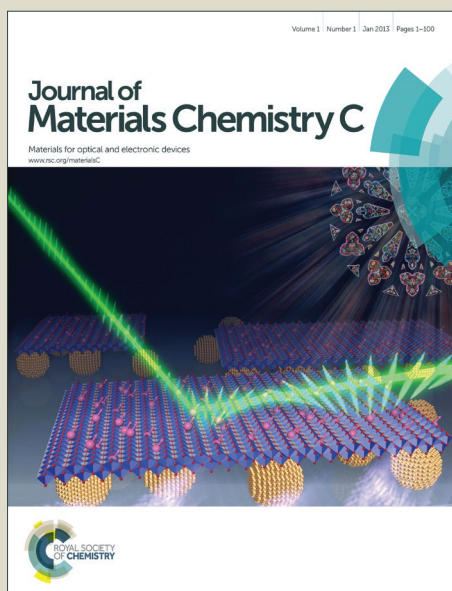


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ARTICLE

Enhancement of Lasing in organic gain media assisted by the metallic nanoparticles-metallic film plasmonic hybrid structure

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Metallic films were widely used in many micro-cavities or as electrodes. However, the quenching of fluorescent molecules and the large absorption loss of metallic films are generally considered fatal for the lasing. In this article, we present the enhanced lasing of organic gain medium in planar waveguide, assisted by the plasmonic hybrid structure of Ag nanoparticles (NPs)-Ag film. Comparing to the devices that gain media deposited on glass, Ag film, Ag NPs island film, the lowest lasing threshold of the gain medium deposited on Ag NPs-Ag film hybrid structure was achieved. It is attributed to the hybrid plasmonics coupling between the localized surface plasmons of Ag NPs and the delocalized surface plasmon polariton of Ag film, leading the more intense localized electric field. In addition, the reinjection and confinement of the leaking photons into the gain medium by the external feedback of Ag film also contribute to the enhanced lasing. Our results could provide us an unique idea to effectively avoid the negative effect of metallic film, enhance the lasing gain of organic dye molecules, and realize the lower pumped threshold and stronger lasing.

1. Introduction

Organic semiconductors are attractive gain media for compact and versatile laser system because these gain media assured wide tenability of wavelength, ease of processing, flexibility, and high efficiency with potentially low cost.^{1,2} In the past decades, although all kinds of optically pumped lasers based on organic solid materials were demonstrated, it has not been possible to obtain the stimulated emission under electrical pumping.³ In general, the metallic electrodes are usually integrated into the electrical pumping, and one of the major challenges for the electrically pumped organic solid lasers is the negative effect of metallic electrode on stimulate emission of organic dyes. The metallic electrodes generally lead to the quenching of the dyes and the large absorption loss, which will be fatal for the lasing.⁴ Therefore, how to avoid the negative effect of metallic electrodes and further enhance the lasing properties are the key issues for the organic lasing.

In order to evaluate the effect of metallic electrodes on lasing of dyes, the optical pumped organic lasers were usually investigated in presence of metallic electrode. For the planar waveguide structure with metallic film, substantial efforts have been made to reduce the negative effect of metallic film and to improve the lasing properties, such as distributed feedback metallic structure,^{5,6} low loss metal cladding,^{4,7,8} and thin spacer of polystyrene or oxidized Ca.⁹ In these previous

published works, although the negative effect of metallic film was reduced, and the lasing thresholds of optical pumped devices with metallic films were restored, however, the lasing of organic gain medium in presence of metallic film with lower pumped threshold is still desired.

Known to all, for the metallic nanoparticles (NPs) and metallic films, besides the quenching effect, localized surface plasmons (LSPs) and surface plasmon polariton (SPP) can be excited, respectively, which both can induce the field enhancement. Various groups have already used metallic NPs to enhance lasing.¹⁰⁻¹³ However, for the metallic NPs-metallic film hybrid structure, it has received somewhat less attention.

Herein, we present a dramatic enhancement of lasing in organic gain medium, assisted by the Ag NPs-Ag film plasmonic hybrid structure with appropriate distance between Ag NPs and Ag film. Comparing with the devices that gain media deposited on glass, Ag film, silver island film (SIF), the lowest lasing threshold of the gain medium deposited on Ag NPs-Ag film hybrid structure was achieved. It was found that the more intense localized electric field could be excited, because the hybrid plasmonic interaction of the localized surface plasmons with the delocalized thin film surface plasmon polariton. At the same time, due to the existing of Ag film, the reinjection of leaking photons could also reduce the lasing threshold. This particularly interesting plasmonic hybrid structure could provide us an unique idea to enhance lasing of organic dyes. To the best of our knowledge, it is the first time to use the metallic NPs-metallic film hybrid structure to enhance lasing properties, which could effectively avoid the negative effect of metallic film in gain medium and realize the lower pumped threshold than that of the metal-free device.

