Random laser emission from a surface-corrugated waveguide

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Here we report the random laser emission from surface corrugated waveguides. Discrete lasing modes, super narrow spectral linewidth, and the existence of lasing threshold behavior have been observed. Single mode emission was observed by controlling the gain length. The lasing modes are strongly polarized. A theoretical model was presented to explain the localization phenomena.

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The problem of transmission properties in waveguides with disordered surface attracted much attention from both theoretical and experimental standpoint.[1,2] Wave propagation with coherent multiple scattering generally occurs in optical waveguides and fibers, remote sensing, radiowave propagation, sonar, shallow water waves, and geophysical probing.[3–5] Some theoretical models and a few experiments in microwave range were developed and reported.[6–8] It was shown that the interference of multiple scattering induced localization was crucial to the phenomena such as intensity correlations, and universal conductance fluctuations. Recently, interest in stochastic resonance of light wave in random media was rekindled in the context of random lasing, wherein the localization might play the role of forming effective cavities for lasing when gain was introduced.[9–11]

Up to now, no theoretical calculation and experimental results can be found for random lasing from surface corrugated dielectric waveguides. Though Frolov *et al.* reported random lasing from a DOO-PPV waveguide, impurities and/or density fluctuation inside the films were considered to be the scattering centers that form random cavities.[12] Interaction of a corrugated surface with the light propagating in an optical waveguide could be significantly different from that of a density-fluctuating film, since the randomness and coupling strength of rough surface with the guided wave are more controllable.

In this paper, we report the observation of random lasing from waveguide with artificially formed rough surface. The properties of lasing from surface disordered waveguide were mixed by properties of both random laser and waveguiding. The scattering source is separated from the gain media, therefore the interaction of scattering with the guided wave can be understood much more clearly and conclusively. Other properties appeared, such as the single mode emission, and strong polarization can have potential applications in the future.

The surface-corrugated dielectric waveguides were fabricated by coating random distributed silica spheres on a glass substrate (refractive index $n=1.51$) and then covered by a 4 wt. % 4-(dicyanomethylene)-2-methyl-6- (4-dimethylaminostyryl)- 4H-pyran (DCM) doped polycarbonate (PC) film (refractive index $n=1.59$). Silica spheres were synthesized by the Stober method.[13] The diameter of the spheres can be well controlled by controlling the pH value of the reaction.

The distribution of silica spheres on the substrate was measured by scanning electron microscope (SEM, Philip XL30 operated at 20 KV). The result is shown in Fig. 1. The average size of the spheres is about 75 nm. The thickness of the covered PC waveguiding layer is 340 nm, which was measured by a Zygo NewView 200 Profiler.

The samples were optically pumped by the frequency-doubled output of a mode-locked Nd:YAG laser (10 Hz repetition rate, 35 ps pulse width). The pump beam was focused by a cylindrical lens to a narrow strip on the film surface at normal incidence. The width of the pump strip was 150 micron; the pump length can be changed from 0.5 mm to 20 mm for different types of experiments. The emitted light from the edge of the waveguide was collected and coupled to a SPECTROPRO 500i (ACTON RESEARCH, $f=0.5$ m) monochromator and detected by a DH 720-18F-03 ICCD (ANDOR Technology). The spectral resolution of the system is about 0.04 nm.

Figure 2(a) shows the evolution of the emission spectra as the pump intensity was increased. At low pump intensity, there is only a broad photoluminescence background. As the pump power increased, very narrow peaks (hereafter called lasing modes) started to emerge. The linewidth of these peaks is about 0.09 nm. The emission spectrum (spectral positions, mode numbers) changes if different part on the planar waveguide is pumped. However, linewidth of the peak

