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Effect of gap width on enhanced magnetic optical fields in metallic split ring resonators

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We analyze the U-shaped metallic split-ring resonators (SRRs) aimed at creating highly confined and enhanced magnetic field in the near-infrared frequency range. At the magnetic resonance, the induced circulating current of the SRRs could lead to a strong enhancement of the surrounding magnetic field. Such a magnetic field enhancement is found to be dominated by the gap width between two SRR arms. By decreasing the gap width to 10 nm, the SRR is predicted to have a 3790-fold enhancement of the magnetic field at the resonance wavelength of 1340 nm.

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Metal nanoparticles have attracted a lot of attention because of their remarkable optical properties.1, 2 When localized surface plasmons (LSPs), i.e., the collective oscillations of conduction-band electrons in metallic particles, are excited by light, the local electric fields around metallic nanoparticles could be greatly enhanced.2 For a long time in the past, when considering the interactions of light with matter at optical frequencies magnetic contribution was generally neglected, because the effect of light on the magnetic permeability is a factor $10^{-4}$ weaker than on the electric permittivity.3 The case may become different in metamaterials containing artificial “magnetic” atoms like split ring resonators (SRRs)4–8 and rod or cut-wire pairs9, 10 that are often tailored to have an enhanced diamagnetic responses to magnetic fields. Such magnetic resonances have enabled the magnetic light-matter interaction, and have been investigated for the possible realization of negative index of refraction.11 It is interesting to note that when illuminated by azimuthally polarized beam, the electric field intensity enhancement in the gaps of the SRRs can be increased by more than one order of magnitude compared to that attained by linearly polarized beam.12

Considering the increasing attention towards the magnetic field enhancement stimulated by its potential applications in magnetic nonlinearity,13–15 probing the vectorial magnetic near-fields,16 and controlling magnetic dipole transition,17 now the realization of a large amplification of magnetic field at optical frequencies is as important an issue in nanophotonics as achieving electric field enhancement. Recent work has shown that metallic nanowire and diabolo nanoantenna structures,18, 19 designed by applying Babinet’s principle to the metallic structures such as nanogaps and nanobowties that were employed previously for achieving huge electric field enhancement,20, 21 can result in highly confined and enhanced localized magnetic fields. For example, magnetic field intensity enhancement by a factor of 2900 is predicted for the metallic diabolo nanoantenna structures at a wavelength of 2540 nm.19

Another approach to enhance the local magnetic fields is to pattern artificial magnetic atoms into one- or two-dimensional arrays.22–24 It has been shown that magnetic resonances in the periodic array of metallic wire pairs can be coupled to the waveguide modes and Bloch surface waves,22, 23 giving rise to an avoided crossing and the formation of hybrid magnetic resonances. More recently,
we have shown that when the coupling took place between the magnetic resonances and lattice surface modes arising from light diffraction in two-dimensional periodic arrays of metallic rod-pairs, an enhancement factor as high as 450 could be achieved for magnetic field intensity at a visible wavelength of 780 nm. 

In this paper, we investigate by numerical calculations the near-field characters of the metallic U-shaped SRRs resonating at the same frequency. We demonstrate that a decreasing gap width between two SRR arms can dramatically narrow the magnetic resonance linewidth, and lead to a continuous increase of the optical near-fields. At the resonance wavelength of 1340 nm, the maximum intensity of the magnetic field for the SRRs with a gap width of 10 nm is about 3790 times of the incident field. Furthermore, the enhancement of the magnetic field is almost independent of the corner roundness, while the enhancement of the electric intensity is dramatically decreased with increasing the outer corner roundness.

The metallic U-shaped SRRs with defined geometrical parameters are schematically depicted in Fig. 1(a), among which the SRR height $h = 30$ nm, the arm width $w_a = 60$ nm and the base-line width $w_b = 80$ nm are fixed, while the SRR arm length ($l$), gap width between two arms ($g$), and the respective inner corner ($r_1$) and outer corner roundness ($r_2$) are varied to investigate their effects. The SRRs are assumed to be surrounded by air ($n = 1.0$) to neglect the effects of the substrate. The permittivity of gold is described by a Drude model: $\varepsilon_{Au} = 1 - \omega_p^2/(\omega^2 + i\omega\gamma)$ with the plasma frequency $\omega_p = 2.175 \times 10^{15}$ Hz and the collision frequency $\gamma = 6.5 \times 10^{12}$ Hz. 