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2. Experimental Section

2.1 Preparation of silver island film

The Ag NPs were synthesized by a seed-mediated growth method, which were prepared in two steps by citrate reduction of silver nitrate (AgNO_3) with NaBH_4 as strong reducing agent in water.¹⁴ First, 20 mL citrate solution (1%, w/v) and 75 mL water were mixed and heated to 70°C for 15 min. After that, 1.7 mL AgNO_3 solution (1%, w/v) was introduced to the mixture, followed by the quick addition of 2 mL freshly prepared NaBH_4 solution (0.1%, w/v). The reaction solution was kept at 70°C for 1 h, the resulting Ag NPs were used as starter seeds. And then, 2 mL citrate solution (1%, w/v) was mixed with 80 mL water and brought to boiling for 15 min, 5 mL of starter seeds solution was added, followed by the addition of 1.7 mL AgNO_3 solution (1%, w/v). Stirring continued for 1 h while keeping reflux. The colloidal solution was centrifuged at 6000 rpm, which produced a final precipitate containing nanoparticles with the diameter of 40 nm.

The SIFs were prepared as dipping the slides in 1% aqueous solution of 3-aminopropyltriethoxysilane (APS) for 30 min at room temperature. Then the slides were washed extensively with water. Finally, kept the APS-coated slides immersing in silver colloidal solutions and allowed to stay at room temperature overnight. The Ag colloid deposited slides were rinsed with deionized water and then put it in a vacuum drying oven at temperature of 160°C for 5 h, which produced smoother surface of nanoparticles.¹⁵ Figure 1 shows the atomic force microscopy (AFM) image of the SIF, which shows that most of the particles are sphere shape with diameter about 40 nm.

2.2 The device based on Ag NPs-Ag film hybrid structure

In order to present the advantages of Ag NPs-Ag film hybrid structure on the enhancement of lasing properties, we developed four kinds of device structures that the gain media deposited on glass, Ag film, SIFs deposited on glass, SIFs deposited on Ag film, respectively. The devices are as follow

(shown in Fig. 2):

device 1: Glass/ LiF (10 nm)/ PS:BMT-TPD

device 2: Glass/ Ag film (50 nm)/ SiO_2 (5 nm)/ LiF (10 nm)/ PS:BMT-TPD

device 3: Glass/ Ag NPs/ LiF (10 nm)/ PS:BMT-TPD

device 4: Glass/ Ag film (50nm)/ SiO_2 (5 nm)/ Ag NPs/ LiF (10 nm)/ PS:BMT-TPD

The preparation process was as follow:

The 50 nm-Ag film was deposited onto the glass substrate by thermal evaporation under a vacuum of 1×10^{-5} Pa at the

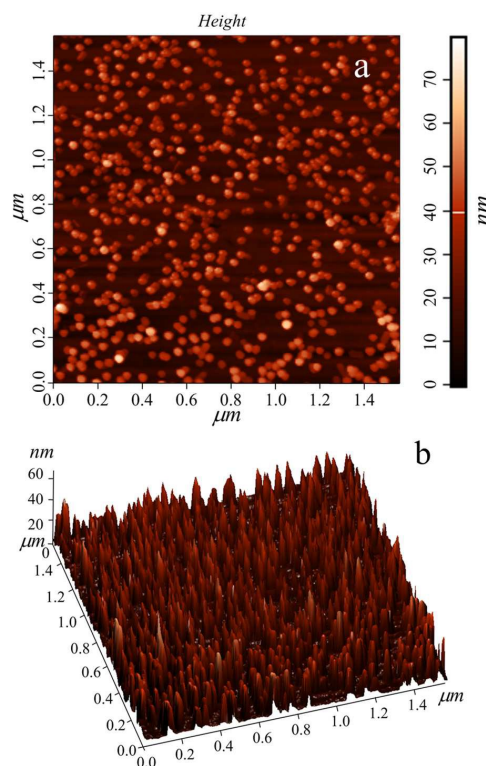


Fig. 1 The AFM images of the Ag NPs with (a) 2D and (b) 3D.

