Optics InfoBase Conference Papers*, 2020, vol. Part F183-, pp. 6–7.

[102] K. W. D. Ledingham and M. Campbell, “Laser-based sensors,” in *Sensor Systems for Environmental Monitoring*, Dordrecht: Springer Netherlands, 1997, pp. 65–99.

[103] L. Clark, B. Shirinzadeh, Y. Tian, and D. Oetomo, “Laser-based sensing, measurement, and misalignment control of coupled linear and angular motion for ultrahigh precision movement,” *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 1, pp. 84–92, Feb. 2015.

[104] D. Hu and R. Kovacevic, “Sensing, modeling and control for laser-based additive manufacturing,” *Int. J. Mach. Tools Manuf.*, vol. 43, no. 1, pp. 51–60, Jan. 2003.

[105] K. R. S. Kodagoda, C. Wang, and G. Dissanayake, “Laser-Based Sensing on Roads,” *Proc. Intell. Veh. Road Infrastruct. Conf.*, pp. 1–8, 2005.

[106] A. Azim and O. Aycard, “Detection, classification and tracking of moving objects in a 3D environment,” in *2012 IEEE Intelligent Vehicles Symposium*, 2012, pp. 802–807.

[107] V. Weldon, D. McInerney, R. Phelan, M. Lynch, and J. Donegan, “Characteristics of several NIR tuneable diode lasers for spectroscopic based gas sensing: A comparison,” *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.*, vol. 63, no. 5, pp. 1013–1020, Apr. 2006.

[108] M. S. Bergholt, W. Zheng, K. Lin, K. Y. Ho, M. Teh, K. G. Yeoh, J. B. Yan So, and Z. Huang, “Raman endoscopy for in vivo differentiation between benign and malignant ulcers in the stomach,” *Analyst*, vol. 135, no. 12, p. 3162, 2010.

[109] T. R. Neu and J. R. Lawrence, “Development and structure of microbial biofilms in river water studied by confocal laser scanning microscopy,” *FEMS Microbiol. Ecol.*, vol. 24, no. 1, pp. 11–25, Jan. 2006.

[110] A. Briney, “An Overview of Remote Sensing,” *ThoughtCo*, 2021.

[111] X. Sun, Y. Wang, and Y. Lei, “Fluorescence based explosive detection: from mechanisms to sensory materials,” *Chem. Soc. Rev.*, vol. 44, no. 22, pp. 8019–8061, 2015.

[112] A. Elia and P. M. Lugarà, “Photoacoustic Techniques for Trace Gas Sensing Based on Semiconductor Laser Sources,” pp. 9616–9628, 2009.

[113] P. L. Teoh, B. Shirinzadeh, and C. W. Foong, “The measurement uncertainties in the laser interferometry-based sensing and tracking technique,” vol. 32, pp. 135–150, 2002.

[114] E. Ignesti, F. Tommasi, L. Fini, F. Martelli, N. Azzali, and S. Cavalieri, “A new class of optical sensors: a random laser based device,” *Sci. Rep.*, vol. 6, no. 1, p. 35225, 2016.

[115] K. Lee, I. Hwang, Y.-M. Kim, H. Lee, M. Kang, and J. Yu, “Real-Time Weld Quality Prediction Using a Laser Vision Sensor in a Lap Fillet Joint during Gas Metal Arc Welding,” *Sensors*, vol. 20, no. 6, p. 1625, Mar. 2020.

[116] G. Agapiou, C. Kasiouras, and A. A. Serafetinides, “Detailed analysis of the MIG spectrum for the development of laser-based seam tracking sensors,” *Opt. Laser Technol.*, vol. 31, no. 2, pp. 157–161, 1999.

[117] M. Hohmann, D. Dörner, F. Mehari, C. Chen, M. Späth, S. Müller, H. Albrecht, F. Klämpfl, and

M. Schmidt, “Investigation of random lasing as a feedback mechanism for tissue differentiation during laser surgery,” *Biomed. Opt. Express*, vol. 10, no. 2, p. 807, Feb. 2019.

[118] A. M. Smith, M. C. Mancini, and S. Nie, “Second window for in vivo imaging,” *Nat. Nanotechnol.*, vol. 4, no. 11, pp. 710–711, Nov. 2009.