The coordinate system is introduced to make that the $x$-axis points along the SRR base line, the $y$-axis is parallel to the SRR arms, the $z$-axis is normal to the sample plane, and the coordinate origin is located on the bottom surface of the SRR [Fig. 1(a)]. In both $x$ and $y$ directions the SRRs are periodically arranged with a period of $p = 400$ nm. Numerical simulations were preformed based on a commercial finite element method (Comsol Multiphysics). Periodic boundary conditions are applied to the four side
FIG. 2. Normalized intensity distributions of (a) $H_x$ component, (b) $H_y$ component, and (c) $H_z$ component of the magnetic field at the $xy$-plane of $z = 0$ nm for the SRR with a gap width of $g = 120$ nm. (d) Normalized intensity distributions of the $H_z$ component at the $xy$-plane of $z = 15$ nm. Image size: 400 nm × 400 nm.

boundaries located in the $xz$ and $yz$ planes. The top and bottom boundaries in the $xy$ plane are terminated with Perfectly Matched Layers to absorb reflected and transmitted light in the $z$-axis. The extremely fine option of the predefined mesh size (maximum element size scaling factor of 0.2, element growth rate of 1.3, mesh curvature factor of 0.2, and mesh curvature cutoff of 0.001) is applied to the metallic SRR subdomain and the surrounding air subdomain, producing $\sim 30000$ finite elements. The normal option of the predefined mesh size (maximum element size scaling factor of 1, element growth rate of 1.5, mesh curvature factor of 0.6, and mesh curvature cutoff of 0.03) is used elsewhere. The number of degrees of freedom is estimated to be $\sim 8.2 \times 10^5$.

In the present studies, the incident light polarization is configured so that its wave vector $k_{in}$ and electric field $E_{in}$ orients along the $z$- and $y$-axes, respectively. Thus, only the electric field couples to the SRR magnetic resonance. Figure 1(b) shows the normal-incidence transmission spectra of SRRs with different gap widths. Note that all the corners are rounded with a radius of $r_1 = r_2 = 5$ nm. For the SRRs with shorter gap width, the magnetic resonance will shift to higher frequencies due to a reduction of the oscillation length of the free electrons. Since the losses in the metal are dependent on the wavelength, these SRRs are highly desired to resonate at the same frequency to achieve a meaningful comparison. By simultaneously varying the SRR arm length and the gap width ($g = 10$ nm, $l = 184$ nm; $g = 20$ nm, $l = 202$ nm; $g = 40$ nm, $l = 211$ nm; $g = 80$ nm, $l = 207$ nm; $g = 120$ nm, $l = 193$ nm; $g = 160$ nm, $l = 172$ nm), magnetic resonances for all the SRRs are observed to be located at the same wavelength of 1340 nm [Fig. 1(b)]. As shown in Fig. 1(c), at such a magnetic resonance a circulating current is present in the current distributions calculated for the SRRs with $g = 120$ nm, in which the anti-parallel currents in two SRR arms cancel each other giving rise to nearly zero dipole moment and thus the net electric dipole moment is mainly contributed from the SRR base-line. Since the radiation damping increases with the particle size, the SRR with larger gap width (equivalently longer SRR base-line) contributes to a more radiation damping. As a consequence, the line-width of the magnetic resonance becomes broader for larger gap width, as demonstrated in Fig. 1(b).

To get an overview of the enhancement of the magnetic field, its $x$-, $y$-, and $z$-component ($H_x$, $H_y$, and $H_z$) are calculated at the bottom surface of the SRR ($xy$-plane of $z = 0$ nm) for a relatively large gap width of $g = 120$ nm [Figs. 2(a)–2(c)]. Note that the field enhancement is the near-field intensity generated by the SRR at a given $xy$-plane normalized by the incident field intensity. At the
magnetic resonance, the U-shaped SRR could also be viewed as a current-carrying bent metallic nanowire. Following the Ampere’s law, the magnetic field should be azimuthally polarized around this central bent metallic nanowire. Therefore, the $H_x$ component with an enhancement factor of 53 arising from the $y$-axis current and the $H_y$ component with an enhancement factor of 85 arising from the $x$-axis current are localized, respectively, on the surfaces of the SRR arms and SRR base line [Figs. 2(a) and 2(b)]. As shown in Fig. 2(c), the $H_z$ component induced by the circulating current is found to be mainly confined within the inner area of the SRR, and its enhancement reaches a value of 138. Actually, at the $xy$-plane of $z = 0$ nm the $H_z$ component does not reach its maximum intensity, unlike that the $H_x$ and $H_y$ components. It is seen from Fig. 2(d) that at the half-height plane of the SRR ($xy$-plane of $z = 15$ nm) the enhancement of the $H_z$ component could reach its highest value of 282 in the SRRs with a gap width of $g = 120$ nm. Note that at the $xy$-plane of $z = 15$ nm there are no enhanced $H_x$ and $H_y$ components (data not shown).

