Surface plasmon coupling in hexagonal textured metallic microcavity

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The coupling of surface plasmons to the photonic modes in hexagonal textured metallic microcavity was studied. The modified photonic modes enable efficient coupling with the luminescence source in the microcavity. Hexagonal photonic crystal lattice has higher folding symmetry providing more channels for surface plasmon coupling in different in-plane directions, i.e., more isotropic light extraction profile than one—or two-dimensional gratings. Results show that strong coupling between surface plasmon modes and the waveguide mode in the microcavity has led to angle-selective enhanced light extraction and it was as much as 12 times more light extracted compare to planar microcavity. © 2006 American Institute of Physics. [DOI: 10.1063/1.2347110]

Surface plasmons (SPs) are generated at a metal/dielectric interface and usually dissipate the excited energy away as heat. However, through designed pattern structure, it is possible to control those interactions and produce optical effects that include, for example, extraordinary optical transmission through subwavelength holes1–3 and periodic structure,4–6 beaming light from a subwavelength aperture,7 full photonic band gap for surface modes in the optical range,8 high gain in surface plasmon band edge,9 plasmonic amplification by stimulated radiation,10 and surface plasmon laser.11 In fact, coupling of surface plasmons to luminescent material can lead to alteration of optical properties such as spontaneous emission rate and emission spectrum due to local field enhancement and photonic density alteration which have been investigated theoretically12 and experimentally.13–22 On the other hand, microcavity structure creates the boundary condition so that the resonance optical mode has large magnitude and thus high local density of state for photons in the resonance energy range in the antinode region. While the density of state in the resonant energy is enhanced, the density of state in off-resonant energy is suppressed in the microcavity. The spontaneous emission rate also can be altered and a number of studies have been made in planar microcavity with inorganic and organic dielectric.23 In this work, we insert a hexagonal periodic texture in a planar metallic microcavity to take advantage of both the field enhancement due to the cavity and the coupling with SP modes in the metal/dielectric interfaces due to the Bragg scattering from the periodic texture. The electromagnetic coupling is reinforced when both the SP mode and the waveguide mode in the cavity are resonant with the same optical wavelength, and this enables the photons inside the cavity to radiate out more efficiently. The suppression of the off-resonant optical mode due to microcavity provides a “clean” environment for studying the characteristics of the scattered SP modes, also coupling of the waveguide mode in the cavity and SP mode which leads to anticrossing in the dispersion relation curve can be investigated. Such changes in photonic modes were observed in textured metallic microcavity.24,25 Moreover, using two-dimensional (2D) rather than one-dimensional periodic nanostructure can recover SP modes propagating in all in-plane directions which are not capable in one-dimensional grating case. Through optically pumped internal luminescence source, detailed surface plasmon coupling to the luminescence and waveguide modes was studied. The coupling between photons and surface plasmons can be achieved whenever Eq. (1) is satisfied,

\[ k_s = k_0 \sin \theta = k_{SP} \pm jG_1 \pm jG_2, \]

where \( k_{SP} \) is the wave vector of the SPs, \( k_0 \) is the wave vector of the free space photon, \( k_s \) is the in-plane wave vector component of the free space photons, \( \theta \) is emission angle in air, \( G_1 \) and \( G_2 \) are the basic Bragg vectors of the hexagonal periodic pattern, and \( i \) and \( j \) are integers. The magnitude of Bragg vector used for coupling the light out from the device is dictated by the periodicity \( a \) of the corrugation, i.e., \( |G_1| = |G_2| = (2\pi/a)(2/\sqrt{3}) \).

The textured metallic microcavity samples were prepared as previously reported26 except the periodic pattern is hexagonal and the active dielectric medium tris(8-quinolinolinate) aluminum (Alq3) was 117 nm in thickness. The schematic diagram of the sample structures is shown in Fig. 1 (inset). Thin film Alq3 emits a broad Gaussian photoluminescence (PL) spectrum with peak at 530 nm with full width half maximum around 100 nm.27 Its broad emission spectrum allows us to study the dispersion of surface plasmon mode as it overlaps a range of photonic energy of the surface plasmon mode in visible regime. The angle-resolved
transmission measurement (ART) and the angled-resolved photoluminescence (PL) measurement (ARPL) were performed in condition reported before.\textsuperscript{26}

We mapped out the photonic mode distribution by scanning the in-plane wave vector at different wavelengths. Whenever the in-plane wave vector and photonic energy matched the photonic modes inside the microcavity, the transmittance/PL signal was enhanced.\textsuperscript{28} Figure 1 showed the ART result for the textured sample. This measurement was done under the conditions that incident light has in-plane wave vector in the $\Gamma M$ direction and with TE polarization. In addition to the usual guiding mode which is the characteristic of planar microcavity, the surface plasmon coupling modes appear as enhancement in transmittance (white circled region) whenever the incident photon energy and in-plane wave vector matched Eq. (1).

Figure 2 showed that the corresponding ARPL result and the photonic band structure are very similar to the results of transmission measurement. This is because the relaxation through the spontaneous emission for the excited Alq$_3$ emitter can only take place via available photonic states. The dominating waveguide mode matches well with its corresponding simulated curve. Within the fine structures, we can observe the surface plasmon coupling modes and they are found to be the air/silver interface SP. The simulated coupling dispersion curves of two coupling orders $(1, 0)$ and $(-2, -1)$ are also shown in Fig. 2; the index $(1, 0)$ means a coupling related to the first order of diffraction in the $G_1$ direction and 0 order in $G_2$ direction (Fig. 2, inset). The reason why $(1, 1)$ coupling order was absent is that the transverse magnetic nature of the SP such that the emitted photons have polarization perpendicular to the polarizer axis in this experiment. It appears that the coupling to the SP is weaker than the guided mode according to Figs. 1 and 2. In fact, the coupling to the SP should be strong and comparable to the guided mode.\textsuperscript{29,30} The reason for weak coupling in our results is due to the fact that SP modes have to be scattered to a photon before it can be detected. For the guided mode, it is a direct process and no scattering process involved for the photon radiated in the resonant wavelength to pass through the partly transparent silver mirror and be detected. The simulated dispersion curves which demonstrate the anticrossing feature are in good agreement with the experimental result. The anticrossing point occurs at the region where the waveguide mode and surface plasmon mode overlap. The fact that the surface plasmon coupling is more evident in the ARPL measurement compared to ART is that there is direct coupling of air/silver SP to free space; the Alq$_3$ relaxes from its excited state and excited the air/silver SP via near field nonradiation process. Then the SP can be Bragg scattered to free space. However, there are at least two scattering steps for the SP coupling to the free space in transmission measurement. Firstly, the incident photon Bragg scattered and its enhanced momentum lead to excitation of SP whenever Eq. (1) is fulfilled. Then the excited SP would be recovered as radiation by Bragg scattering again at any subsequent corrugated interface. Only part of these photons can reach the free space after passing through the 40 nm bottom silver layer. Thus the signal contrast for the SP coupling in

![FIG. 1. Angle-resolved transmission of the hexagonal textured metallic microcavity sample. The measurement was done in TE polarization and the in-plane wave vector was in the $\Gamma M$ direction. Left inset shows a schematic diagram of the hexagonal textured metallic microcavity cross section. Right inset shows the high symmetric points of the hexagonal lattice and define the incident light in-plane wave vectors.](image)

![FIG. 2. Angle-resolved photoluminescence result for the hexagonal textured metallic microcavity sample. The measurement was done in TE polarization and the in-plane wave vector was in the $\Gamma M$ direction. The simulated curves (dotted lines) for the $(1, 0)$ and $(-2, -1)$ coupled air/silver interface SP mode and TE waveguided mode (solid line) are also shown.](image)

![FIG. 3. Simulated E-field strength profile inside the planar microcavity. (a) The Alq$_3$/silver SP is excited by TM polarized light with 505 nm and in-plane wave vector $k_x = 4.53\, \mu$m$^{-1}$. (b) The air/silver SP is excited by TM polarized light with 505 nm and in-plane wave vector $k_x = 2.04\, \mu$m$^{-1}$. Inset shows the simulated dispersion curves for Alq$_3$/silver SP and air/silver SP inside the planar microcavity.](image)
the transmission measurement is smaller than the ARPL measurement. Also, we observed that the air/silver SPs dominate over the Alq3/silver SPs from the experimental results. To elucidate this observation, we derived the electric field profile inside a simulated textured microcavity and we observed strong $E$ field at the interfaces corresponding to the excited SP (Fig. 3). The Alq3/silver SP can be excited when the TM-polarized incident light possesses with wavelength equal to 505 nm (1/1.98 μm$^{-1}$) and in-plane wave vector $k_x$ equal to 4.53 μm$^{-1}$. In Fig. 3 (inset), we show the simulated dispersion curves for silver/air SP and silver/Alq3 in the planar cavity structure for comparison. For the air/silver SP, we changed the in-plane wave vector $k_x$ to 2.04 μm$^{-1}$. By comparing the $E$-field strength in Fig. 3, we see that the simulated $E$-field strength for the air/silver SP is about three times stronger than Alq3/silver SP and this is consistent with our experimental result that the air/silver SP was dominant. The simulation of the SP dispersion curves was performed in two steps. Firstly, we calculated the SP mode dispersion relationship by the scatter matrix method. Then Eq. (1) was used to trace the Bragg scattered dispersion curves within the light cone. The refractive index of the Alq3 layer was measured by the ellipsometer (model V- VASE from J. A. Woollam). We set the refractive index of glass to 1.46 and the values for silver were obtained from Ref. 32.

To compare the light extraction efficiency of the 2D hexagonal textured cavity relative to the planar cavity, we integrated the ARPL spectrum at different angles up to 60°. Taking the ratio of the integrated intensities from the textured and planar cavity sample as the average extraction efficiency enhancement factor, the average improvement factor is around 1.1. However, at specific angles, the enhancement can be as much as 12 times more (Fig. 4).

In summary, we have performed ART and ARPL measurements to investigate the plasmonic coupling characteristics of two-dimensional hexagonal textured metallic microcavity. The alteration of the emission properties by the modified photonic modes through introducing corrugation in the microcavity is clearly demonstrated. The experimental results showed that the average extraction efficiency enhancement over the planar microcavity is 10% and the intensity can be 12 times greater than the planar microcavity in specific emission directions. The results indicate that metallic textured microcavity has the potential for efficient angle-selective chromatic separation waveguide. Greater extraction enhancement can be achieved through improving the coupling by optimizing the structure further.

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