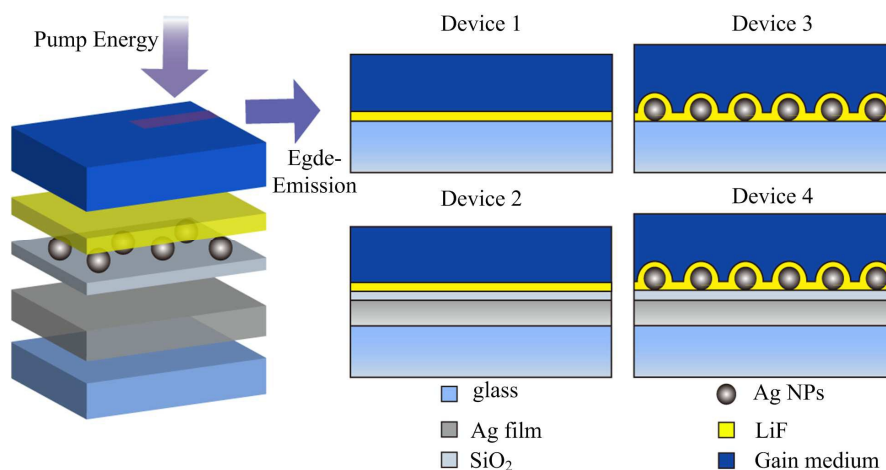


Fig. 2 The schematic illustration of different devices. Device 1: Glass/ LiF (10 nm)/ PS:BMT-TPD; Device 2: Glass/ Ag film (50 nm)/ SiO_2 (5 nm)/ LiF (10 nm)/ PS:BMT-TPD; Device 3: Glass/ Ag NPs/ LiF (10 nm)/ PS:BMT-TPD; Device 4: Glass/ Ag film (50nm)/ SiO_2 (5 nm)/ Ag NPs/ LiF (10 nm)/ PS:BMT-TPD.

rate of 0.3 nm/s. And the 10 nm-LiF layer was also obtained by thermal evaporation for preventing the quenching caused by direct contact between Ag NPs and gain medium. 5 nm-SiO₂ spacer layer was prepared by radio frequency sputtering. For the device 4, the metal deposition step was followed by the deposition of 5 nm-SiO₂ spacer layer, this step served to protect the metal surface from chemical attack, and to provide a means to chemically attach silver colloids. And N,N'-bis(3-methylphenyl)-N,N'-diphenyl- [1,1':4',1''-terphenyl] -4,4''-diamine (BMT-TPD) was used as gain medium.¹⁶ The planar waveguide with gain medium was fabricated as follows: Polystyrene (PS) and BMT-TPD were fully dissolved in chloroform solution (PS: BMT-TPD =4:1, wt%), and then was spin-coated on top of the LiF layer with the speed of 4000 rpm, the spin-coated film was annealed at 110 °C for 10 min. The thickness of gain medium layer is approximately 250 nm.

2.3 Characterization

In experiments, the thickness of polymer film was measured by Stylus Profiler (Dektak 6M, USA). The absorption and photoluminescence (PL) spectra were obtained by UV-Vis spectrophotometer (HITACHI U-3010, Japan) and Fluorescence Spectrometer (fluoromax-4 spectrofluorometer) respectively. The experimental setup used to investigate the stimulated emission in these devices had been reported previously.¹⁷ The devices were photopumped at normal incidence with a pulsed Nd:YAG laser (Surelite I, Continuum Corp, USA) operating at 355 nm with a pulse duration of 5.5 ns and repetition rate of 10 Hz. The energy of the pulses was controlled using neutral density filters. An adjustable slit and a cylindrical lens were then used to shape the beam into a stripe with the size of 7 mm×1 mm. For the waveguide structures in our devices, the light is partially confined into the waveguide and amplified by the gain medium. As a result, the light emitted from the edge of the waveguide could undergo the longer light path in gain medium, which has the lower lasing threshold and stronger emission intensity according to the optical confinement of the waveguide. Therefore, the edge emission was measured to study the properties of devices.^{18,19} The pump stripe was placed at the edge of the film as shown in Fig. 2 and edge emission spectra were collected along the stripe by an optical fiber and transmitted to a spectrometer (Ocean Optics SpectraSuite, USB2000). The lasing threshold, peak intensity and the full width at half maximum (FWHM) were measured.

3. Results and Discussion

Figure 3 shows the localized surface-plasmon resonance (LSPR) spectrum of 40 nm Ag NPs, together with the absorption and emission spectra of BMT-TPD. We can know that the LSPR peak is wavelength of 417 nm. It is also found that the LSPR of Ag NPs has a sufficient overlap with both absorption and emission spectra of BMT-TPD to ensure the enhancement of the lasing.²⁰

For comparison, the device that gain medium without Ag NPs and Ag film (device 1 shown in Fig. 2) was prepared as reference. Figure 4(a) shows the dependence of edge

