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Fatemeh Hosseini Alast  
*Hong Kong Baptist University*

Guixin Li  
*Hong Kong Baptist University*

K. W. Cheah  
*Hong Kong Baptist University, kwcheah@hkbu.edu.hk*

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Rabi-like splitting from large area plasmonic microcavity

Fatemeh Hosseini Alast, Guixin Li, and K. W. Cheah

Department of Physics and Institute of Advanced Materials, Hong Kong Baptist University, Kowloon Tong, Hong Kong

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Rabi-like splitting was observed from a hybrid plasmonic microcavity. The splitting comes from the coupling of cavity mode with the surface plasmon polariton mode; anti-crossing was observed alongside the modal conversional channel on the reflection light measurement. The hybrid device consists of a 10×10 mm$^2$ ruled metal grating integrated onto the Fabry-Perot microcavity. The 10×10 mm$^2$ ruled metal grating fabricated from laser interference and the area is sufficiently large to be used in the practical optical device. The larger area hybrid plasmonic microcavity can be employed in polariton lasers and biosensors.

The surface plasmon polaritons, at the planar metal/dielectric interface, cannot be excited by incident light. However, momentum transfer from incident light to Surface Plasmon Polaritons (SPPs) inside the light line can be achieved by adding a periodic structure at the interface. The grating wave vector can compensate the difference between incident light and surface wave momentum and satisfy momentum matching requirement. Two methods are commonly used to achieve this goal: first, using prism and second, surface engineering using different array apertures at the metal/dielectric interfaces. In general two different geometries are designed for prism coupling; Kretschmann and Otto configurations, being widely used in biosensing devices. Several lithography techniques have been employed to fabricate periodic array apertures at the interfaces which promise their own specific pros and cons: Ion-beam milling, Electron beam lithography, Nanoimprint lithography and photolithography. However, beside the precision of fabrication structure, it is important to consider the cost and production convenience in producing a device with dimension suitable for commercial applications.

Ion beam milling and electron beam lithography can produce high precision nano-structures but only in nano-micro dimensions. With the emergent demand, nanoimprint lithography has recently improved considerably in fabricating large area plasmonic arrays although there is still a long haul from research to mass production on metallic layers. In fact the periodic structure can be fabricated cost-effectively using conventional photolithography. Plasmonic nanostructure integrated with photonic devices would provide additional manipulation of the device optical properties. Among these type of integrated plasmonic structure is hybrid plasmonic microcavities. Plasmonic periodic aperture can be fabricated on top or inlaid into the photonic cavity to induce SPP-cavity mode coupling. The SPP-cavity mode coupling exhibits Rabi-like splitting in analogy to quantum electrodynamic phenomenon of Rabi-splitting in the interaction of a single emitter with resonant structures. Rabi-like splitting of plasmonic microcavities serves to improve performance of various optoelectronic devices by controlling and tailoring the energy distribution. However the demonstration of coupling was achieved in array of aperture in micro size which is not ideal for optoelectronic applications. In this work, we prepared large area ruled grating pattern, 10×10 mm$^2$, on top of the microcavity structure that allows cavity mode-SPP coupling. We fabricated the ruled grating pattern at the metal/dielectric interface using conventional photolithography technique. The dimension of ruled grating pattern is proportional to expanding/collimating light system in interference set-up.

Author to whom correspondence should be addressed. Electronic mail: kwcheah@hkbu.edu.hk

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In fact, efficiency ruled grating is a relatively simple nano-structure to produce yet this work shows that SPP modes generated from ruled grating is efficient enough to couple with the cavity modes. The large area plasmonic cavity can be practically employed in different optoelectronic devices for instance plaritons lasers,\textsuperscript{22} biosensors,\textsuperscript{23,24} metamaterials,\textsuperscript{25} organic/photonic-plasmonic systems.\textsuperscript{12,18}

A two beam-interferometric set-up was used to generate the grating pattern onto photoresist coated on glass substrate. The pitch size of generated optical ruled grating pattern can be tuned by laser wavelength and two-beam interference angle, Eq. (1),\textsuperscript{26} thus the nanostructure can be made with desired pitch size for final structures.

\[ \Lambda = \frac{\lambda}{2 \sin \theta} \]  

In this work, the incident laser used for interference pattern generation was He-Cd laser with 442 nm and a 180 nm thick photoresist film (AR-P 5300) was spin-coated at 3000 rpm for 30s onto the substrate. Then the photosensitive film was exposed to laser interference to generate the optical pattern; after the developing process, the grating pattern was created on the resist film. Silver is used as the plasmonic material and silver film was deposited onto the photosensitive grating pattern by thermal evaporation technique. Two main parameters: skin depth and absorption length of silver dictate the effective surface plasmon for the modal coupling.\textsuperscript{27} The silver grating structures is 180 nm width and 30 nm heights and the pitch size of 390 nm on the substrate in 10 ×10 mm\textsuperscript{2} area, figure (1a). The area of array apertures can be adjusted to several centimeters by the expanding/collimating setup of high quality laser beam.

