Surface plasmon generation and field intensification by sub-wavelength double-ring structure of plasmas

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ABSTRACT

In this paper, we propose a plasma structure that can effectively enhance surface plasmon resonance and achieve significant local field enhancement. For specific incident wave frequencies, two plasma rings and a vacuum layer between them can form a metal-insulator-metal (MIM) waveguide, which can resonate as a Fabry–Perot cavity and couple the incident wave energy to the vicinity of the plasma ring slit, and thus effectively enhance the localized surface plasmon resonance inside the plasma ring. The simulation results show that, by adjusting the thickness and angle of the outer plasma ring, the average electric field of the incident wave inside the structure can be increased by a factor of 9. Moreover, at the same plasma frequency and incident wave band, the local field enhancement of the double-ring structure is better than that of a circular ring structure or a circular ring structure with a slit. We have also analyzed the physical mechanism of field enhancement and calculated the dispersion relation of surface plasmon polaritons in the Fabry–Perot cavity. The results are in good agreement with the theory of the MIM waveguide cavity.

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I. INTRODUCTION

Surface plasmon (SP), as a type of surface waves generated on an interface between the plasma and the dielectric, can effectively confine energy near the interface. Such a unique property introduces the SP to extensive applications such as enhanced spectroscopy and single molecule fluorescence, ultra-high density optical storage and lithography, nanophotonic devices, nano-waveguides, etc.

Previous studies on surface plasmons mainly focused on nanoscales for interactions between metal nano-structures and visible light. In those cases, the plasma frequency of metals is much higher than that of visible light (the overdense plasma condition), while the characteristic size of the metal structure is much less than that of visible light wavelength (the subwavelength condition). Meanwhile, for microwaves with 1–10 GHz frequency and wavelength around centimeters, gas discharge plasmas with a plasma density of $10^{10}$–$10^{13}$ cm$^{-3}$ and centimeters in size provide a possible way to excite the SP on them so as to modulate and/or enhance microwave signals around the plasma because the overdense plasma and subwavelength conditions are easy to accomplish in the laboratory. The Drude model can be used to describe the reaction of the plasma/metal to microwaves/visible light. For example, radiation enhancement was first achieved by coating a subwavelength plasma layer on a spherical electric dipole transmitting antenna operating in the ~300–400 MHz frequency range. Also, recently, such electromagnetic (EM) signal intensification processes, for both transmitting and receiving functions, by overdense subwavelength plasma structures have been realized in the GHz regime for a compact dipole antenna.

Most experimental and simulation studies on microwave SP excitation and signal enhancement mainly focus on the spherical and ring plasma structure since it is easy to produce in the laboratory. In order to excite localized surface plasmon (LSP) resonance, overdense plasma conditions are necessary to intensify the surface field on the outer surface of the plasma ring. Thus, the incident signals may not be able to propagate into the area enclosed by the ring. Therefore, we need to design new subwavelength plasma structures to enhance the LSP resonance on the inner surface of the ring to...
achieve higher microwave signal enhancement inside of the ring, where a detector or an antenna is placed. In fact, in nanoscales, a variety of plasmon resonance structures have been proposed to provide large local field enhancement and high spatial resolution for surface-enhanced Raman scattering. Among them, a ring-shaped gold nanoparticle structure was designed for applications in near-infrared surface-enhanced spectroscopy and sensing. Compared with common solid gold particles of similar size, nanorings exhibit a redshifted LSP that can be tuned over a large wavelength range by varying the ratio of the ring thickness to its radius. To achieve a stronger field emitting effect, novel gold nanophotonic crescent moon structures are fabricated, which have a higher sharpness than the previously demonstrated nanoring, so the circular sharp edge of the nanocrescent moon can have a stronger field emitting or “antenna” effect. In addition, a controllable method of compressing visible light is proposed, in which a dielectric sheet is used between two precious metal sheets to form a metal-insulator-metal (MIM) waveguide cavity for compressing the visible light. For red light, the surface plasmon wavelength comes down to 51 nm (less than 8% of the free space wavelength). On this basis, Cui and He introduced a resonant cavity to enhance the transmission efficiency through certain metallic nanoslits. One can apply such a structure to the microwave regime for signal intensification, by a subwavelength slits structure in a plasma ring covering a receiving antenna, to the microwave regime for signal intensification, by a subwavelength scale double-ring plasma (DRP) structure by finite element method simulations. The two-dimensional (2D) schematic diagram of the DRP structure is shown in Fig. 1(a).

The blue region in Fig. 1(a) is plasma with the frequency \( \omega_{pe} = (4\pi n_0 e^2/m_e)^{1/2} \) fixed at \( 20 \times 2\pi \) s\(^{-1} \) for \( \nu_{pe} = \omega_{pe}/2\pi = 20 \) GHz and the collision rate \( 0.2 \times 2\pi \) GHz. Also, the plasma dielectric constant is given by the Drude model,

\[
\epsilon_p = 1 - \frac{\omega_p^2}{\omega(\omega + iv)}.
\]

The opening angle of the slit in the inner ring (with an inner radius \( R \) and a thickness \( t_1 \)) is \( \theta_1 \), and the outer plasma ring (with a thickness \( t_2 \) and a flare angle \( \theta_2 \)) is introduced to symmetrically cover the slit. The vacuum layer thickness between the inner and outer rings is \( t \). The incident direction of the plane TM wave is shown by arrows.

The energy flux distribution around the DRP structure is shown in Fig. 1(b) when the wave propagates in the positive direction. It can be seen that, by the Fabry–Perot cavity structure and resonance excitation, the energy flux in the vacuum layer region increases significantly. Thus, more incident EM energy is coupled to the slit of the inner ring to enhance the LSP resonance. To characterize the local field enhancement effect of the LSP, for a fixed incident frequency band, we calculate the average electric field intensity in the plasma ring under different geometric parameters to determine the optimum field-enhanced structure parameters.

III. RESULTS AND DISCUSSIONS

In previous studies, we found that when the resonance mode of the LSP in the plasma ring is the dipole field (at the resonance frequency \( \sim 7 \) GHz), the field enhancement in the ring is the most intensive. Thus, in latter simulations, we fix the incident frequency near 7 GHz (\( \nu_{pe} = 20 \) GHz).

Simulations with the results shown in Fig. 2 are for an incident wave from the direction other than that in Fig. 1(a). Figure 2(a) shows that the field enhancement spectrum for the simple ring structure (the black curve) reaches a sharp peak of \( -3 \) (normalized by the incident field) by the LSP resonance. Nevertheless, a large amount of EM energy is scattered by the overdense plasma, as shown in the red curve.

The layout of this paper is as follows. In Sec. II, we present the model for numerical simulations, a double-ring structure as a Fabry–Perot cavity, in detail. In Sec. III, we exhibit and discuss the simulation results. This paper is then concluded in Sec. IV with discussions.

II. MODEL OF SIMULATION

In this work, we simulate the SP excited on a subwavelength scale double-ring plasma (DRP) structure by finite element method.
FIG. 2. Field enhancement spectra (normalized by the incident field) (a) and distributions of the magnetic field and energy flux (by white arrows) for a single ring only (b), a ring with a slit (c), and a double-ring structure (d).

FIG. 3. (a) Field enhancement for different flare angles $\theta_2$ and distributions of the magnetic field with (b) $\theta_2 = 80^\circ$, (c) $\theta_2 = 110^\circ$, and (d) $\theta_2 = 138^\circ$. 
By inserting a slit (with an open angle of $\theta_1 = 20^\circ$) in the ring, one can see in Fig. 2(c) that the field distribution is disturbed. A smoothened but much broadened spectrum [the red curve in Fig. 2(a)] is then formed in comparison with the single ring case of Fig. 2(b). Clearly, the slit guides incident energy into the structure to broaden resonance. Furthermore, by introducing a thin ring (with a thickness $t_2 = 2$ mm and a flare angle $\theta_2 = 66^\circ$) in front of the slit, the field enhancement reaches a peak of $\sim 9$. Figure 2(d) shows three peaks of the magnetic field distribution by structural interference in the Fabry–Perot cavity. Obviously, the Fabry–Perot resonance in the vacuum layer greatly increases the EM energy flux in the slit, and the maximum electric field in the ring is 20 times of the incident. It should be pointed out that a strong field enhancement can also be achieved by adjusting the thickness of the plasma ring (when the thickness of the ring $t = 0.13\lambda_0$, the field enhancement reaches 6), while the field enhancement of the DRP structure can be increased by 50% in comparison with that of the ring with the optimum thickness.

Figure 3(a) shows the dependence of field enhancement on $\theta_2$. As is known, each field enhancement peak satisfies the Fabry–Perot resonance condition

$$(R + t_1 + t/2)\theta_2 = m\lambda_{\text{pp}} - \Delta\varphi_{\text{pp}}/2\pi.$$  

Here, $\lambda_{\text{pp}}$ is the wavelength of surface plasmon polaritons (SPPs) in the MIM cavity, $\Delta\varphi$ is the phase difference of EM fields at both ends of the outer ring, and $m$ is an integer. Thus, the second peak of field enhancement in Fig. 3(a), with a magnetic field distribution shown in Fig. 3(b), corresponds to $m = 1$. Also, the third peak with a magnetic field distribution shown in Fig. 3(d) corresponds to $m = 2$. It can be seen in Figs. 3(b) and 3(d) that when $m = 1, 2$, the corresponding magnetic field magnitudes have three and five peaks in the MIM cavity, respectively, which indicates that the distance between two adjacent interference peaks is a half of the SPP wavelength. Similarly, when $m$ is a half-integer, the resonance condition is destroyed and the field enhancement is minimized with a magnetic field distribution shown in Fig. 3(c) where the field enhancement is only 3. In addition, the enhancement of the first peak in Fig. 3(a) is not obvious because $\theta_2$ is too small to collect enough incident energy in the MIM cavity. However, when $\theta_2$ approaches $360^\circ$, most of the incident energy can be scattered by the outer ring to sharply reduce the field enhancement. Thus, generally, the optimum $\theta_2$ for field enhancement should be $\sim 180^\circ$.