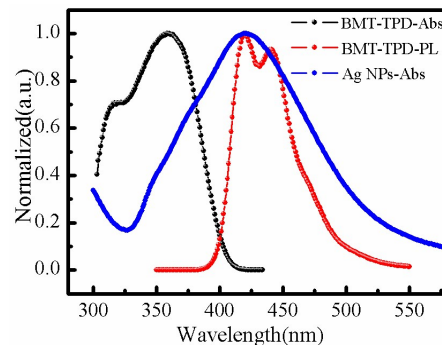


Fig. 3 The LSPR spectrum of 40 nm Ag NPs, together with the absorption and emission spectra of BMT-TPD.

emission spectra of reference device on the pump energy intensity. The gain medium film exhibits an obvious amplified spontaneous emission (ASE) behavior. When it is pumped at low energy, it exhibits a broad spontaneous emission spectrum and the FWHM is about 70 nm. Once the excitation energy becomes large enough, the emission spectrum collapses to a much narrow emission with FWHM of 7 nm. As shown in Fig. 4(a), the ASE threshold of 43.3 $\mu\text{J}/\text{cm}^2$ is then determined.

In order to investigate the emission properties of the device that the gain medium deposited on Ag NPs-Ag film and achieve the optimized condition of lasing, the optimal distance between Ag NPs and Ag film was investigated by changing the SiO₂ spacer thicknesses between them (shown in Fig. 2). For comparison, the devices that gain medium deposited on Ag film (device 2), SIFs deposited on glass (device 3) were also prepared and investigated simultaneously. Figure 4(b)-(d) show the edge-emission spectra of the gain media deposited on Ag film (device 2), SIFs (device 3), and Ag NPs-Ag film with 5 nm-SiO₂ spacer (device 4). We can find Fig. 4(c) and (d) present the discrete peaks in emission spectra above the lasing threshold. For the waveguide-plasmonic scheme of device 3 and 4, the multiple scattering of Ag NPs and waveguide confinement mechanisms provide effective gain channels. A large part of the scattered light may be totally reflected back at the gain medium/air interface to propagate within the waveguide and scattered further by the Ag NPs, then the scattered light is enhanced or amplified by the gain medium through the confinement of the scattered light into the waveguide.²¹⁻²³ In this process, the "round-trip" was formed between the total reflection at the gain medium/air interface and the scattering by the Ag NPs in form of "scattering-total reflection-scattering". Each "round trip" corresponds to a gain process and the lasing action depends on the minimum mean free path length, defined as $l_{\min} = 2n^2d/(n^2-1)^{1/2}$, where n and d are the refractive index and the thickness of the gain medium.²³ In our devices, $n \approx 1.59$, $d \approx 250$ nm, then $l_{\min} \approx 1.02$ μm is obtained. And this minimum mean free path length needs that the separation between the Ag NPs is smaller than $S = l_{\min} \sin \vartheta_c$, where $\vartheta_c = \sin^{-1}(1/n)$ is the critical angle for total reflection at the gain medium/air interface, then $S \approx 0.64$ μm is obtained. As shown in Fig. 1, the separation between the Ag NPs is always smaller than the S . Therefore, the random lasing could occur shown in Fig. 4(c) and (d).

