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Split ring aperture for optical magnetic field enhancement by radially polarized beam

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Abstract: Inspired by Babinet’s principle, we proposed a new plasmonic structure for enhancing the optical magnetic field, i.e. split ring aperture, whose complement is the well-known split ring. The split ring aperture exhibits a much better performance under radially polarized excitation than linearly polarized excitation. We attribute the ultra-high intensity enhancement in magnetic field to the symmetric matching between the aperture geometry and the direction of the electric field vector in each direction of radially excitation. The impact of the design parameters on the intensity enhancement and resonant wavelength is also investigated in details.

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References and links

1. Introduction

Optical antennas (OAs) [1,2] enable the control and manipulation of optical fields at the subwavelength scale, and thus hold promise for enhancing the performance of photodetection [3], spectroscopy [4], nano-lithography [5], sensing [6] etc. Due to the well-established radiowave and microwave antenna theories and structures, many structures in optical antennas for electric field enhancement, e.g. bowties, dipole antennas and split ring rings (SRRs), are introduced from their counterparts in radiowave and microwave region. In addition to electric field enhancement, the OAs for enhancing the optical magnetic field in near field has drawn much attention recently due to its potential applications, such as magnetic sensor [7, 8], magnetic nonlinearity [9] and magneto-optic modulation of plasmon polaritons [10]. Recent works have shown that by applying the well-known Babinet’s principle, magnetic field can be confined and enhanced in near-IR by means of the complementary structures of bowtie aperture antennas (BAA) or bowtie antennas (BA) called diabolo antennas (DA) [10] or complementary bowtie apertures (CBA) [11]. As is well known, SRRs is one important structure for electric field enhancement and has been studied extensively, including many previous studies related to the extraordinary electromagnetic properties, e.g. the negative permittivity metamaterials, using arrays of SRR and their complements [12]. Of most interest, therefore, is to investigate that whether the complement of SRR can exhibit the same behavior as DA and CBA in enhancing and localizing optical magnetic field.

Meanwhile, the optical features of all the structures aforementioned is found to be dominated by localized surface plasmon resonance, the collective electron density oscillations found in noble metal nanostructures, which is strongly dependent on the geometry of the structures and the polarization state of the incident light. Linear polarized and circularly polarized field are commonly used to excite the OAs. Recently, radially polarized beams, a subset of cylindrical vector beams, has been proved to be promising sources in several applications, such as super-resolution imaging and plasmonic focusing [13].

In this paper, we propose the complementary structure of a split ring, i.e. split ring aperture (SRA, as shown in Fig. 1(a)) to achieve optical magnetic field enhancement. The most promising optical feature of SRA, as well as the distinct discrepancy comparing to DA and CBA, is the capability to efficiently couple the radially polarized light into localized surface plasmon that leads to the near-field magnetic field enhancement. Moreover, several interesting optical features in SRAs are observed through the simulation, which show that it is possible to tune the resonance by altering the width of the strips or adding strips.

2. Radially polarized beam and split ring aperture

2.1 Radially polarized beam

As shown in Fig. 1(b), radially polarized beam is the optical field in which the electric field at each point is oriented parallelly to the radial vector from the beam axis and its electric component can be described by the following equation [13]:

\[ \vec{E}_r = H_{G_{10}} \vec{e}_r + H_{G_{10}} \vec{e}_r \]  

(1)

where \( \vec{E}_r \) denotes the electric field with radially polarization, \( H_{G_{10}} \) and \( H_{G_{10}} \) represent Hermite–Gauss modes. \( \vec{e}_r \) and \( \vec{e}_r \) are unit vectors in their respective direction. For this radially polarized electric field, the corresponding magnetic field in the transverse plane is aligned in the azimuthal direction and thus forms the complementary field of azimuthally polarized electric field. The Hermite-Gauss mode can be expressed as:
\[ E(x, y, z) = E_\theta H_m \left( \sqrt{\frac{2}{w(z)}} \right) H_n \left( \sqrt{\frac{2}{w(z)}} \right) \frac{w_0}{w(z)} \exp(-i\varphi_{mn}(z)) \exp \left( i \frac{kr^2}{2q(z)} \right) \] (2)

Here \( H_m(x) \) denotes the Hermite polynomials. \( E_\theta \) is the constant electric field amplitude, \( w(z) = \sqrt{\frac{w_0^2}{1 + \left( \frac{2z}{kw_0} \right)^2}} \) is the beam size, \( w_0 \) is the size at the beam waist \((w_0 = w(0))\), \( z_0 = (\pi w_0^2) / \lambda \) is the Rayleigh range, \( q(z) = z - iz_0 \) is the complex beam parameter, \( \varphi_{mn} = (m + n + 1) \tan^{-1} \left( \frac{z}{z_0} \right) \) is the Gouy phase shift, \( r \) is the radial coordinate and \( k = 2\pi / \lambda \).