[119] J. Rocha, C. D. S. Brites, and L. D. Carlos, “Lanthanide Organic Framework Luminescent Thermometers,” *Chem. - A Eur. J.*, vol. 22, no. 42, pp. 14782–14795, Oct. 2016.

[120] F. Zhao, B. Koo, H. Liu, C. Eun Jin, and Y. Shin, “A single-tube approach for in vitro diagnostics using diatomaceous earth and optical sensor,” *Biosens. Bioelectron.*, vol. 99, pp. 443–449, Jan. 2018.

[121] T. Fujii and T. Fukuchi, *Laser Remote Sensing*. CRC Press, 2005.

[122] D. K. Killinger and A. Mooradian, *Optical and Laser Remote Sensing*. Springer Berlin Heidelberg, 2013.

[123] B. M. Walsh, H. R. Lee, and N. P. Barnes, “Mid infrared lasers for remote sensing applications,” *J. Lumin.*, vol. 169, pp. 400–405, Jan. 2016.

[124] R. Lang and K. Kobayashi, “External optical feedback effects on semiconductor injection laser properties,” *IEEE J. Quantum Electron.*, vol. 16, no. 3, pp. 347–355, Mar. 1980.

[125] T. Taimre, M. Nikolić, K. Bertling, Y. L. Lim, T. Bosch, and A. D. Rakić, “Laser feedback interferometry: a tutorial on the self-mixing effect for coherent sensing,” *Adv. Opt. Photonics*, vol. 7, no. 3, p. 570, Sep. 2015.

[126] J. Li, H. Niu, and Y. Niu, “Laser feedback interferometry and applications: a review,” *Opt. Eng.*, vol. 56, no. 5, p. 050901, May 2017.

[127] K. S. Reichel, E. A. A. Pogna, S. Biasco, L. Viti, A. Di Gaspare, H. E. Beere, D. A. Ritchie, and M. S. Vitiello, “Self-mixing interferometry and near-field nanoscopy in quantum cascade random lasers at terahertz frequencies,” *Nanophotonics*, vol. 10, no. 5, pp. 1495–1503, Mar. 2021.

[128] S. Lin, Z. Wang, Y. Qi, B. Han, H. Wu, and Y.-J. Rao, “Wideband remote-sensing based on random fiber laser,” *J. Light. Technol.*, pp. 1–1, 2022.

[129] Z. N. Wang, Y. J. Rao, H. Wu, P. Y. Li, Y. Jiang, X. H. Jia, and W. L. Zhang, “Long-distance fiber-optic point-sensing systems based on random fiber lasers,” *Opt. Express*, vol. 20, no. 16, p. 17695, Jul. 2012.

[130] S. H. Choi and Y. L. Kim, “The potential of naturally occurring lasing for biological and chemical sensors,” *Biomed. Eng. Lett.*, vol. 4, no. 3, pp. 201–212, Sep. 2014.

[131] M. C. Gather and S. H. Yun, “Lasing from Escherichia coli bacteria genetically programmed to express green fluorescent protein,” *Opt. Lett.*, vol. 36, no. 16, p. 3299, Aug. 2011.

[132] M. Humar and S. Hyun Yun, “Intracellular microlasers,” *Nat. Photonics*, vol. 9, no. 9, pp. 572–576, Sep. 2015.

[133] M. Schubert, L. Woolfson, I. R. M. Barnard, A. M. Dorward, B. Casement, A. Morton, G. B. Robertson, P. L. Appleton, G. B. Miles, C. S. Tucker, *et al.*, “Monitoring contractility in cardiac tissue with cellular resolution using biointegrated microlasers,” *Nat. Photonics*, vol. 14, no. 7, pp. 452–458, Jul. 2020.

[134] W. Z. Song, X. M. Zhang, A. Q. Liu, C. S. Lim, P. H. Yap, and H. M. M. Hosseini, “Refractive

index measurement of single living cells using on-chip Fabry-Pérot cavity," *Appl. Phys. Lett.*, vol. 89, no. 20, p. 203901, Nov. 2006.

[135] A. Jian, Y. Wu, J. Ji, D. Li, Y. Zhang, X. Xue, and S. Sang, "Low cell concentration detection by Fabry-Pérot resonator with sensitivity enhancement by dielectrophoresis," *Sensors Actuators A Phys.*, vol. 331, p. 112977, Nov. 2021.