Figure 4(a) reveals that when the outer ring thickness ($t_2$) is on the same order of the skin depth ($\delta_e = \lambda_0\text{Im}(\varepsilon_p^{-1/2}) \approx 16$ mm), for a positive incidence, field enhancement decreases slowly with the outer ring thickness. When the outer ring thickness is far less...
than the skin depth, field enhancement decreases sharply with the thickness. It is due to the fact that, as shown in Fig. 4(c), the EM wave can easily transmit through the outer ring whose thickness is far less than the skin depth. Therefore, under the positive incidence of the thin outer ring, the incident energy can hardly be collected into the MIM cavity. Thus, in order to obtain a better field enhancement effect, the outer ring thickness must be comparable to the skin depth. On the contrary, for a negative incidence, Fig. 4(b) exhibits that the thinner outer ring structure has a better field enhancement effect. When $t_2 = 2$ mm, the field enhancement can reach 9 by adjusting $\theta_2$. This phenomenon can be explained as follows. When the outer ring thickness is far less than the skin depth, the incident EM wave on the surface of the outer ring can pass through the ring, as shown in Fig. 4(d), and become an additional source of Fabry–Perot resonance to further enhance the LSP resonance. Moreover, unlike the positive incidence, a larger $\theta_2$ for the negative incidence can scatter more incident energy to significantly reduce field enhancement with increasing $\theta_2$. It should be noted that a thinner outer ring ($t_2 = 2$ mm) will cause a larger blue shift of the resonance peak for both positive and negative incidence. Since the skin depth for a long wavelength SPP mode is much greater than the thickness of the outer ring, it is then easy to escape from the MIM cavity. Thus, the short wavelength SPP propagates in the thin MIM cavity to make the short wavelength Fabry–Perot resonance dominant.

In the above simulations, we have mainly fixed the wavelength of the incident wave and analyzed the effect of different geometric parameters on field enhancement. Now, we further study the dependence of field enhancement on the wavelength of the incident wave in DRP structures. Figure 5 shows the field enhancement at different flare angles $\theta_2$ and incident wave wavelengths when the vacuum layer thickness is (a) $t = 1$ mm, (b) $t = 2$ mm, and (c) $t = 3$ mm, respectively.

It can be found in Fig. 5 that the field enhancement of the double-ring structure is strongly dependent on the incident wavelength with significant field enhancement near the LSP resonance of $\lambda_{LSP} = 4.29$ cm, due to the small broadening of the LSP resonance itself. Furthermore, for a thinner vacuum layer, the spacing of the field enhancement peaks also gets smaller, due to a shorter SPP wavelength. In addition, for different incident wavelengths and vacuum layer thicknesses, the highest field enhancement peak is always near $\theta_2 = 180^\circ$. By calculating the SPP wavelength at different incident wavelengths, we can get the dispersion relation of the SPP in the Fabry–Perot cavity. When the slit on the plasma ring has a negligible effect on the Fabry–Perot resonance, and the SPP wavelength is far less than the radius of the plasma ring, the combination of

![Figure 5](image_url)

**FIG. 5.** Field enhancement for different $\theta_2$ and incident wavelengths when the thickness of the vacuum layer is (a) $t = 1$ mm, (b) $t = 2$ mm, and (c) $t = 3$ mm. Also, the dispersion relation of the SPP at different thicknesses of the vacuum layer is compared with the theoretical result (d).
the inner and outer rings with the vacuum layer between them can be approximately considered a flat MIM cavity. Thus, the SPP dispersion relation can be obtained theoretically. Figure 5(d) shows the comparison between the simulation and theoretical results of SPP dispersion in the MIM cavity, with different vacuum layer thicknesses. It is clear that the MIM cavity theory can approximately describe the field enhancement mechanism of the DRP structure.

IV. CONCLUSIONS

In this paper, we have proposed and optimized subwavelength DRP structures. In comparison with previous plasma ring structures, we achieve further enhancement of the local electric field intensity. For the LSP resonance mode of the dipole field in the DRP, the field enhancement of the new structure is tripled compared with that of a simple ring structure at a fixed incident frequency band. Furthermore, by selecting the optimum thickness and flare angle of the outer ring, and considering different incident directions, the field intensity in the structure can be enhanced up to 9 times on average, compared with the incident energy flux. Specifically, it is found that the thickness of the outer ring should be greater than the skin depth for a positive incident case. Correspondingly, the thickness of the outer ring should be thinner than the skin depth for a negative incident case. We also investigate the dependence of the field enhancement by the DRP structure on the thickness of the vacuum layer. As the distance between the inner and outer rings decreases, the separation of the field enhancement peaks also gets smaller. Finally, the SPP dispersion relation in the vacuum layer is compared with the theoretical formula of the MIM cavity. The results show that MIM cavity theory can explain the physical mechanism of field enhancement of the DRP structure. One may expect that this DRP structure will be able to play an important role in future applications of microwave surface plasmons.

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