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Fractal complementary bowtie aperture for confining and enhancing optical magnetic field

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ABSTRACT

A new kind of bowtie related structures, Sierpiński complementary bowtie aperture (SCBA), is proposed for enhancing and confining optical magnetic field. The magnetic field enhancement factor can be improved with the presence of the fractal. Numerical simulation shows that higher iteration of the SCBA is responsible for the variation of the resonant wavelengths. The magnetic field distributions illustrated 10nm above the output plane prove the magnetic intensity is confined in the sub-wavelength scale. Further investigation demonstrates current can be enhanced in the center of the apertures while electric fields are found to be easier to concentrate at the tiny fractal structures. Magnetic intensity distributions at several resonant points in the spectrum of the third-iteration SCBA are also plotted and the longer wavelength region in near infrared is found to be unsuited for confining magnetic field in SCBA due to weak interaction with the fractals.

Keywords: Nanophotonics, aperture antenna, optical magnetic field, subwavelength structures

1. INTRODUCTION

Due to the capability of dramatically enhancing electromagnetic field, optical antennas (OAs), e.g. bowtie antenna (BA) and bowtie aperture antenna (BAA), have attracted much attention for near-field applications in biosensing¹⁻², spectroscopy³, nanolithography⁴⁻⁷, etc. Optical antennas are strongly analogous to their microwave counterparts, but a crucial difference exists between them, which is that metals are not perfect electric conductor in the optical region⁸. This is essentially decided by the fact that imaginary part of the dielectric constant of most metals increases with the wavelength decreasing.

OAs can be divided into two kinds by their enhancing objects: OAs for enhancing electric fields and magnetic fields. Most traditional OAs are engineered to localize and enhance electric fields, e.g. BAs and BAAs, the two metal triangles of which are electrically isolated. Under optical excitation, charges accumulate at the opposite apexes, which cause a large electric field in the gap. While when it comes to enhancing magnetic fields, Babinet's principle will be introduced. Babinet's principle is a classical theory in electromagnetism and optics, which states that for an infinitely thin, perfectly conducting plane, a similar response can be anticipated if a complementary structure is illuminated with the same excitation. Recently, this principle was extended to OAs⁹ for magnetic field enhancement, i.e. diabolito antenna (DA) and complementary bowtie aperture (CBA)¹⁰, which are the complementary parts of BAA and BA. DA or CBA can be also seen as the structures that join two apexes of BA or BAA with a metal strip together. Generally speaking, if a kind of the four bowtie related structures (i.e. BA, BAA, DA, and CBA) has a smaller resonant wavelength, its field enhancement will be weakened as well^{9, 11, 12}, which is due to the stronger losses at the smaller wavelength in metal. Comparing to its counterpart, DA, CBA has resonates at a smaller wavelength and is anticipated for applications near visible wavelengths¹⁰. However, due to the structural difference (CBA has a surrounding metallic film), CBA produces a much weaker magnetic field enhancement comparing to DA. In order to further enhance the near-field magnetic intensity, a effective strategy by placing periodic groove structures around the aperture, which is aiming at increasing optical transmission in a bull's eye structure^{13, 14}, was introduced and the magnetic enhancement was significantly improved by about thirty times¹⁰. However, the footprint of CBA could reach to 100 times larger due to the presence of these structures, which is not conducive for the chip integration.

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In recent works, the fractal geometries, which are incorporated in plenty of microwave and radio frequency antennas design, have been employed to enhance the performance of enhancement and footprint in bowtie antennas^{11, 15}, i.e. Sierpiński Fractal Plasmonic Antenna (SFPA) and Pascal Fractal Plasmonic Antenna (PFPA). Hence, for improving the enhancement and tuning the resonance under a constant antenna footprint, in this article, we will introduce a kind of fractal geometry, Sierpiński triangles, into CBA to construct Sierpiński complementary bowtie aperture (SCBA). Three dimensional finite difference time domain simulations are performed to explore the magnetic intensity enhancement of these apertures. Numerical investigation shows that when iteration varies from 0 to 1, a blue shift of resonant wavelength was observed. As the iteration further increasing, resonant wavelengths of the second- and third-iteration were red-shifted again, though still smaller, comparing to CBA. After further simulation, it is found that electric field and current were adjusted to more confinement in the first-iteration SCBA than CBA. In order to understand the behavior of SCBAs, magnetic intensity distributions at points of interest in its spectrum are plotted for the third-iteration SCBA, which proved that magnetic field can't be perfectly confined in the whole near-infrared region in SCBAs.