In the context of the enhanced optical fields, the broader line-widths or the shorter lifetimes of the emissive plasmons caused by the rapid depletion of the plasmon energy usually means a lower field enhancement and vice versa. Therefore, it is expected that the SRRs with shorter gap width having a narrower linewidth of resonance should generate higher localized optical fields. As shown in Fig. 3(a), upon decreasing the gap width to $g = 40$ nm the intensity enhancement of the $H_z$ component at the half-height plane of the SRR reaches a value of 1244, and is more than 4 times higher than that for the gap width of $g = 120$ nm [Fig. 2(d)]. In particular, when the gap width is decreased to $g = 10$ nm, a strong near-field coupling occurs between two spatially closed SRR inner corners, leading to a redistribution of the $H_z$ component. It is seen from Fig. 3(b) that enhanced magnetic fields previously observed around two SRR inner corners for the gap width of $g = 40$ nm [Fig. 3(a)] now are coupled to generate one magnetic hot spot within the inner area of the SRR. In this case, the maximum enhancement factor as high as 3790 is readily to be achieved for the $H_z$ component. Figure 3(c) shows the field enhancements as a function of the gap width. Clearly, it is found that a decrease of the gap width leads to a continuous increase of the magnetic intensity.

At the magnetic resonance, accompanying with the enhanced magnetic field, charge accumulations of opposite signs arising near the end faces of the SRR arms could also generate high enhancements of the electric field. As shown in Fig. 4(a), the electric fields simulated at the $xy$-plane of $z = 15$ nm for the SRRs with a gap width of $g = 40$ nm are enhanced by a factor of 5390.
FIG. 4. Normalized intensity distributions of the electric fields at the \( xy \)-plane of \( z = 15 \) nm for the outer corner roundness (a) \( r_2 = 5 \) nm and (b) \( r_2 = 30 \) nm. The gap width and inner corner roundness equal to \( g = 40 \) nm and \( r_1 = 5 \) nm. Image size: 400 nm \( \times \) 400 nm. (c) and (d) Field enhancements simulated at the \( xy \)-plane of \( z = 15 \) nm as a function of the outer and inner corner roundness, respectively.

Furthermore, similar to the case of the magnetic field, the enhancement of the electric intensity is increased exponentially with decreasing the gap width due to the near-field coupling between two SRR arms [Fig. 3(c)]. Since the enhanced electric fields are mainly concentrated around the outer corners of the SRR arms [Fig. 4(a)], it provides a possible way to tune the enhancement of the electric intensity by varying the outer corner roundness \( (r_2) \). For example, when the outer corner roundness is increased to \( r_2 = 30 \) nm the enhancement of the electric intensity is dramatically decreased to a value of 2157 [Fig. 4(b)]. The dependence of the electric field enhancement on the outer corner roundness shown in Fig. 4(c) directly indicates that an increase of the outer corner roundness leads to a decrease in the electric field enhancement. In contrast, with varying the outer corner roundness the enhancement of the magnetic field maintains a constant factor of \( \sim 1240 \), because the magnetic field is highly confined within the inner area of the SRR [Fig. 4(c)]. In addition, the field enhancements against the inner corner roundness \( (r_1) \) are plotted in Fig. 4(d). It is found that the enhancements of both the electric and magnetic intensities are independent of the inner corner roundness.

Since the SRRs are patterned into two-dimensional arrays, the enhancement of the magnetic fields might be influenced by the spacing between SRRs. To demonstrate the effect of the periodicity on the magnetic field enhancement, three additional periodicities \( p = 800 \) nm, 1400 nm, and 1600 nm are investigated for the SRRs with a gap width of \( g = 40 \) nm. It is well known that the arrangement of metallic nanoparticles into a periodic lattice can give rise to an in-plane propagating lattice surface mode, which appears near the Wood anomaly.\(^{30}\) The wavelength of the Wood anomaly can be calculated by matching the wave vector \( k_{in} \) of incident light in the surrounding air medium (refractive index \( n = 1.0 \)) with the reciprocal vector \( G_{i,j} \) of a two-dimensional square lattice under normal incidence: 

\[
\lambda_{wood}^{i,j} = p/\sqrt{i^2 + j^2},
\]