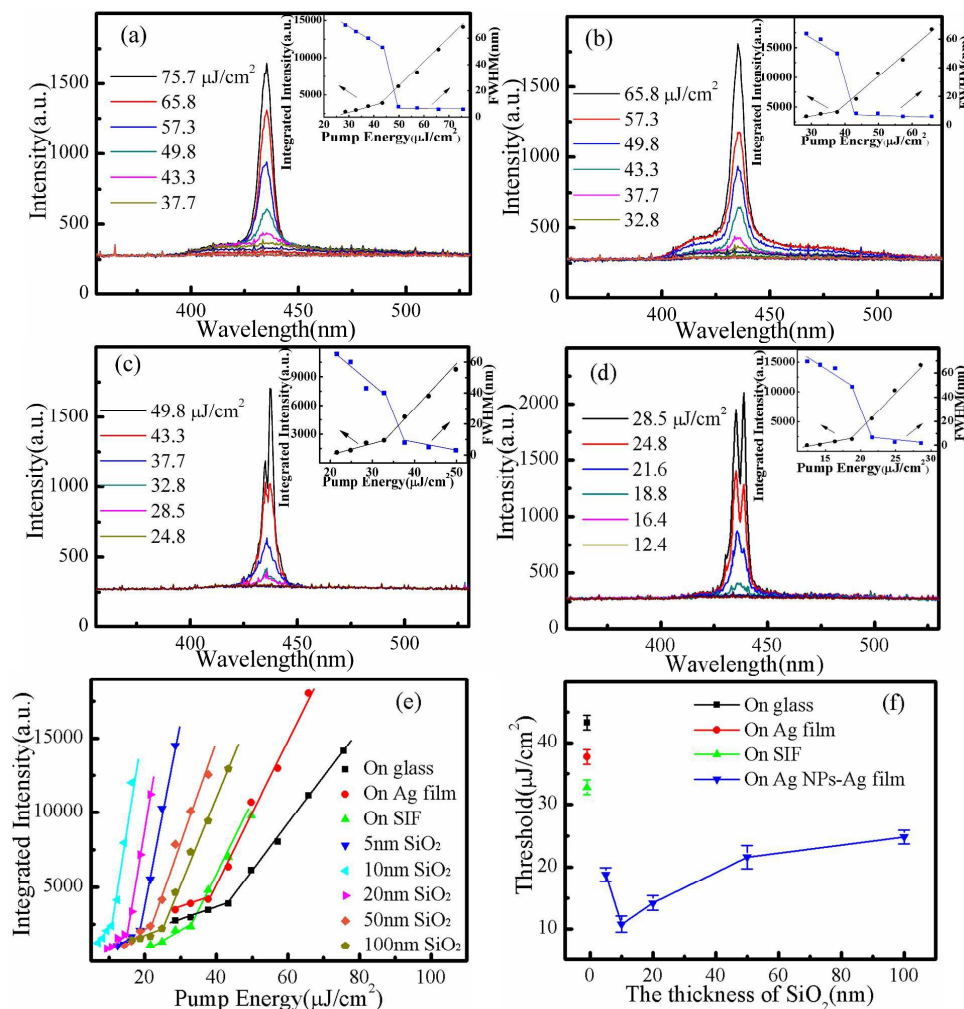


Fig. 4 The emission spectra of the devices that gain media deposited on (a) glass (device 1), (b) Ag film (device 2), (c) SIF deposited on glass (device 3), (d) Ag NPs-Ag film hybrid structure with 5 nm SiO₂ spacer (device 4). The insets show the dependence of the integrated emission intensity and the FWHM of the emission spectra on the pump intensity. For the sharp spikes of spectra appear in (c) and (d), the FWHMs above the lasing threshold were estimated from those of sharp spikes, instead of that of the broad background. (e) Dependences of the integrated emission intensity on the pump energy intensity for devices with different structures. (f) The lasing thresholds of the gain media deposited on glass (device 1), Ag film (device 2), Ag NPs (device 3), and the Ag NPs-Ag film with different SiO₂ thicknesses.

From the inserts of Fig. 4(b)-(d), we can know that the lasing threshold of device 4 is lower than that of device 2 and device 3. Therefore, comparing with independent Ag NPs and Ag film, the Ag NPs-Ag film hybrid structure could more effectively enhance the lasing properties. At the meanwhile, the appropriate distance between Ag NPs and Ag film was investigated. Fig. 4(e) illustrates the integrated emission intensity as a function of pump energy for devices based Ag NPs-Ag film with different SiO₂ thicknesses of 5, 10, 20, 50, and 100 nm. And Fig. 4(f) shows the thresholds of the gain media deposited on glass (device 1), Ag film (device 2), SIFs (device 3), and the Ag NPs-Ag film with different SiO₂ thicknesses, which are shown in Table 1. It is found that the thresholds of devices based Ag NPs-Ag film are all lower than that of the gain media

deposited on the other substrates. And for the devices based Ag NPs-Ag film, they show that with the increasing of SiO₂ thickness, the lasing threshold reduces at first, and then increases. The lowest lasing threshold of 10.8 μJ/cm² is found when the SiO₂ thickness is 10 nm.

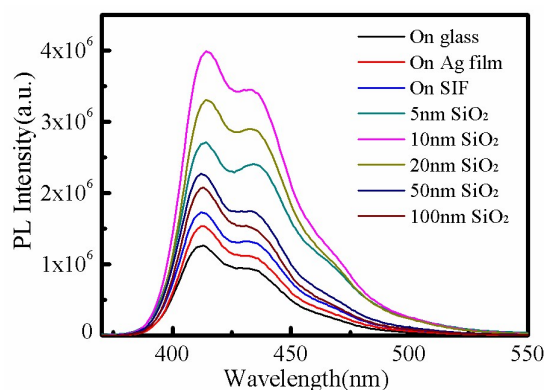
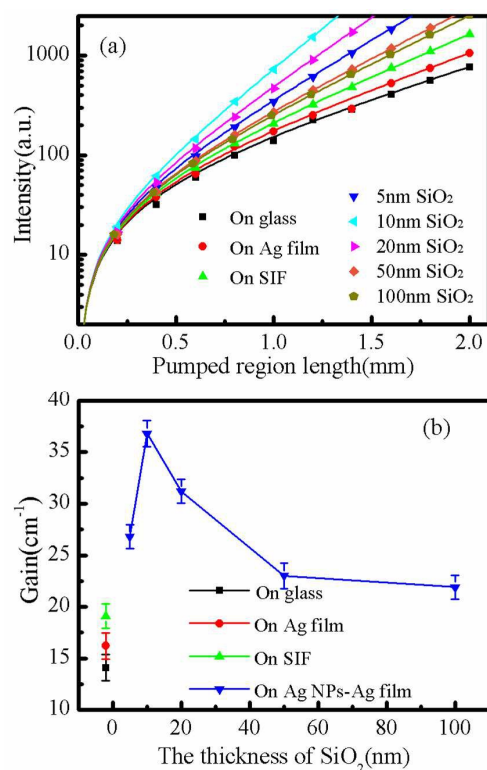
In order to demonstrate the enhancement of the devices based Ag NPs-Ag film hybrid structure, the net gains of those devices were studied in detail. The gains were measured by the variable-stripe-length method which observes laser emission from the film edge as a function of excitation length. The output emission $I(\lambda)$ should obey the following:²⁴