[136] D. Kumar, H. Shao, and K. L. Lear, "Vertical Cavity Laser and Passive Fabry Perot Interferometer Based Microfluidic Biosensors," in *Laser Applilcations to Chemical, Security and Environmental Analysis*, 2006, p. TuD3.

[137] K. L. Lear, H. Shao, W. Wang, and S. E. Lana, "Optofluidic Intracavity Spectroscopy of Canine Lymphoma and Lymphocytes," in *2007 Digest of the IEEE/LEOS Summer Topical Meetings*, 2007, pp. 121–122.

[138] X. Shi, K. Ge, J.-H. Tong, and T. Zhai, "Low-cost biosensors based on a plasmonic random laser on fiber facet," *Opt. Express*, vol. 28, no. 8, p. 12233, Apr. 2020.

[139] E. I. Galanzha, R. Weingold, D. A. Nedosekin, M. Sarimollaoglu, J. Nolan, W. Harrington, A. S. Kuchyanov, R. G. Parkhomenko, F. Watanabe, Z. Nima, *et al.*, "Spaser as a biological probe," *Nat. Commun.*, vol. 8, no. 1, p. 15528, Aug. 2017.

[140] D. Zhang, Y. Wang, J. Tang, and H. Mu, "Random laser marked PLCD1 gene therapy effect on human breast cancer," *J. Appl. Phys.*, vol. 125, no. 20, p. 203102, May 2019.

[141] S. de Armas-Rillo, F. Fumagallo-Reading, D. Luis-Ravelo, B. Abdul-Jalbar, T. González-Hernández, and F. Lahoz, "Random Lasing Detection of Mutant Huntingtin Expression in Cells," *Sensors*, vol. 21, no. 11, p. 3825, May 2021.

[142] B. Helbo, S. Kragh, B. G. Kjeldsen, J. L. Reimers, and A. Kristensen, "Investigation of the dye concentration influence on the lasing wavelength and threshold for a micro-fluidic dye laser," *Sensors Actuators A Phys.*, vol. 111, no. 1, pp. 21–25, Mar. 2004.

[143] A. L. Moura, P. I. R. Pincheira, L. J. Q. Maia, A. S. L. Gomes, and C. B. de Araújo, "Two-color random laser based on a Nd3+ doped crystalline powder," *J. Lumin.*, vol. 181, pp. 44–48, 2017.

[144] S. Balabhadra, M. L. Debasu, C. D. S. Brites, L. A. O. Nunes, O. L. Malta, J. Rocha, M. Bettinelli, and L. D. Carlos, "Boosting the sensitivity of Nd 3+ -based luminescent nanothermometers," *Nanoscale*, vol. 7, no. 41, pp. 17261–17267, 2015.

[145] B. Abaie, E. Mobini, S. Karbasi, T. Hawkins, J. Ballato, and A. Mafi, "Random lasing in an Anderson localizing optical fiber," *Light Sci. Appl.*, vol. 6, no. 8, pp. e17041–e17041, Aug. 2017.

[146] I. Konidakis, M. Androulidaki, G. Zito, and S. Pissadakis, "Growth of ZnO nanolayers inside the capillaries of photonic crystal fibres," *Thin Solid Films*, vol. 555, pp. 76–80, Mar. 2014.

[147] T. Bora, H. Fallah, M. Chaudhari, T. Apiwattanadej, S. W. Harun, W. S. Mohammed, and J. Dutta, "Controlled side coupling of light to cladding mode of ZnO nanorod coated optical fibers and its implications for chemical vapor sensing," *Sensors Actuators B Chem.*, vol. 202, pp. 543–550, Oct. 2014.

[148] V. Kapoor, N. K. Sharma, S. Gupta, and P. Kumar, "Fiber optic SPR sensing of liquids using copper and zinc oxide," *Optik (Stuttg).*, vol. 238, p. 166727, Jul. 2021.

[149] H. Wu, Y. Wang, L. Zhang, K. Guo, Y. Huang, C. Liao, and Y. Wang, "ZnO Microwire-Based Fiber-Tip Fabry-Pérot Interferometer for Deep Ultraviolet Sensing," *J. Light. Technol.*, vol. 39,

no. 12, pp. 4225–4229, Jun. 2021.

For TOC only: