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Transverse localization of Tamm plasmon in metal-DBR structure with disordered layer*

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Transverse localization of the optical Tamm plasmon (OTP) is studied in a metal-distributed Bragg reflector (DBR) structure with a one-dimensional disordered layer embedded at the interface between the metal and the DBR. The embedded disordered layer induces multiple scattering and interference of light, forming the light localization in the transverse direction. This together with the formation of Tamm plasmonic modes at the metal-DBR interface (i.e., the confinement of light in the longitudinal direction), gives birth to the so called transverse-localized Tamm plasmon. It is shown that for both transverse electric (TE) and transverse magnetic (TM) polarized light injection, the excited transverse-localized Tamm plasmon broadens and splits the dispersion curve due to spatial incoherence in the transverse direction, thus proving the stronger light confinement especially in the TE polarized injection. By adding the gain medium, specific random lasing modes are observed. The proposed study could be an efficient way of trapping and locally enhancing light on a subwavelength scale, which is useful in applications of random lasers, optical sensing, and imaging.

Keywords: optical Tamm plasmon, light localization, random laser, distributed Bragg reflector

PACS: 73.20.–r, 71.36.+c, 78.67.–n, 78.67.Pt **DOI:** 10.1088/1674-1056/27/8/087301

1. Introduction

Light localization has been extensively investigated in recent years since its potential applications in many fields, such as photonic integrations, optical manipulation, optical sensing, novel light source designing, light harvesting, etc.[1–9] It is known that light localization in a structured optical medium resembles that of electrons in solids,[1,3] causing the propagation of photons to be completely suppressed on account of the interference effect of multiple scattering waves in the scattering medium.[7–9] Usually, light localization can be obtained in many optical structures, such as microcavities, photonic crystals with defects, surface plasmon devices, and disordered nanostructures.[4–6] A relatively hot research branch of the light localization is the transverse localization, proposed first by Raedt *et al.* in 1989.[8] In 2007, Schwartz *et al.* observed the transverse localization experimentally for the first time by using two-dimensional (2D) photonic crystals.[2] Since then, the observation of the transverse localization has been reported sequentially in optical fiber,[7] disordered optical waveguide,[10] triangular optical lattices,[11] and so on.

Optical Tamm plasmon (OTP) is defined as a confined optical mode localized at the crystal surface, which was proposed at the beginning of the 21st century and opened up an attractive research subject.[12] The OTP can confine light at interface between two different DBRs or interface between a metal film and a DBR.[13–17] Compared with normal surface plasmon, OTP can be excited by both transverse electric (TE) and transverse magnetic (TM) polarized light with a much narrower resonance peak,[14–17] and it provides comparable or even stronger field enhancement. In addition, the OTP can find various applications, such as in high-performance low-cost hot-electron photodetection,[18] wavelength selective thermal emitters,[19] compact lasers, bistable switch, photovoltaic devices, filters, and optical sensors.[20–30] However, the confinement of OTP in the direction parallel to the interface between the metal and the DBR, i.e., the so-called transverse localization of OTP, is less studied currently.

Here, an OTP structure is presented by introducing a disordered layer at the interface of a metal-DBR structure, and transverse light localization at the interface (i.e., transverse localized Tamm plasmon) is demonstrated theoretically. Due to scattering of the disordered layer, several localized modes could be formed, showing spatially incoherent characteristics in the transverse direction. On the other hand, field distribution of the localized modes is also well confined in the longitudinal direction through the formation of OTP, providing considerably stronger intensity enhancement than the scenario of regular OTP. Besides, eigen wavelengths of the localized modes are also tailored by the dispersion relation of Tamm plasmon,

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thus broadening the bandwidth and inducing partially-random resonances. The proposed way of forming transverse OTP provides a novel way to trap light and form a spatially dependent mode of light-matter interaction, which is significant for realizing the optical control devices and random lasers in applications of imaging, sensing, and light harvesting.

2. Numerical results and analysis

Schematic diagram of the proposed structure is given in Fig. 1(a). In the order from top to bottom, the three sections are the metal layer, the disordered layer, which can provide light scattering,[31] and the DBR. In the simulation, a TiO_2/SiO_2 periodically alternate-layered Bragg mirror is covered by an Ag film. Transverse disorder is introduced into the structure by replacing the homogeneous top TiO_2 layer with a one-dimensional (1D) disordered layer with alternate TiO_2/air sections on a sub-wavelength scale in the y direction (we did not introduce the transverse disorder into the Ag film to avoid exciting the surface plasmon) as indicated in the subplot of Fig. 1(a). The width of the random layer is chosen randomly between 100 nm and 800 nm, whose scale is comparable to the wavelength, and can influence scattering and interference efficiently. In our study, the period of the DBR is 10, and thickness of the TiO_2/SiO_2 layer is $\lambda/4n_{1,2}$ ($\lambda = 550$ nm, $n_{1,2} = 1.47$ and 2.10, which correspond to the refractive indices of the SiO_2 and the TiO_2, respectively). Thickness of the metal layer is 30 nm. The results are analyzed numerically through the finite element method.[32]

First, we consider the case where there is no disordered layer in the top dielectric layer (case 1). The reflection spectrum of the homogeneous Tamm plasmon is given in Fig. 1(b), and the well-known dip that corresponds to the formation of OTP is observed at 608 nm within the bandgap of the DBR mirror.[12–17,20] The dip wavelength as a function of the injection angle is shown in Fig. 1(c), reflecting the nondegeneracy of dispersion characteristics of the TE- and TM-polarized modes when the injection angle is nonzero. Second, we consider the case that the Ag film is removed and the top dielectric layer is disordered (case 2). Reflection spectra in Figs. 1(d) and 1(e) indicate that the disordered layer will cause the reflectivity to fluctuate within the DBR's bandgap. Besides, the TM mode is much more influenced by the introduced randomness. This is because the continuous condition of the x-direction electric field between different sections of the random layer is supposed to induce stronger scattering of light than that of the x-directional magnetic field. In the successive study, the whole structure, i.e., both the metal layer and the disordered layer (case 3), will be discussed in detail. As the structure is aperiodic, perfect matching layer boundary conditions are used in the simulation.

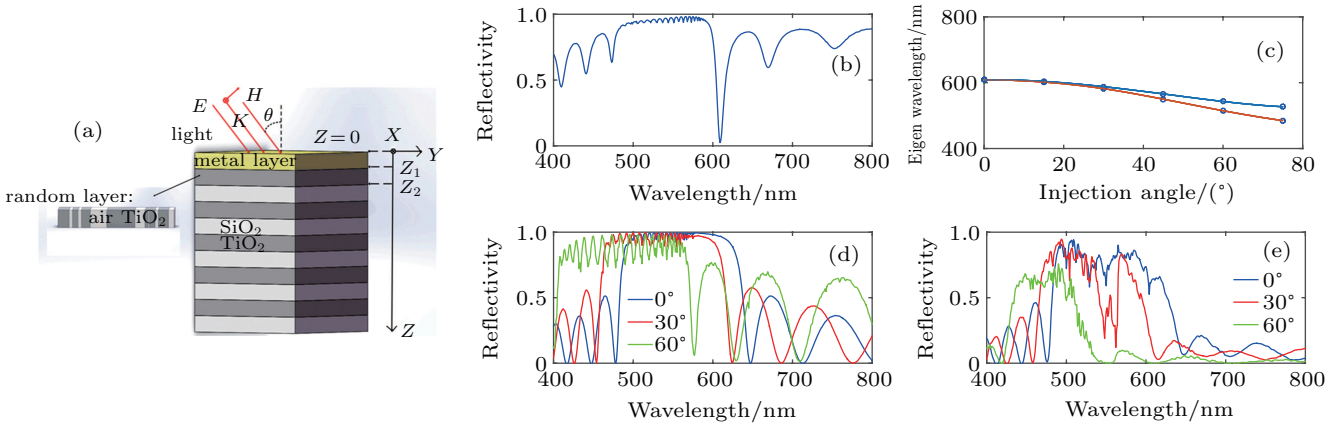


Fig. 1. (color online) (a) Schematic diagram, (b) reflection spectrum of case 1 at zero injection angle, (c) dispersion curves of case 1, (d) TE-polarized reflection spectra of case 2, and (e) TM-polarized reflection spectra of case 2.