2. THE FRACTAL COMPLEMENTARY BOWTIE APERTURE

Sierpiński triangle is one of well-known structures in fractals. Fig. 1(a) shows a regular triangle and first-, second-, third-iteration of the Sierpiński triangles. It also demonstrates the constructing rule: in the first iteration of the structure, a sub-triangle, formed by connecting all the midpoints of the regular triangle, excluded from the shape. In subsequent iterations, the same operation is repeated to each of the new triangles formed in the last iteration. Hence, each triangle becomes tinier and tinier in the higher order iterations. In the third iteration, each triangle is reduced by 8 times compared with the original one. The fractal structures can be characterized by the fractal dimension or Hausdorff dimension, as shown in Eq. (1):

$$D = \frac{\log(B)}{\log(A)}. \quad (1)$$

It states a law that if a Sierpiński triangle is composed of B triangles which are similar to it and the length scale reduced by A times, the Hausdorff dimension of this Sierpiński triangle is D. According to Eq. (1), the Hausdorff dimension of the regular triangle and the Sierpiński triangles are 1 and 1.585, respectively.

Figure 1. (a) Sierpiński triangle basis shape and the three iterations of Sierpiński triangle. (b) Side view and (c) top view of the complementary bowtie antenna, and top view of Sierpiński complementary bowtie antennas of first- (d), second- (e) and third- iteration (f).

3. SIMULATIONS

As shown in Fig. 1(b), with the film thickness T of 50nm, a gold aperture antenna, which is deposited on a glass substrate with a refractive index of 1.5 and surrounded by air, is illuminated by a plane wave in a form of broadband

pulse from the substrate side at normal incidence and polarized along the x direction. Fig. 1(c) illustrates a traditional complementary bowtie aperture with a 45° flare angle and an antenna length L of 475nm. The pulse length of the input source is 95fs. G defines both the width and the length of the central square strip and is kept 30nm. The antenna length and G of the three Sierpiński triangle complementary bowtie aperture equal to the traditional CBA, as represented in Fig. 1(d), (e) and (f). For investigating the output magnetic response, a commercial tool (Lumerical FDTD-Solutions) is employed to run the three dimensional finite difference time domain (3D-FDTD) simulation. To ensure an adequate stability and accuracy in the simulation process, a time step of Δt is kept smaller than 0.005fs and a mesh size of $\Delta x = \Delta y = 2\text{nm}$, $\Delta z = 5\text{nm}$. A perfectly-matched layer is adopted to minimize non-physical reflections and a non-uniform mesh is employed to enhance the performance of simulation near the metal film. Symmetric and anti-symmetric boundary conditions are also configured in x and y direction to make the simulation run four times faster. The magnetic intensity is recorded by a point monitor 10nm above the output plane. It is noteworthy that each triangle in SCBA is connected to its neighbors by a thin strip to avoid geometric singularities through the simulation process (i.e. all the triangles are connected together).

3.1 Magnetic field enhancement factor

First of all, the magnetic field enhancing performances of the four apertures are investigated. The definition of the magnetic field enhancement factor (ME factor) is the ratio of the magnetic intensity at the point monitor at the center of aperture with and without the gold layer¹⁸. One remarkable conclusion can be drawn from Fig. 1(a) is that the three apertures incorporating fractal geometries act in a quite different way compared to common CBA since more sharp peaks appear in SCBA than CBA. However, some of them won't be treated as main resonances due to the corresponding magnetic fields are not confined in the center position, especially for second- and third-iteration SCBAs. The ME factors for the traditional CBA, first-, second- and third- iteration of SCBAs are 41, 43.8, 39.4 and 44, respectively. Therefore, the ME factor can be increased by 6% and 7.3% for the first- and third-iteration SCBA. Although it's reported that resonant wavelength in SFPAs red shifts as the iteration increasing, for SCBAs, a quite different behavior was observed from Fig. 1(a) and (b). The corresponding resonant wavelengths are 1.381 μm , 1.141 μm , 1.301 μm and 1.338 μm , respectively. For the first-iteration SCBA, an obvious blue shift occurs compared to the common CBA. As the iteration is altered to the higher order, resonant wavelength is red-shifted again. Due to the fact that obvious red shift of the resonant wavelength in SFPAs occurred comparing to the bowtie antenna, and the enhancement was improved dramatically by the fractals, it's necessary to analyze the reason. The reason lies in the loss of optical field in the metal are associated with imaginary part of the dielectric constant, which tends to increase with decreasing wavelength. Since the resonant wavelength of SCBAs are smaller than CBA, it's inevitable for the ME factor to get smaller and smaller with decreasing wavelength.

