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Planar Hyperbolic Metamaterials Enhanced Spontaneous Emission of Two-Dimensional Transition Metal Dichalcogenide (TMDC) Atomic Layer

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Abstract

In this work, we investigated the effect of spontaneous emission enhancement and strong coupling of 2D materials with planar-type hyperbolic metamaterials (P-HMMs). One-dimensional P-HMMs, which support high k modes and strong coupling, perform better than common multilayer hyperbolic metamaterials (HMMs).

1. Introduction

Nowadays, two-dimensional transition metal dichalcogenide (TMDC) is widely noted for its direct band gap light emission and weak quantum yield. In this study, we enhance the spontaneous emission by P-HMMs which possessed some extraordinary characteristics like high anisotropy, supporting high k states and near field coupling [1].

There are many researches for putting emitters on top or embedded in the multilayers HMMs to show the radiative decay rate enhancement. For example, Vinod M. Menon group [2] and V. M. Shalaev group [3] utilized dye gain medium or quantum dots on top of HMMs to achieve the spontaneous emission enhancement and reduction of life time. However, on isofrequency curve the direction of wave vector isn't along HMMs metal/dielectric period, and thus produces weak coupling and light matter interaction. Therefore, we try another design based on Xiang Chang group's demonstration [4], which talked about the miniaturization of HMMs could further enhance the photon density and the mode profile of electric field was well confined perpendicularly to the layers stacked. Making 1D P-HMMs have periodic grating in in-plane direction and putting MoS_2 on top of it, MoS_2 atomic layer will have better light-matter interaction with the leakage from top of P-HMMs.

2. Experiment and Results

To realize the metal/SiO_2 P-HMMs gratings, we set the period and width of gratings as 70 nm and 35 nm for achieving anisotropy, as shown in Fig. 1(a). Next, we chose the transparent sapphire polished on both side as the substrate. 30 nm thick gold film was evaporated on the sapphire by E-gun evaporation method. The subwavelength gratings were patterned on the metal film and cut through by focus ion beam (FIB). Further, to prevent the huge radiation loss from direct contact of metal, the SiO_2 spacer layer was deposited 10 nm thick to fill up the air gaps between metal gratings by plasma-enhanced chemical vapor deposition (PECVD). Finally, monolayer MoS_2 was transferred onto Au/SiO_2 gratings to finish our design (Fig. 1(b)).

(a) (b)

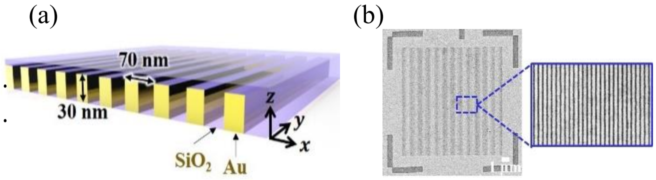

Fig. 1 (a) Schematic of the designed P-HMMs and the defined Cartesian coordinate. (b) SEM images of the Au/SiO_2 gratings.

The calculated effective permittivity of $\varepsilon_{\perp}$ *and* $\varepsilon_{/\!/}$ at the emission wavelength of MoS_2 were around -4.96 and 5.7, which agreed with the assumption that fill fraction of 0.5 would have anisotropic property of HMMs (Fig. 2(a)). As for measurement, the MoS_2 was optically pumped at room temperature by 532 nm continuous wave laser with 1 mW to examine how P-HMMs influence the optical characteristics. Fig. 2(b) showed the photoluminescence(PL) spectrum of MoS_2 with and without P-HMMs. First, we could see a peak at 665 nm for MoS_2 with P-HMMs and 660 nm for only MoS_2. Besides, there are other two peaks around 630 and 700 nm being observed in our PL spectrum. By searching the PL or Raman peak of materials in our device, we found out the main two signals at 630 and 700 nm were respectively originated from the Raman peak of PMMA residual and PL peak of sapphire. Most important of all, the PL spectrum of MoS_2 on P-HMMs showed the spontaneous

(a) (b)

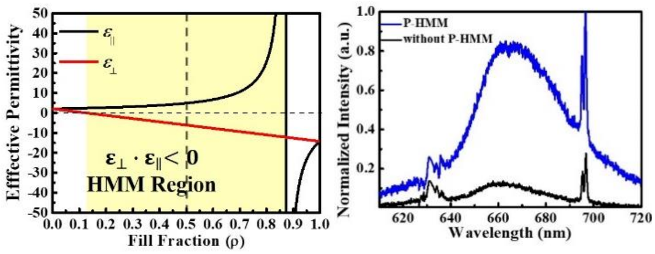

Fig. 2 (a) Dispersion of effective permittivity at the wavelength of 660nm. (b) PL spectrum of MoS_2 on P-HMMs and on surface.

emission intensity was enhanced about five times compared to that of MoS_2 on bare uniform surface. This broadband enhancement could be explained by the concept of HMMs which could support the large wave vector (high k mode) and thus gave radiative decay rate enhancement.