Dispersion characteristics of the transverse-localized OTP are discussed through reflection spectra of different injection angles as given by Fig. 2. In Figs. 2(a) and 2(b), the TM polarized mode is considered. It is observed that dip/dips appears/appear within the DBR bandgap, which corresponds to the formation of OTP, i.e., incident waves at eigen wavelengths can resonate with the OTP and enter into the structure. In addition, the homogeneous OTP will be redistributed in the transverse direction due to the random scattering of light in the disordered layer. Thus, bandwidths of these dips are broadened and even split, which is obvious for an injection angle between 2° and 50°, reflecting the spatial incoherence of light localization in the transverse direction.

Figure 2(b) shows the reflectivity versus injection angle and wavelength. The blue region corresponds to the dip(s) in the reflection spectrum, and its variation reflects dispersion characteristics of the structure. We can see that the localized modes still obey the dispersion relationship defined by the homogeneous OTP, indicating that these localized modes are mediated by the excitation of OTP. For example, only those that

are close to eigen wavelengths of the OTP can be supported by the proposed structure, i.e., the so-called transverse localization of OTP. For the TE-polarized injection, splitting of the reflection dips is more obvious (see Figs. 2(c) and 2(d)). This reflects the stronger transverse localization of OTP, which is consistent with the results of Fig. 1(e).

To observe the photon localization phenomenon, electric field distributions in the neighborhood of dip wavelength for cases 1, 2, and 3 are given in Figs. 3(a)–3(c), respectively. In case 1, the electric field is mainly confined near the metal-DBR interface (for $z \approx -30$ nm), i.e., the so-called homogeneous OTP. In case 2, the electric field is distributed in almost the whole structure, with weak and random fluctuations of intensity. In case 3, a few peaks of the electric field are observed near the metal-DBR interface, and appear randomly in the transverse direction (i.e., the y direction), indicating that the laser beam is localized at the random layer position, which is called transverse localization of light.