The fabricated Fabry-Perot cavity\textsuperscript{26} involved bottom and top mirrors of 120 nm and 30 nm thick silver films respectively; the top silver film is sufficiently thin for transmission of cavity modes. The spin-coated PMMA (polymethyl methacrylate) with thickness of 500 nm acts as the passive dielectric medium of cavity. A ruled grating of silver was then fabricated onto the top mirror of the cavity by using the interference technique described above in which the silver grating was made with height of 15 nm and pitch size of 390 nm, figure (1b). It is essential to pay attention that the uniformity and surface quality of metal grating is important factor in obtaining the strong modal coupling beside the height and aspect ratio of fabricated grating.

Thus the microcavity was integrated with the silver grating such that the strong coupling of cavity mode-SPP could occur; in fact the coupling generated Rabi-like splitting anti-crossing along with the modal conversional channel.

Primarily, the reflectivity of TM (Transverse Magnetic) and TE (Transverse Electric) modes with incident light coming from the plasmonic microcavity were measured. The reflectivity of TM polarized incident light is shown in the figure (2a), two modes coupled around a common wavelength, exhibiting Rabi-like splitting in the strong coupling regime where the minimum energy gap of upper and lower branches occurred. The reflectivity results show that strong modal coupling occurs in TM reflection from 48 degree with Rabi-like splitting at 50 degree and wavelength of 715 nm where

![FIG. 1. (a) SEM image of fabricated ruled grating with pitch size of Λ=390 nm, (b) the structure of fabricated plasmonic microcavity.](image-url)
the splitting energy is minimum value. The mode coupling is generally estimated as ‘strong’ when the ratio of splitting and the mode linewidth is larger than one,\textsuperscript{19} here we derive the ratio of larger than one at 50 degree with splitting energy of 70 meV (27 nm linewidth in the spectrum). The range of cavity window spectral and SPP mode excitation can be controlled by tuning the cavity length and the grating period respectively. If both cavity and SPP modes are not sufficiently close in energy, the modal coupling does not occur in the hybrid system. Plasmonic nanostructures generate SPP excitations with strong local field but it suffers from broad linewidth due to high dissipation inside the metal. On the other hand, the cavity mode has narrow linewidth with the weak local resonance field inside the cavity. The hybrid plasmonic microcavity allows the cavity mode and SPPs to couple generating Rabi-like splitting around common wavelength in the strong coupling regime. Therefore there is exchange energy between two resonance modes where the coupled system possesses two modes with the reinforced and improved characteristics; strong local field and narrow linewidth. The modified modes can be employed in various applications especially in polariton laser fabrication\textsuperscript{16,22,28} to decrease pumping threshold and in biosensor\textsuperscript{29} to detect small molecules with red shift of SPP excitation wavelength due to refractive index variations.\textsuperscript{19} The mode coupling is from 50 to 57 degree. This extended channel of mode conversion could be employed for mode selection of photonic devices to minimize losses in the visible spectral range, figure (2b). The coupling strength of the mode coupling can be derived using the approach described in Ref. 18.

We did theoretical calculation of SPP and cavity modes independently to verify the experimental results. The theoretical result shows that the observed SPPs and cavity modes are indeed originated from the grating and microcavity, figure (3a, b). The first order of SPP excitation was calculated using Eq. (2, 3), $K_{SPP}$, the wave vector of surface plasmons for different angles at the metal/air interface.
and, similarly $K_0$, the incident light wave vector are represented. For the calculation, the grating period $\Lambda$ in Eq. (2) is set at 390 nm, the same as the fabricated device and $\varepsilon_{\text{silver}}$ is the silver dielectric constant. We also used the transfer matrix method to calculate cavity modes of designed structures.

\[
K_{\text{SPP}}(\omega) = m(2\pi/\Lambda) - K_0(\omega) \sin(\theta)
\]

(2)

\[
K_{\text{SPP}}(\omega) = K_0(\omega) \sqrt{\varepsilon_{\text{silver}}/\varepsilon_{\text{silver}} + 1}
\]

(3)

Finally, the theoretical calculation also shows that at TE mode there is no coupling with SPP mode excitation verifying the measurement of TE mode reflectivity result, (figure 4a, b).

Using conventional laser interference photolithography, a larger area plasmonic microcavity with coupled metal grating was fabricated in this project. The fabrication technique used was a conventional interference lithography method so it demonstrates that a simple structure such as ruled grating can also be used for the SPP-cavity mode coupling. As it is indicated, the hybrid plasmonic device demonstrated coupling of cavity mode-SPP, producing anti-crossing modes with Rabi-like splitting. Furthermore, an extended modal conversional channel was observed which is useful for optional mode selection. The result demonstrates that the fabrication process of the large area plasmonic hybrid device with a simple ruled grating structure is sufficient to generate the Rabi-like split. It has
potential applications in polariton laser, biosensor and optical switch therefore will generate novel applications in optoelectronic devices.

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