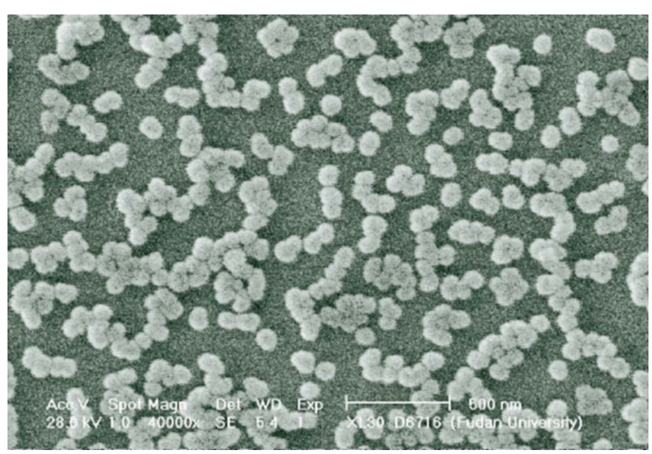

FIG. 1. SEM image of the randomly distributed silica spheres on glass substrate.

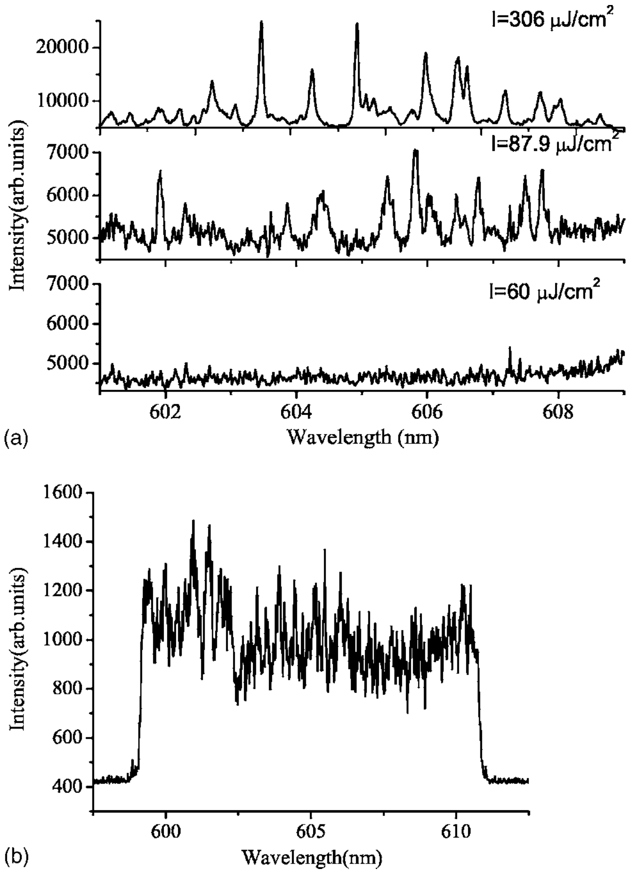

FIG. 2. (a) The emission spectra at different pump intensity. Note that the scale of the intensities in the three plots is different. (b) The emission spectra of waveguide without the disordered silica spheres.

hardly changes. In comparison, a waveguide without silica spheres was also prepared and optically pumped under the same experimental condition. Emission from the edge of the waveguide was presented in Fig. 2(b). The emission spectrum basically comprises of amplified simulated emission (ASE) with very broad spectral width, and no obvious narrow spectral peaks can be observed. Thus we can conclude that the disordered spheres on the surface induced the generation of narrow spectral peaks.

Figure 3 shows the spectrally integrated emission intensity as a function of the pump power. A threshold of 70 $\mu J/cm^2$ was observed. The spectra below and above the threshold detected by a 300 lines/mm low resolution grating, which can be compared with the normal ASE spectra, are shown in the inset of Fig. 3. The two spectra at the bottom were enhanced by 150 times. Above the threshold, multiple sharp peaks emerge, and the integrated emission intensity increases at a much steeper slope. From the narrowed linewidth peaks and the threshold behavior, it can be concluded that random lasing action in the surface corrugated waveguide was observed.