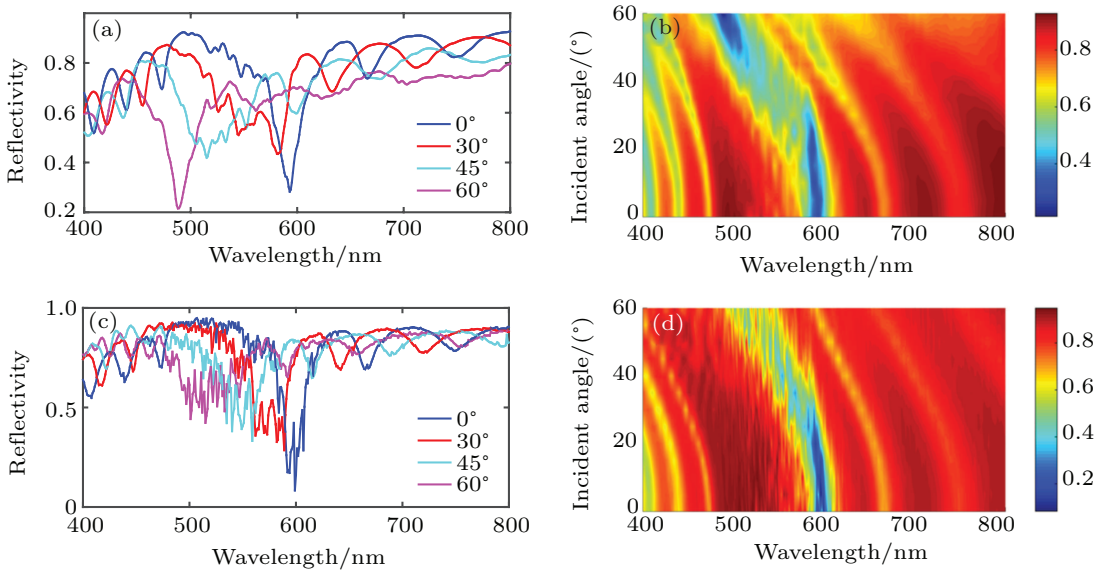


Fig. 2. (color online) (a) TM-polarized spectra, (b) TM-polarized reflectivity versus injection angle and wavelength, (c) TE-polarized spectra, and (d) TE-polarized reflectivity versus injection angle and wavelength.

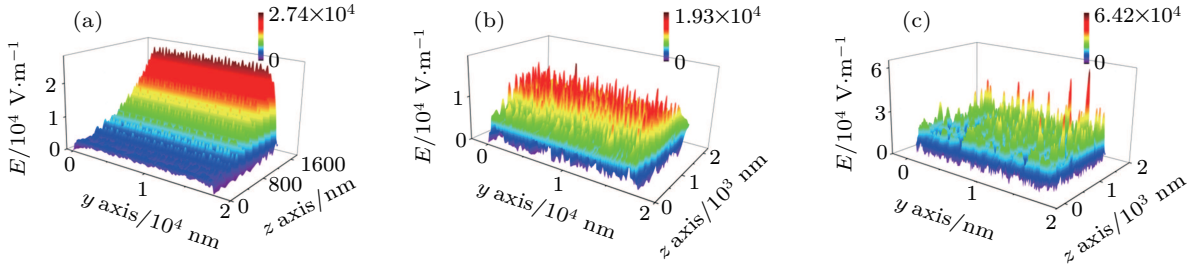


Fig. 3. (color online) Electric field distributions. (a) Case 1 for injection angle 0 and injection wavelength 609 nm; (b) case 2 for injection angle 0 and injection wavelength 644 nm, (c) case 3 for injection angle 0 and injection wavelength 599 nm.

The plots of normalized electric field distribution $|E/E_0|$ (where E is the electric field intensity and E_0 is the electric field intensity of the incident light) versus the transverse location and the injection wavelength for a fixed value of z ($z = 62.738$ nm) are shown in Fig. 4, and Figs. 4(a) and 4(b) correspond to the TM and TE polarization respectively. As is well known, the multiple scattering of light inside the random system results in light localization for some specified wavelengths and the formation of bright spots.[11,33,34] In our case, several bright spots relate to localized modes appearing randomly in the y direction and varying with wavelength. Besides, the field enhancement of the TE-polarized mode is stronger than that of the TM-polarized mode, and light spots concentrate more at some positions in Fig. 4(b), indicating that the localization of light is more likely to occur when the TE-polarized light is injected. Meanwhile, wavelengths of the localized modes are also tailored by conditions of forming OTP, and they only show partial randomness.

Besides using the proposed structure (case 3), we also calculate the wavelength shift of the reflection dip at 594 nm when increasing the refractive index of the air gap. The sensitivity (the minimum detection limit of this sensing structure) is found to be ~ 100 nm per refractive index unit, which is better than the reported result in Ref. [35] in which an OTP structure is used without random layers.