Figure 2. (a) Magnetic enhancement for the complementary bowtie aperture (a) and Sierpiński complementary bowtie apertures (b). The antenna color in Fig.1 (c)-(e) corresponds to the curve color in Figure 2.

3.2 Magnetic field intensity and current density distribution

A magnetic field and current density distribution in SCBA will be illustrated in order to explore the reason that leads to such a behavior of ME factor and the resonant wavelength in SCBA. Fig. 3 plots normalized magnetic intensity distributions at their resonances for CBA and SCBAs. The magnetic intensity in these relative intensity distributions are

taken from a plane 10 nm above the output plane of the antenna and normalized by the intensity at the same position without the antenna layer. It can be seen from Fig. 3 that, for CBA (a) and SCBAs (b-d) at resonance, the majority of the magnetic fields are confined at the central position of the antenna while other parts at the four corners. It has already been proved that for CBA, current density along the central strip will be reduced comparing to DA due to the presence the surrounding structure¹⁰, which would form two other paths for current. Yet for the first-iteration SCBA, the magnetic distribution is more concentrated near the center, comparing to CBA, as depicted in Fig. 3 (a-b). Since the first-iteration SCBA has a largest enhancement, for a further discussion of magnetic field, the electric field and corresponding current of CBA and first-iteration SCBA will be illustrated below.

Figure 3. (a) Magnetic intensity distribution for the complementary bowtie aperture (a) and Sierpiński complementary bowtie apertures (b-d). The outlines of the antennas are shown as the white lines.

Figure 4. Distribution of electric field (a, c) and current density (b, d) for the complementary bowtie aperture (a, b) and the first-iteration Sierpiński complementary bowtie apertures (c, d), all calculated in the middle plane of the antenna (i.e. at the plane $z=25\text{nm}$). The units of the electric field and current density are V/m and A/m².

Fig. 4 depicts the 2D distribution of current density and electric field in xy plane at the middle plane of the metal film. Unlike the distribution behavior of electric field in CBA (Fig. 4(a)), which is localized along the edges of the two isosceles triangles and get stronger as getting closer to the central strip, for the first-iteration SCBA, electric fields are more enhanced at the four corners of the two removed sub-triangles instead of the center (Fig. 4(c)). This is largely because electric fields are easier to be enhanced in the tiny structures, which are formed by the operation in first fractal operation. This characteristic of electric field distribution also leads to a decrease in current density distribution, as shown in Fig. 4(b-d).

3.3 Intensity distributions at spectral points of interest for the third-iteration SCBA

Comparing to the other, two comparable peaks appear for the second- and third-iteration antenna in its enhancing behavior, as Fig. 1(b) illustrates. In order to explore the reason for such a enhancing behavior, Fig. 5 plots the magnetic intensity distributions at points of interest in its spectrum for third-iteration SCBA. When excited on the primary resonance and secondary resonance, the intensity distributions show that most incident energy is confined to the center, as shown in Fig. 5(b, c). One obvious difference between primary and secondary resonance is that comparing with center, the moderate enhancement emerges at the four corners, which is not negligible. Such distribution directly weaken the peak value of the secondary resonance at $\lambda=1.45\mu\text{m}$. When excited at its third resonance (Fig. 5(a)), the enhancement surrounding the center is still not negligible. While when the aperture is excited at $\lambda=3\mu\text{m}$, there is minimal interaction between incident field and tiny fractal structures. Due to the longer incident wavelength, most magnetic fields are directly located at the two straight edges parallel to x axis.

Figure 5. Distribution of magnetic field for the third- iteration SCBA at four spectral points: (a) Third resonance at $0.8\mu\text{m}$, (b) primary resonance at $1.34\mu\text{m}$, (c) secondary resonance at $1.45\mu\text{m}$ and (d) above resonance at $3\mu\text{m}$

4. CONCLUSION

In summary, we introduce the fractals into the traditional complementary bowtie aperture. Numerical investigation demonstrates magnetic field can be localized and enhanced in fractal apertures in the near-infrared and mid- infrared region. Compared to CBA, magnetic field enhancement in the STDA is further improved by a moderate enhancement and resonant wavelength is blue-shifted in the first-iteration aperture. When continue increasing the iteration, the red shift appears. For CBA and the first-iteration SCBA, electric field and current density distribution at respective resonance is analyzed. Current can be enhanced in the center of the aperture for the both while electric fields are found to be easier to concentrate at the tiny fractal structures. Magnetic intensity distributions at points of interest in the spectrum of the third-iteration SCBA are also investigated and longer wavelengths are not suitable for confining magnetic field in SCBA due to weak interaction with the fractals.

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