In normal laser cavities, feedback was provided by cavity mirrors. On the other hand, in distributed feedback Bragg (DFB) lasers, the grating beneath the gain media acts as the feedback reflector.[14] Forward and backward propagating

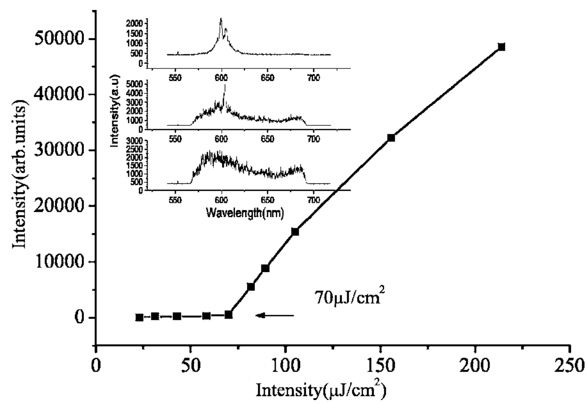

FIG. 3. The relation between integrated emission intensity versus pump intensity. Lasing threshold is 70 $\mu J/cm^2$. Inset: emission spectra measured below, above, and high above the threshold.

beams generated by the grating form stable standing waves inside the waveguide at certain wavelength, which give intense laser output with very narrow linewidth. The corrugated surface of the waveguide can be considered as a nonperiodic grating which comprises numerous periodic gratings. Strong emission occurs when resonant condition is satisfied. As the corrugated surface consists of random refractive index distribution, resonant condition at different part of the surface should be quite different. In addition, those minigratings have different feedback efficiencies. Therefore, the lasing modes have different power dependence. When the pump intensity decreases, laser oscillation does not occur in those cavities of high loss, so the number of discrete lasing modes decreases. As the pump power decreases further, gain will be too small to sustain any lasing modes.

When the pump intensity was above the threshold, a bright emitted spot was observed from the edge of the waveguide. Figure 4 shows the CCD camera recorded far field image of the emitted lasing spot on a screen 3.15 cm away

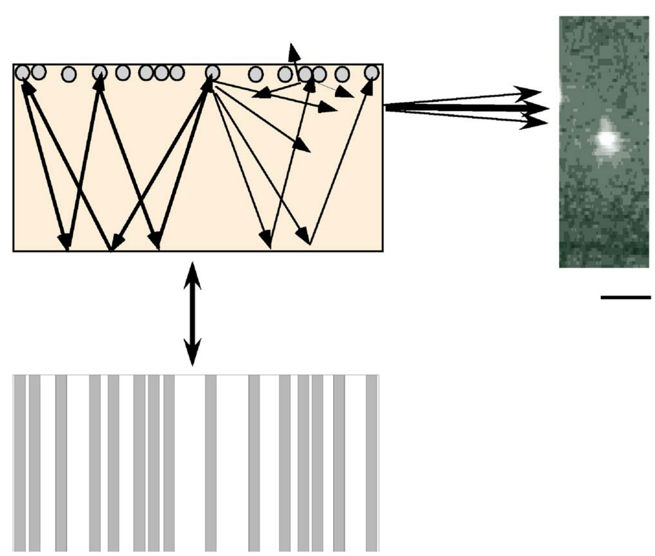

FIG. 4. (Color online) The schematic picture and far field picture of the emitted laser. The bar in (b) is 1 cm.

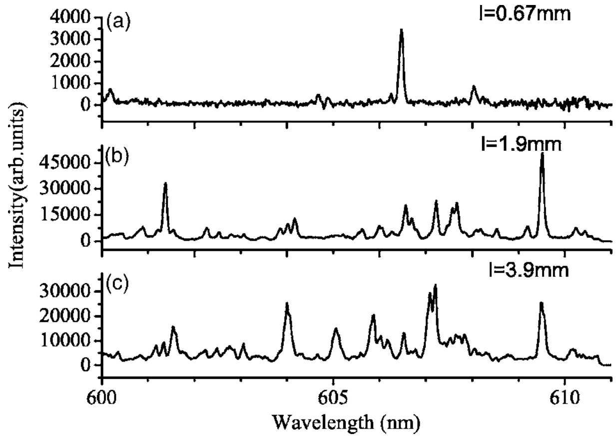

FIG. 5. The emission spectra at different pump length. (a) $L=0.67$ mm, (b) $L=1.9$ mm, and (c) $L=3.9$ mm. The pump intensity was kept at 615 $\mu J/cm^2$.