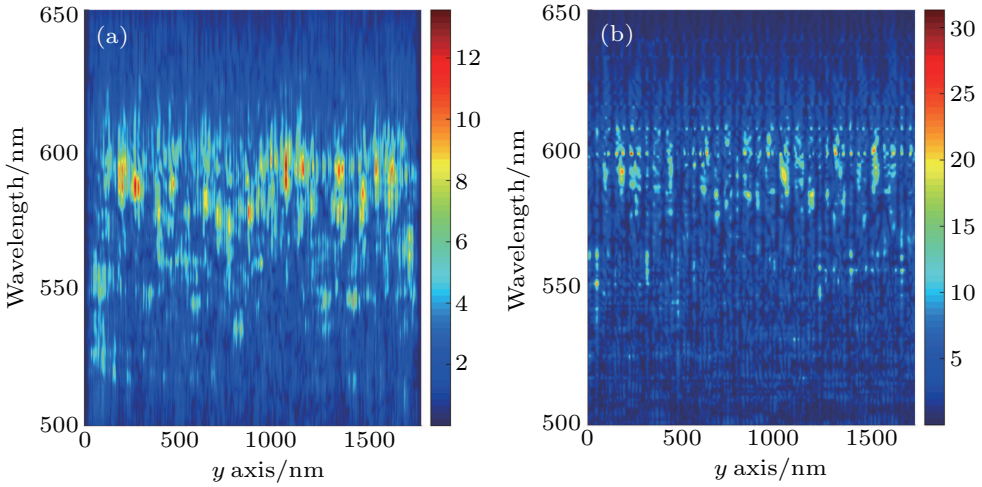


Fig. 4. (color online) Plots of normalized electric field distribution versus transverse location and wavelength, and panels (a) and (b) correspond to the injection angle of 0° for TM and TE polarizations, respectively.

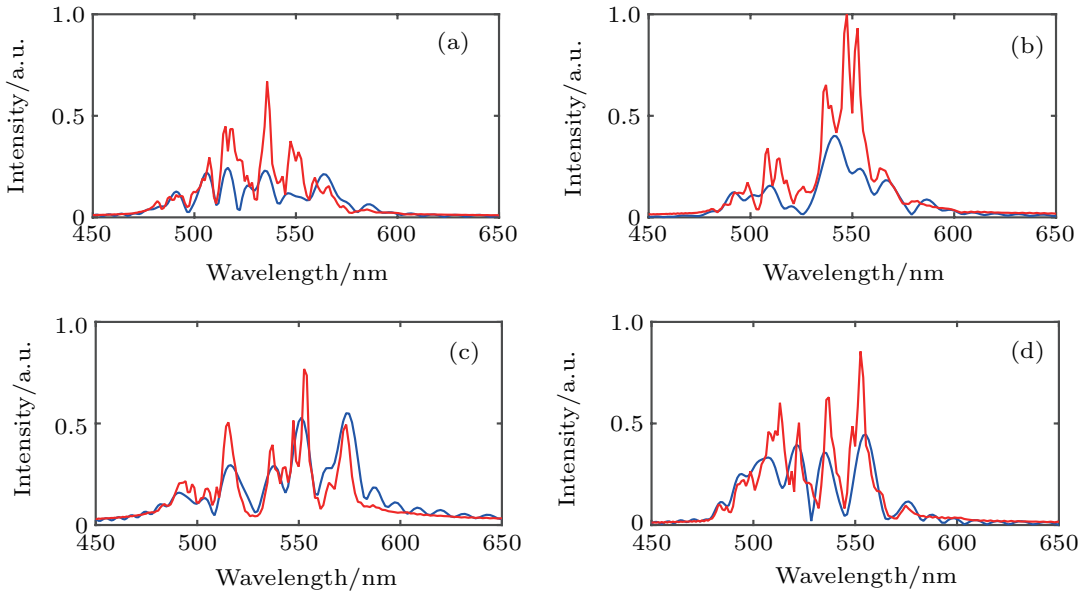


Fig. 5. (color online) Lasing spectra of four different monitoring positions: (a) P1 (10182.4 nm, 126.276 nm, 0 nm), (b) P2 (12958.2 nm, 126.276 nm, 0 nm), (c) P3 (3251.88 nm, 126.276 nm, 0 nm), and (d) P4 (3063.57 nm, 126.276 nm, 0 nm). The red and blue curves correspond to the cases with and without the consideration of gain, and the intensity of blue curve is enlarged 5 times just for being seen clearly. The unit a.u. is short for arbitrary units.