Thus, the diameter of the circle formed by the maximum of the incident field can be deduced as \( d_{\text{max}} = 2\sqrt{z_0} / k \). For a given \( d_{\text{max}} \), the beam parameters can be decided completely.

2.2 Split ring aperture

As shown in Fig. 1(a), a typical split ring aperture is actually an aperture whose shape is like a split ring, i.e. the complement of a split ring aperture. The geometry of the aperture can be characterized by four parameters: the aperture diameter, \( D \); the strip width, \( W \); the gap width, \( G \) and the aperture thickness, \( T \) (not labeled in the Fig. 1(a)). \( T \) is kept constant at 50nm, which is thinner than the skin depth of gold in near-infrared region. The aperture is standalone and deposited on a glass substrate with a refractive index of 1.5 and surrounded by air.

![Fig. 1](image_url)

3. Simulation results

Lumerical FDTD Solutions [14], a commercial electromagnetic software based on the finite-difference time-domain method, is employed to investigate the magnetic response. A time step of \( \Delta t = 0.004 \) fs and a mesh size of \( \Delta x = \Delta y = \Delta z = 3 \) nm were used to ensure the stability and precision of the simulation. The perfectly-matched layers (PMLs) are used to minimize non-physical reflections at the simulation space boundaries. The permittivity function of gold used in the simulations is taken from Ref. 15 and fitted by the Lumerical’s Multi-coefficient Materials in near- and mid-infrared region. The structure will be excited by either a plane wave polarized along \( x \) or a radially polarized beam from the substrate side at normal incidence. The incident wave will propagate along \( z + \) direction. In the case of the radially polarized illumination, \( D \) equals to \( d_{\text{max}} \) (refer to the white circle in Fig. 1(b)).
3.1 Field enhancement

In typical structure such as DA, the area of cross section of the central strip is found to be a key geometry parameter for magnetic field enhancing. Thus, the optical behavior of SRA with various strip width is firstly investigated. Here, the magnetic field intensity enhancement for the aperture is defined as the ratio between the magnetic field intensity at one point 10 nm above the strip and the maximum intensity of whole incident magnetic field without the metal layer \([10, 11]\). \(G\) and \(D\) are kept 50 nm and 300 nm, respectively. The magnetic field intensity enhancement of \(W = \{30, 40, 50\} \) nm are shown in Fig. 2(a) for both the radially and linearly polarized excitation. It is evident that enhancement factor is improved for both the radially and linearly polarized excitation with decreasing \(W\) accompanied by red shift of the resonant wavelength \((\lambda_{res})\). As the strip width decreases from \(W = 50\) nm to 30 nm, \(\lambda_{res}\) shifts from 2.93 \(\mu\)m to 3.15 \(\mu\)m and the enhancement factor increases from \(4.00 \times 10^4\) to 7.24 \(\times 10^4\) times for radially polarized excitation. For given \(W\), the \(\lambda_{res}\) didn’t shift under different polarized excitations due to the invariant resonant conditions. The enhancement factors with radial polarization, however, are improved by two orders than that with the linearly polarization.

This strip-dependent enhancement and red shift of \(\lambda_{res}\) in SRAs can be interpreted as the gap-dependent optical coupling in electric field enhancement. In the typical end-to-end structures, such as bowties, two nanorods (nanoparticles) or split rings, smaller gaps will produce larger field enhancements and bring longer \(\lambda_{res}\) [16, 17]. Therefore, in SRAs, smaller strip width corresponds to the smaller gap and gives rise to the same effect on the enhancement and \(\lambda_{res}\) of the magnetic field as well. The trend to enhancement and \(\lambda_{res}\) related to various \(W\) (that is enhancement and red shift of \(\lambda_{res}\) increase with decreasing \(W\)) can be also interpreted as the result of a decrease in the cross section of the strip [10]. In magnetic field intensity enhancement, the effective length of one antenna is found to be determined by the path in which current density flows [11]. The length of such a path is identical to the same antenna geometry. So unlike the circumstance in SRR [18], even excited by two types of illumination, the effective length of SRA keeps constant. The resonant wavelengths of SRA, therefore, are identical for the two illuminations.

As we all know, the surface plasmons can only be excited in noble metal structures by the TM polarized wave. For a SRA, which exhibits rotational symmetry, a radially polarized beam is TM polarized along the entire metal/dielectric interface of SRA and thus allows...
efficient coupling all incident power to surface plasmon modes. Subsequently, higher field enhancement factor can be achieved with radially polarized wave in circular symmetric SRA.

To illustrate plasmonic resonance, Figs. 2(b), 2(c), 2(d) and 2(e) show the near-field distributions of the magnetic field intensity (xy and xz plane), current density (xy plane), and the electric field intensity (xy plane) generated by a SRA at a wavelength of 3.15 μm for the radial case. The structure parameters used is of \(D = 300\, \text{nm}, W = 30\, \text{nm}\) and \(G = 50\, \text{nm}\). The magnetic field intensity distribution is taken at the plane 10 nm above the nanoantenna whereas the current density and electric field distributions are taken in the middle plane of the metal layer.