where \( i \) and \( j \) are integers related to different diffraction orders, and \( p \) is the square lattice constant.\(^{31}\) With increasing the periodicity, the excited lattice surface mode is continuously shifted to longer resonance wavelengths, which provides a possibility that the lattice surface mode can coincide with and couple to the magnetic resonance at a certain range of periodicities.\(^{24}\) As shown in Fig. 5(a), for a periodicity of \( p = 800 \) nm a weak coupling occurs between the lattice surface mode and the magnetic resonance of the SRRs with a gap width of \( g = 40 \) nm. Upon increasing the periodicity to \( p = 1400 \) nm, the lattice surface mode (\( \lambda_{wood}^{0,1} = 1400nm \)) mostly
FIG. 5. (a) Normal incidence transmission spectra for the SRR (gap width \( g = 40 \) nm) arrays with different periodicities. (b)-(d) Normalized intensity distributions of \( H_z \) component of the magnetic field at the \( xy \)-plane of \( z = 15 \) nm calculated at the resonances for the SRR arrays with a periodicity of \( p = 800 \) nm, 1400 nm, and 1600 nm. Image sizes: (b) 800 nm \( \times \) 800 nm, (c) 1400 nm \( \times \) 1400 nm, (d) 1600 nm \( \times \) 1600 nm.

Overlaps with the magnetic resonance (\( \lambda = 1340 \) nm), which leads to the formation of two mixed modes as a result of the strong coupling between these two modes [Fig. 5(a)]. When the periodicity is further increased to \( p = 1600 \) nm, the lattice surface mode is resonant out of the magnetic resonance, and only a weak coupling between these two modes is observed [Fig. 5(a)]. The corresponding magnetic fields of the SRRs with a gap width of \( g = 40 \) nm simulated at the \( xy \)-plane of \( z = 15 \) nm for the periodicities of \( p = 800 \) nm, 1400 nm, and 1600 nm are shown in Figs. 5(b)-5(d), respectively. Compared to the magnetic field enhancement achieved in the SRR arrays with a periodicity of \( p = 400 \) nm [Fig. 3(a)], it is found that the coupling between the lattice surface mode and the magnetic resonance could further enhance local magnetic fields. In particular, it is seen from Fig. 5(c) that due to the strong diffraction coupling the enhancement of the magnetic fields for the SRRs with a gap width of \( g = 40 \) nm could reach a factor as high as 11,440 at the hybridized magnetic resonance of \( \lambda = 1415 \) nm.

In the above discussions, the SRR arrays are assumed to be surrounded by air. However, in the practice the substrate has to be taken into account. For this purpose, we will investigate the substrate effect on the enhancement of the magnetic fields. In Fig. 6(a), we show normal incidence transmission spectra for the SRRs with a gap width of \( g = 40 \) nm (blue line) and \( g = 10 \) nm (red line) placed on the substrate with a refractive index of \( n = 1.46 \). Note that in the calculations the periodicity of \( p = 400 \) nm is applied. Compared to the transmission spectra calculated for the SRRs without the substrate [Fig. 1(b)], it is found that the magnetic resonance of the SRRs with the substrate red-shifts from the wavelength of 1340 nm to 1600 nm. As shown in Fig. 6(b) and 6(c), at the magnetic resonance the enhancement of the magnetic fields for the SRRs with a gap width of \( g = 40 \) nm and \( g = 10 \) nm reaches a value of 1097 and 3032, respectively, which is slightly lower than the enhancement factor achieved in the SRRs without the substrate [Figs. 3(a) and 3(b)]. By comparing Fig. 6(b) with Fig. 6(c), it is worth noting that even when the substrate is taken into account the local magnetic fields could still be greatly enhanced by decreasing the gap width.

In conclusion, we have numerically investigated the localized optical field enhancement of the U-shaped metallic SRRs resonating at the same frequency. We demonstrate that the enhancement
FIG. 6. (a) Normal incidence transmission spectra for the SRRs (gap width $g = 40$ nm and $g = 10$ nm) sitting on the substrate with a refractive index of $n = 1.46$. (b) and (c) Normalized intensity distributions of $H_z$ component of the magnetic field at the $xy$-plane of $z = 15$ nm for the SRRs with a gap width of $g = 40$ nm and $g = 10$ nm, respectively. Image size: 400 nm $\times$ 400 nm.

of the magnetic field is dominated by the gap width between two SRR arms. However, both the gap width and the outer corner roundness are found to play key roles in the enhancement of the electric intensity. Our results show that an enhancement factor as high as 3790 could be achieved for the magnetic field at a near-infrared wavelength of 1340 nm by decreasing the SRR gap width to 10 nm. Even higher enhancement of the magnetic intensity is possible provided that the size of the SRR is increased to shift the magnetic resonance to a longer wavelength, which at the losses in the metal could get smaller. It should be noted that although the magnetic field enhancement achieved in the SRRs could be much higher than that obtained from the metallic diabolo nanoantennas (the enhancement factor of 2950 at a wavelength of 2540 nm), the electric field background in the diabolo structures is much lower than that in the SRRs. Such a highly enhanced magnetic field may have important applications in magnetic sensors or detectors, magnetic nonlinearity and devices based thereon, and inducing magnetic dipole transitions.

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