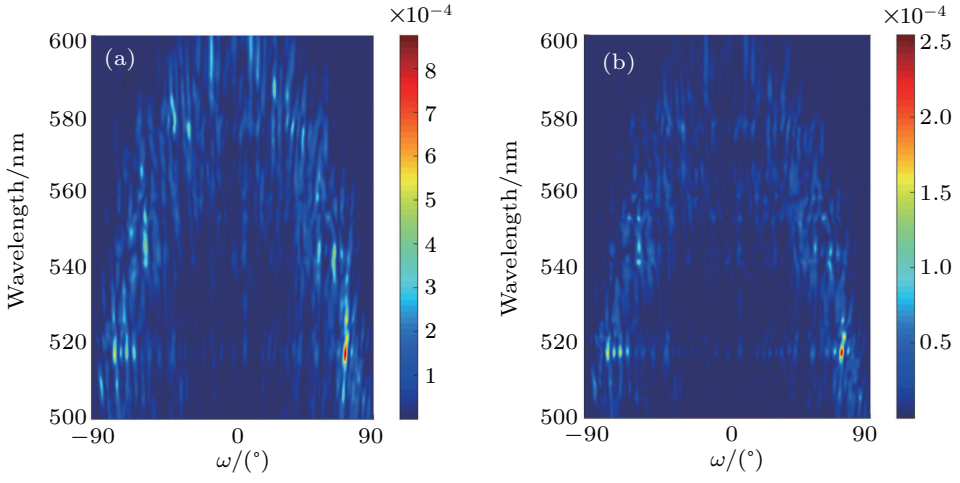


Fig. 6. (color online) Far-field intensity pattern without and with consideration of gain in the random layer of case 3, and air in the random layer is replaced by a medium whose refractive index is 1.31 in the case without consideration of gain (ω is azimuth angle)

Strong scattering and amplification are necessary conditions for random lasing. In the successive study, the air gap in the random layer is replaced by a gain medium, which is the amplification mechanism introduced into case 3. To simulate this, dipoles' sources are used in the center of each gain medium to mimic spontaneous light emission, and the gain medium is defined by the well-known Lorentz model with a central wavelength of 550 nm and bandwidth of 64.2 nm.[36] Figure 5 gives the spectra at four different random monitoring points, P1–P4, with (the red curves) and without (the blue curves) consideration of the gain medium. It is obvious that the random laser modes will be emitted selectively when gain is considered, and part of the resonance modes of the structure will be selected by the gain profile and become dominant.[31] For example, a few modes near the peak of the gain profile (around 550 nm) increase their intensity many times, which is a typical characteristic of lasing. Moreover, the laser spectrum varies notably for different monitor positions, indicating spatial incoherence and strong localization of the lasing system.

Finally, far-field intensity patterns with and without consideration of gain in the random layer of case 3 are given in Fig. 6. As is well known, the far-field radiation reflects the superposition of all the localized modes in the proposed structure. It is observed that the far-field pattern shows angle-dependent luminescence that grossly obeys the dispersion relationship of the TP, while the bright spots show partial randomness due to the scattering of the random layer. When gain is added, only a few lasing modes are selectively emitted, which is a typical characteristic of TP tailored random lasing.

3. Conclusions

In this work, we propose a scheme to realize strong confinement of light in a Tamm plasmonic structure embedded in a disordered layer. Through the combined effect of light confinement at the metal-DBR interface and random light scattering and interference in the disordered layer, the transverse localization of Tamm plasmon is obtained. The new formed Tamm plasmon shows stronger light confinement with an inhomogeneous distribution of eigen modes as well as broadened and split dispersion curves. When gain is introduced into the structure, a random laser can be emitted, showing a partially random emission pattern that is tailored by the dispersion relationship of the TP. The proposed device could be useful for light trapping and enhancement in applications of random lasers, optical sensing, and imaging. The unique advantage of this work in sensing applications is that the transverse localization of OTP has a sharper dip as well as a larger quality factor than that of surface plasma (SP), and different localization modes correspond to different dips, which can be used to realize position-dependent sensing.

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