According to Fig. 2(b), the magnetic hot spot is generated resonantly above the strip with the full width at half maximum (FWHM) size of 67.8 nm (x) \(\times 51.6\, \text{nm (y)}\), which is determined by the width of the strip. Figure 2(c) shows that the magnetic field is intensely trapped along strip in the x-z plane. Although the maximum of the two hot spot in Fig. 2(c) is close, the magnetic field in the substrate side is still higher than the air side due to the different refractive index between both sides of SPA and the asymmetric incident. This phenomenon is also observed in Ref. 10. Figure 2(d) clearly shows the current density is concentrated in the same location of the magnetic spot. Actually, a SRA can be seen as a composition of a circular disc and a circular aperture connected by a strip. If excited at resonance, the aperture is polarized and charges accumulated on the edges of the disc will lead to high electric field enhancement along the edges (Fig. 2(e)). Subsequently, the current density will be concentrated in the strip and amplified by the central disc efficiently.

Following Ampere’s law, the local concentration of the current intensity will lead to a strong magnetic field intensity enhancement surround the strip. In another point of view, magnetic hot spot can be considered as the result of Babinet’s principle, which states a complementary structure illuminated by a complementary wave field causes a complementary scattering response. As it is well known, the azimuthally polarized electric field could improve the electric hot spot in split ring [18], the complementary wave of the azimuthally polarized electric field, i.e. azimuthally polarized magnetic field, therefore, can improve the magnetic hot spot in split ring aperture, which denotes as the complementary structure of split ring.

3.2 Structural investigation

In order to further develop the design rules to describe the operation of SRA, the resonant enhancement factor and \(\lambda_{\text{res}}\) have been plotted versus the aperture length \((D)\) and the gap width \((G)\). As shown in Figs. 3(a) and 3(b), both enhancement and \(\lambda_{\text{res}}\) increase as increasing the aperture dimension (increasing \(D\)) or increasing the disc (decreasing \(G\)), which is equivalent to increase the effective length of the aperture. The red shift of \(\lambda_{\text{res}}\) is understood as the result of the longer antenna length while longer \(\lambda_{\text{res}}\) leads to higher enhancement, which is ascribed to the decrease of loss in metal with increasing incident wavelength.

![Fig. 3. The variation of resonant wavelength (indicated as dots with full lines) with \(D\) (a) and \(G\) (b) for radially polarized illumination. The resonant wavelengths by linearly polarized excitation are almost identical comparing to that by radially polarized excitation. The relationship of magnetic field intensity enhancement (indicated as triangles with dotted lines) with \(D\) (a) and \(G\) (b) for both the two illumination. \(G\) is kept 50 nm in (a) and \(D\) is kept 300 nm in (b).](image-url)
Fig. 4. Magnetic spectral response under the radially polarized illumination for one- (in red), two- (in blue) and four-strip (in black) split ring aperture, whose resonant wavelength are 3.15 μm, 1.90 μm and 1.23 μm, respectively.

Besides altering the structural parameters above, it is also possible to modify the resonance behavior and enhancement factors by introducing additional strips to the structure. Figure 4 presents the schematics of SRA with one (in red), two (in blue) and four strips (in black), and their respective magnetic response. It is obvious that the more strips a SRA have, the smaller the enhancement and \( \lambda_{res} \) will be. For example, the enhancement decrease from \( 7.24 \times 10^4 \) to \( 1.46 \times 10^4 \) times after adding a strip to the one-strip SRA. A similar condition is also observed in a split ring resonator [18]. When coming to four-strip case, the enhancement factor decreases to 614 times. Unlike the one-strip SRA, in a multi-strip structure, the current density won’t be concentrated in the one and only strip and the effective length of SRA will be dramatically reduced by the additional strips. Therefore, both \( \lambda_{res} \) and the enhancement decrease with increasing the number of the strip. In addition, another factor that contributes to the decrease of the magnetic field intensity enhancement in a multi-strip SRA is the blue shift of \( \lambda_{res} \), which will increase the imaginary part of the dielectric constant and the loss in metal.

4. Conclusion

In conclusion, inspired by Babinet’s principle, we have investigated the operation of split ring apertures in near-infrared region, whose complement is the well-known split ring. Magnetic field intensity enhancement for the apertures is presented. Radially polarized beam can be more efficiently coupled into SPPs modes via the circular symmetric structure and lead to higher enhancing factor of the magnetic field. The resonance can be easily tuned into the near infrared or even visible region by add more strips. We anticipate that the results from this investigation will contribute to both theoretical and experimental investigations into optical antennas for higher magnetic field intensity enhancement.

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