$$I(\lambda) = \frac{A(\lambda)I_p}{g(\lambda)}(e^{g(\lambda)L} - 1) \quad (1)$$

Table 1 The characteristics of the devices that gain media deposited on glass (device 1), Ag film (device 2), SIF (device 3), Ag NPs-Ag film with different SiO₂ thicknesses.

Parameters	On glass	On Ag film	On SIF	On Ag NPs-Ag film				
				5nm	10nm	20nm	50nm	100nm
Peak(nm)	355.2	355.2	355.4	354.9	355.3	355.1	355.4	354.8
FWHM(nm)	7.8	7.2	3.2	3.1	2.8	2.9	3.1	2.9
Threshold($\mu\text{J}/\text{cm}^2$)	43.3	37.7	32.8	18.8	10.8	14.2	21.6	24.8
Gain(cm^{-1})	14.1	16.2	19.1	26.8	36.8	31.2	23.0	21.9
FE	1	1.2	1.4	2.2	3.2	2.6	1.8	1.7

Where $A(\lambda)$ is a constant related to the cross section, I_p is the pump intensity, g is the net gain coefficient, and L is the length of the pumped stripe. Figure 5(a) shows the spectra intensities of gain media with different device structures, each as a function of excitation length at $58.6 \mu\text{J}/\text{cm}^2$ pump influence. The experimental data and the solid curves in Fig. 5(a) are then fitted with Eq. (1), and giving net gains are shown in Table 1. Fig. 5(b) shows the gain of media deposited on glass (device 1), Ag film (device 2), SIF deposited on glass (device 3), and Ag NPs-Ag film with different SiO₂ thicknesses. In Fig. 5, it found that the gain of device 4 based Ag NPs-Ag film hybrid structure with 5 nm SiO₂ spacer is larger than that of device 2 and 3. Therefore, comparing to the independent Ag NPs and Ag film, the Ag NPs-Ag film hybrid structure could more effectively enhance the gain. And for the devices based Ag NPs-Ag film, with the increasing of SiO₂ thickness, the gain increases at first,

**Fig. 6** The fluorescence spectra of the gain media deposited on glass (device 1), Ag film (device 2), SIF (device 3), and the Ag NPs-Ag film with different SiO₂ thicknesses.**Fig. 5** (a) Dependences of emission intensity on the excitation length at $58.6 \mu\text{J}/\text{cm}^2$ pump intensity for different devices. (b) The gains of different devices.

and then reduces. The maximum of net gain is achieved when the thickness of SiO₂ spacer is 10 nm, which leads to the lowest lasing threshold of organic gain media.

At the same time, the fluorescence spectra of the different devices were also measured and shown in Fig. 6. It shows that the fluorescence intensities of devices that gain media deposited on Ag NPs-Ag film are stronger than that on glass, Ag film, SIF. Table 1 shows the fluorescence enhancement factor (EF) of different devices, which defined as the ratio of the fluorescence peak that gain media deposited on different substrates to the peak that deposited on glass. And there is the strongest fluorescence from the gain medium deposited on Ag NPs-Ag film with 10 nm SiO₂, which shows the EF of 3.2 shown in Table 1.

As we know, the metallic nanostructures are used to enhance the lasing, the two different mechanisms are accepted as: (a) Enhancement of localized electromagnetic (EM) field and (b) Enhancement of scattering strength.¹³ When the localized EM field is enhanced, it can increase the density of pump light for the gain media, and increase the probability that more molecules are excited to the higher energy levels, then the excitation rate is enhanced. In the meantime, the quantum yield and radiative decay rate could also be increased. In addition, the metallic NPs could also scatter the emitter energy with the greater scattering cross sections, the lasing threshold is reduced.