To understand more details of emission from the MoS_2/P-HMMs device, the PL spectra from the different pumping position were characterized. We defined the edge and center of P-HMMs as $Edge_A$, $Edge_B$ and Center which were plotted in the Fig. 3(a). Then, Fig. 3(b) showed the corresponding PL spectrum of different area. In this plot, the PL intensities on edges were slightly higher than the center part. Especially, the $Edge_A$ performed the highest PL intensity than the other. The reason of intensity variation could be explained by isofrequency in the x-y plane which was shown in the Fig. 3(c). Due to the size of P-HMMs, the wave vector inside would be relative small. It caused near zero value of k so that the total k was approximated to k_y. The lack of the k_x in P-HMMs caused the confinement in x direction and let the waves only propagate through y direction. Therefore, the waves were resonant in y direction and part of light leaked out the grating. That was the reason why high PL intensity was emerged at the edges of P-HMMs, and the highest shown at $Edge_A$.

For the reassurance to our concept, we used finite element method (FEM) and commercial COMSOL Multiphysics 5.1 modeling software to simulate resonant mode. After searching the Eigen frequency around light emission wavelength of MoS_2, we observed the corresponding mode profile in the structure. For x-y cut plane in Fig. 3(d), the mode profile laid in the dielectric and had confinement in x direction. And for x-z cut plane in Fig. 3(e), the electric field mode profile trapped and looked like an emitter in each dielectric layer due to its high effective index. Also, the confinement in P-HMMs which had no propagation in x direction confirmed our theory that P-HMMs lack k_x. Moreover, from the theory of HMMs, we'd known that the quantum emitters nearby HMMs would couple to high k mode. Therefore, the simulation results showed the well in-plane confinement due to not only the property of HMMs and the gratings structure. On the other hand, compared to the layered HMMs, from z-x cut plane, the mode profile showed the mode overlapping to the top of P-HMMs. It gave the possibility of the strong mode coupling to thin quantum emitter.

3. Conclusions

In summary, we utilized the integration of one-dimensional P-HMMs and two-dimensional MoS_2 monolayer to obtain more than five times of spontaneous emission enhancement. Furthermore, by observing the PL intensity at different locations, we could see the slight enhancement difference between the edge and the center.

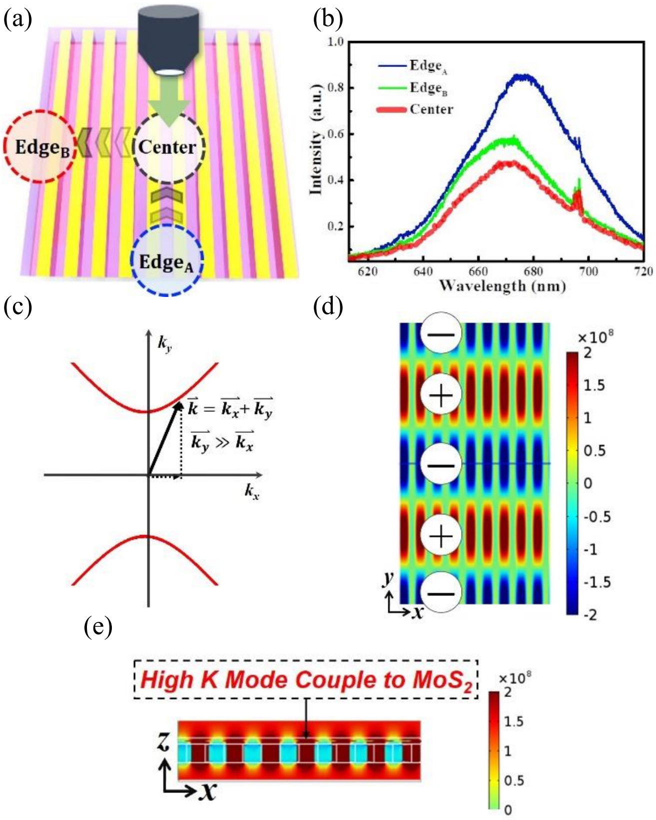

Fig. 3 (a) Illustration of the pumping positions. (b) PL Spectrum of MoS_2 at the different positions. (c) The iso-frequency curve of P-HMMs in x-y cut plane. (d) The x component E-field distribution was shown on x-y cut plane, the cut plane was set and placed on top of SPASER layer to simulate behavior of MoS_2. (e) x-z cut plane.

4. Acknowledgement

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