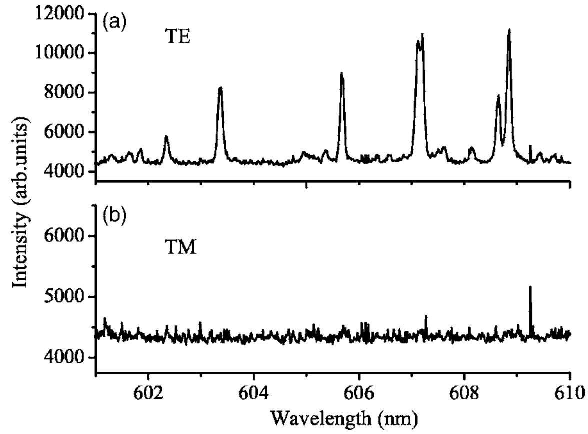

FIG. 6. The emission spectra observed after linear polarizer. (a) TE polarization; (b) TM polarization.

from the edge. The divergence angle calculated is smaller than 4°, which is surprisingly small, especially in the vertical plane direction. As from diffraction limit and numerical aperture of the waveguide, the vertical divergence should be larger than 30°. A comparison experiment on dye-doped PC waveguide (with no silica spheres on the interface) confirmed that the emission pattern was a dime long line with very large divergence angle. The substantial change of vertical divergence could be from the scattering effect of the corrugated surface. The lights with large propagation angle in the waveguide have larger loss, since they will be scattered by the rough surface more times.

The dependence of random laser action on the gain length was also investigated. The gain length was changed by blocking part of the pump strip. Figure 5 shows the evolution of the emission spectra as the pump length changes while keeping the pump intensity as a constant (615 $\mu J/cm^2$). With the decrease of pump length, the total number of lasing modes becomes less and less, at the pump length of 0.67 mm, only a single lasing mode exists. This can be considered that there are more minigratings that can afford feedback when the pump length is larger, laser action occurs in more cavities formed by the coherent scattering. As the pump length decreases, some laser oscillations stop. When the pump length is reduced further to a critical size, only one or several modes exist.

The lasing modes emitted from the edge of the waveguide were found to be totally TE polarized (see Fig. 6). This happens in an asymmetric waveguide in which TE and TM mode cutoff thickness is different. If the thickness of the waveguide was controlled to be such that only TE_0 mode is allowed to propagate at the lasing wavelength, the output is TE polarized.[15]

In the following, we present a numerical study of the transmission properties in the corrugated waveguide. The real sample studied here is a two-dimensional waveguide with corrugated surface, but it can be simplified to a waveguide consisting of randomly refractive index modulated thin layers (Fig. 4) by using the effective refractive index as the simulation of a normal DFB waveguide laser. Consequently a multilayer structure treatment can be adopted, electric field distribution and its spectrum can be numerically studied with the transfer matrix method.[16–19] Comparing with the finite element time domain (FDTD) method, it is much easier to find the localization in these two-dimensional disordered systems.[20]

In this paper, we modified the simulation process further for simplification by keeping the refractive indices of the alternating layers as constants ($n_H=1.545$, $n_L=1.515$; here n_H and n_L are the effective refractive indices of TE_0 mode of the waveguide without and with silica sphere), but let the thickness of each layer be random between 75 nm to 120 nm (note that 75 nm is the diameter of the silica sphere). The modification should give the same simulation result as optical path $n\times L$ is the effective physical element (n is the refractive index; L is the thickness of each layer).