For one of the mechanism of enhanced localized EM field, when the frequency of incident light is located in the range of

the resonant frequency of metallic NPs, the resonance will occur to form the LSPR effect.²⁵ And for the metallic film, the SPP exists at the interface between the metallic film and medium, spreads along the metal surface. The light can directly excite the LSPR of metallic NPs, but it cannot directly couple to the SPP of metallic film because of the inherent mismatch between the SPP wavevector and that of the photons traveling in the air region.²⁶ As seen from the SPP dispersion relations, the SPP wavevector is always larger than the photon wavevector. Thus the wavevector compensation for the photons should be provided to match the SPP wavevector. Researches have shown that for the rough surface on metallic film, the SPP excitation conditions can be achieved without any special arrangements.^{26,27} In our device, for the randomly distributed Ag NPs structure on metallic film, the diffraction of light on rough metal surface could provide wavevector compensation for the excitation of SPP on metallic film. This is since in the near-field region the diffracted components of light with all wavevectors are presented on rough surface.^{26,27} Thus, the Ag NPs could provide an indirect way to excite the SPPs of the Ag film by the diffraction effect. And the SPP can be excited in the hybrid structure.

In order to investigate the enhanced localized electric-field of the Ag NPs-Ag film hybrid structure, the simulations of electric-field distribution of the Ag NPs-Ag film with different thicknesses of SiO₂ spacers between Ag film and Ag NPs were performed using the COMSOL software. Figure 7 shows the electric-field distribution of Ag NPs (Fig. 7(a)) and Ag NPs-Ag film hybrid structure with incident plane wave at 435 nm which is wavelength of emission light, the SiO₂ spacer thicknesses between the Ag film and Ag NPs are 5, 10, 20, 50, 100 nm, respectively, corresponding to the Fig. 7(b)-(f). Consequently, it is found that the stronger field enhancement

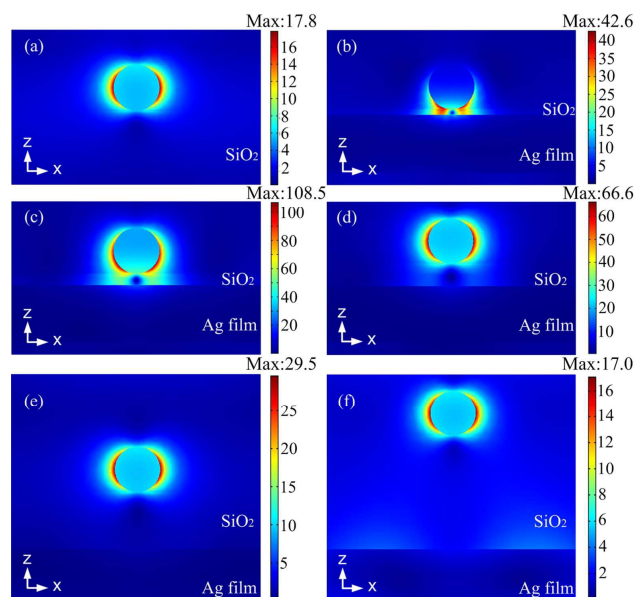


Fig. 7 The electric-field distribution of (a) Ag NPs on SiO₂ without Ag film, Ag NPs and Ag film with (b) 5 nm, (c) 10 nm, (d) 20 nm, (e) 50 nm and (f) 100 nm SiO₂ spacer.

can be obtained in case of the hybrid structures comparing with that of Ag NPs only. And we can know that the electric-field intensity of hybrid structure strongly depends on the distance between Ag NPs and Ag film, with the increasing of SiO₂ thickness, the localized electric-field intensity of hybrid structure increases at first, and then reduces, there is the strongest electric-field when the SiO₂ thickness between Ag film and Ag NPs is 10 nm, which corresponds to the device with lowest lasing threshold. In addition, when the distance between Ag film and Ag NPs is 100 nm, the electric field intensity is about the same as that of Ag NPs only, which suggested that there is no plasmon coupling interaction between LSPR of Ag NPs and SPP of Ag film when the distance between Ag film and Ag NPs is large. Thus the corresponding lasing threshold of device with 100 nm SiO₂ spacer is higher than that of devices with other SiO₂ spacer. The Fig. 7 confirmed the intense localized electric field of hybrid structure due to the plasmon coupling interaction between LSPR of Ag NPs and SPP of Ag films, which plays the important role in dramatic enhancement of lasing.

In order to explain the results of Fig. 7, the extinction spectra of the Ag NPs-Ag film in Fig. 7 were calculated. According to the previous studies on the interplay between LSPR of metallic NPs and SPP of metallic film, the localized plasmon resonance wavelength and electric field enhancement of metallic NPs-metallic film hybrid structure are found to strongly depend on the distance between the metallic particle and the film.²⁷⁻²⁹ Fig. 8(a) shows the extinction spectra, which represent surface plasmon resonance, as a function of the SiO₂ spacer thickness between Ag NPs and Ag film. It reveals that the plasmonic resonance wavelength undergoes a blue shift as

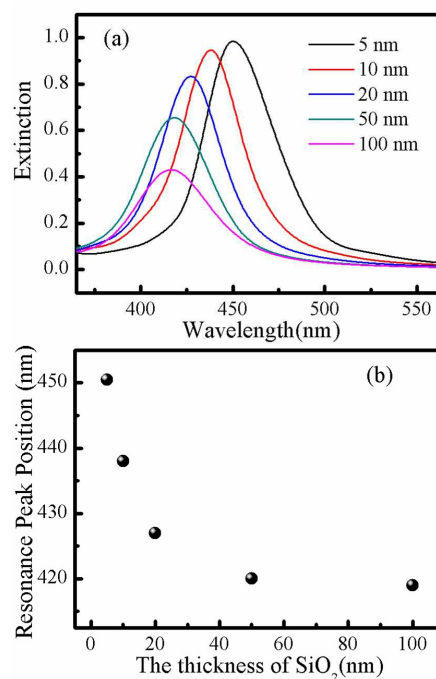


Fig. 8 (a) the extinction spectrum as a function of the spacer thickness between Ag NPs and Ag film; (b) the plasmon resonance wavelength as a function of the spacer thickness.

the distance between the particle and the film is increased, which is consistent with previous work.^{27,29-31} Fig. 8(b) shows plasmon resonance wavelength as a function of the SiO₂ spacer thickness. It shows that when the SiO₂ spacer between Ag NPs and Ag film is 10 nm, the plasmon resonance wavelength, 438 nm, is closer to the lasing emission wavelength (435 nm) than that with 5 nm SiO₂ spacer (451 nm), thus it could lead to a stronger electric field than that of the hybrid structure with 5 nm SiO₂ spacer shown in Fig. 7. When the SiO₂ spacer becomes 20 nm, the plasmon resonance wavelength is blue shifted, which is far away from the lasing emission wavelength, thus the electric field is reduced compared that of the hybrid structure with 10 nm. With the spacer further increasing, the plasmon coupling effect becomes weaker, the electric field would be further decrease shown in Fig. 7.³² Therefore, the hybrid structure with 10 nm SiO₂ layer has the strongest electric field. As a result, the device with 10 nm-SiO₂ spacer has the lowest lasing threshold and strongest lasing.

For another mechanism of scattering effect, comparing with the Ag NPs, the scattering effect of Ag NPs-Ag film hybrid structure is stronger. Theoretical and experimental have already verified that the emitted light which attempts to escape from the gain medium could be reflected and reinjected into gain medium by the external feedback of metallic films.³³⁻³⁵ Fig. 4 shows the device based hybrid structure with 100 nm SiO₂ spacer has lower threshold than that the device based independent Ag NPs, this phenomena is attributed to the stronger scattering effect due to the external feedback of Ag film (the electric field intensity of two structures is about the same shown in Fig. 7). Therefore, comparing with the independent Ag NPs or Ag film, the two mechanisms of localized EM field and scattering effect are all stronger for the Ag NPs-Ag film hybrid structure, which lead to the significantly enhanced lasing.

4. Conclusions

In summary, the way to avoid the negative effect of metallic film on the lasing has been an important issue for the electrical pumped laser. In this article, we developed a specific Ag NPs-Ag film hybrid structure, and demonstrated a dramatic enhancement of lasing in the optically pumped planar waveguide structure. Comparing with the devices that gain media deposited on glass, Ag film, SiF, the lowest lasing threshold of the gain medium deposited on Ag NPs-Ag film hybrid structure was achieved. The field enhancement effect of hybrid structure due to the plasmon coupling of Ag NPs with Ag film plays a significant role on the enhanced lasing. In the meantime, the re-injection of emitted light into the organic gain medium by the external feedback of Ag film could also enhance the lasing properties. To the best of our knowledge, it is the first time to use the metallic NPs-metallic film hybrid structure to enhance lasing properties, which could effectively avoid the negative effect of metallic film and realize the lower pumped threshold. And based on those advantages of hybrid structure, for the exploration of electrical pumping, the dielectric layers in metallic NPs-metallic film in our experiment

could be substituted by the conducting material under electrical pumping for further research.

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Graphical Abstract

A dramatic enhancement of lasing in organic gain medium was achieved, assisted by metallic nanoparticles - metallic film hybrid structure.