The transmission through the multilayer-structure waveguide was simulated. The dashed lines in Figs. 7(a)–7(c) are the reflection spectra of 1000-layer, 1200-layer, and 2500-layer structures, respectively. We focused at three wavelengths: 602.90 nm, 605.17 nm, and 606.09 nm. High transmittance at 602.90 nm appears for the 1000- and 1200-layer

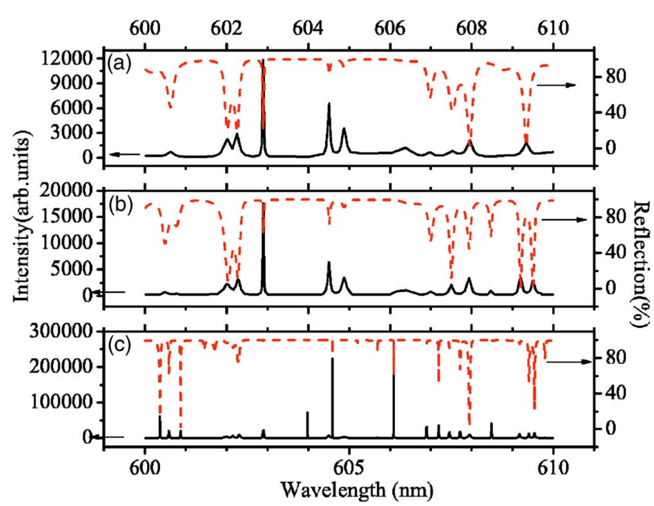

FIG. 7. (Color online) The spectra of reflection and field distribution in (a) 1000-layer, (b) 1200-layer, and (c) 2500-layer structure.

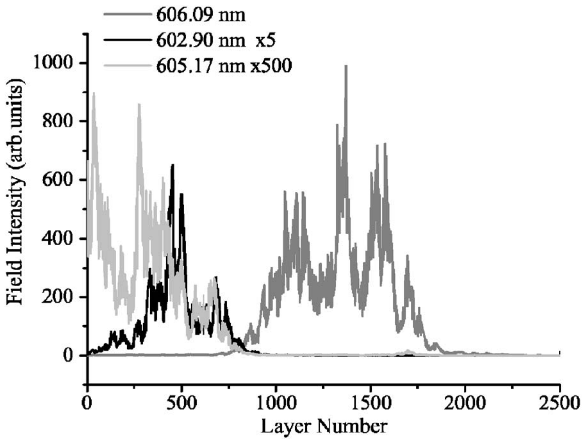

FIG. 8. The electrical field distributions at three wavelengths in a 2500-layer structure versus the layer number. Note the field intensities at 602.90 nm and 605.17 nm were magnified by 5 and 500 times, respectively.

structure, but drops to very low for the 2500-layer structure. On the other hand, transmittance at 606.09 nm is almost zero for the 1000- and 1200-layer structure, but becomes high for the 2500-layer structure. The transmittance at 605.17 nm is zero for all the cases. Figure 8 shows the field intensity distributions at the three wavelengths along the propagating layers. Note the difference in magnitude amplification factor for the three wavelengths. The field at 605.17 nm drops continuously after it was launched into the structure, so no transmission can be observed. The field at 602.90 nm is localized in the first 1000 layers and its strength is greatly enhanced comparing with the strength at 605.17 nm, transmittance at that wavelength is high but becomes very low for the 2500-layer structure. The field at 606.09 nm has very high strength (500 times higher than that of 605.17 nm) and localized in the mid part of the structure (from layer number 700 to 2000), therefore high transmission does not exist for the structures of small layer numbers. Thus we know that the whole structure can be considered as many minicavities formed by the feedback of different parts of the structure and more modes can be localized with the increasing of the structure length. The calculated field intensity distributions of the localized modes are shown as the solid lines in Figs. 7(a)–7(c). There are more modes localized in the 2500-layer structure than in the 1000-layer one. As the intensity of the emitted laser is affected by both of the localization and the transmission, the lasing threshold should be different for different modes. Single mode oscillation is expected when the pump length is short enough. All these phenomena match qualitatively with our experimental results.

In summary, random lasing was observed for the first time in a surface disordered waveguide that is formed of a SiO_2 spheres surface and a DCM dye doped PC film. The properties of the random laser action in the surface disordered waveguide combine the properties of a planar waveguide and a random laser that occurs in bulk disordered systems. Phenomena such as the single mode emission, and strong polarization were observed. The lasing behavior can be understood well by using the modified transfer matrix method to simulate the light field distribution and transmission spectrum. Lasing modes correspond to the light that has very high localization inside the waveguide.

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