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Citation: AIP Advances 5, 107149 (2015); doi: 10.1063/1.4935194
View online: http://dx.doi.org/10.1063/1.4935194
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Resonance spectra of diabolo optical antenna arrays

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(Received 1 August 2015; accepted 21 October 2015; published online 30 October 2015)

A complete set of diabolo optical antenna arrays with different waist widths and periods was fabricated on a sapphire substrate by using a standard e-beam lithography and lift-off process. Fabricated diabolo optical antenna arrays were characterized by measuring the transmittance and reflectance with a microscope-coupled FTIR spectrometer. It was found experimentally that reducing the waist width significantly shifts the resonance to longer wavelength and narrowing the waist of the antennas is more effective than increasing the period of the array for tuning the resonance wavelength. Also it is found that the magnetic field enhancement near the antenna waist is correlated to the shift of the resonance wavelength. © 2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License.

Optical antennas have been extensively investigated in the past decade for potential applications in biochemical sensing,1,2 surface enhanced Raman spectroscopy (SERS),3,4 optical tweezers,5 and photochemistry.6–8 Earlier studies have been focused on bowtie optical antennas with different shapes of metal patches and apertures.9–20 Recently, rectangular metal bar optical antenna arrays have been investigated due to the easy tuning of the resonance wavelength and near-field spatial distributions through modifying antenna bar length, array period, and substrate.21–27 A diabolo antenna is a variation of a rectangular metal bar antenna with reduced waist width. The shape of diabolo metal bar can be considered as two triangular shaped metal patches overlapping each other. Recent studies have shown that strong magnetic field enhancements around the narrow waist of diabolo antennas, which has proven useful for low power nano-particle optical vortex trapping to reduce heating and damaging in biological particles.28 The antenna parameters significant for near field enhancement are the thickness of the metal film, the metal antenna length, array period, and width of the waist. Previous works predicted that thinner metal film thicknesses and smaller central strip widths can produce larger magnetic field enhancement, with electromagnetic simulations indicating that this induces resonance wavelength red-shifts.29 Previous studies also have found that the scattering and absorption cross sections of single metal bar optical antennas can be increased by narrowing the waist of diabolo bars and that the resonance shifts to longer wavelength by reducing the waist of metal bars.30 However, these results are based on the numerical simulations. In this work, we fabricated metal diabolo antenna arrays with various waist widths and periods on a sapphire substrate. Optical reflectance and transmittance of the fabricated diabolo optical antenna arrays were measured by using a microscope-coupled FTIR optical spectrometer. It is found that the structure, in terms of the resonance wavelength shifting, responds significantly to reductions in waist width as opposed to change of the array period. It is also found that magnetic field enhancement near the diabolo waist is proportional to the resonance wavelength shift.

Diabolo optical antenna arrays of various waists and periods were fabricated by using an e-beam lithography and lift-off process on a sapphire substrate. During the fabrication, the sapphire substrate was first cleaned with acetone and deionized (DI) water. A PMMA 495k e-beam resist layer was spin-coated on the sapphire substrate at the spin speed of 2000 rpm. The substrate was
then baked on a hot plate at 180 °C for 120 seconds. Narrow waist bars were patterned by using electron beam lithography. After the e-beam lithography patterning, the sample was developed in the solution of 1:3 MIBK/IPA for 150 seconds and rinsed by using the IPA and followed by a spin-dry process. A 2 nm chromium layer and a 33 nm gold film were evaporated on the patterned sample, with Cr serving as the adhesion layer. A lift-off process was carried out in acetone solution for 12 hours, which left periodic arrays of narrow waist diabolo gold bars on the sapphire substrate. The length of the metal bars is 1.1 µm, while the width at two ends was maintained at 260 nm. Each antenna array has a 250 µm by 250 µm area and the antenna arrays are separated by 3 mm distance. We fabricated metal bar optical antenna arrays with four periods of P = 2.6 µm, 2.7 µm, 2.8 µm, and 2.9 µm. For each period, we fabricated five antenna arrays with waist width of 60 nm, 80 nm, 140 nm, 200 nm, 260 nm, respectively. Fig. 1 shows SEM images of four arrays. Narrow waist metal bars are arranged periodically on a sapphire substrate with equal periods in the two lateral x and y directions. In this figure, all arrays have the same period of 2.7 µm but different waist widths. The insert to Fig. 1(a) indicates the geometric parameters of a single diabolo antenna with waist width w = 60 nm. The example arrays pictured in Fig. 1(a)–1(d) have waist widths of 60, 80, 140, and 260 nm. The thickness of the gold metal bar antenna is 33 nm in the z direction. When the waist width equals to the width at the ends, i.e. w = 260 nm, the diabolo antennas become rectangular metal bar antennas. Due to the fabrication difficulties, the designed minimum waist width is 60 nm.

Transmission and reflection spectra from fabricated optical antenna arrays were measured by using a FTIR microscope optical spectrometer (Thermoscientific Nicolet Continuum) with a Cassegrain reflective objective (15x, 0.58 numerical aperture) that illuminates the antenna array over a range of incidence angles spanning ~10° to 35° from the surface normal, with a weighted average angle of approximately 22°. Polarization of the incident light was aligned with the antenna’s long axis. Spectra collected with polarization set transverse to the antennas produced no spectral features in the IR region. The relative reflectivity is used for analysis purpose. Relative reflectivity is defined as the power reflection difference from the antenna array and a bare sapphire substrate normalized to the optical reflection from the bare sapphire substrate. In the experiment, we focus

![Diagram of diabolo antenna arrays](image-url)
FIG. 2. Measured relative reflectivity and transmittance spectra from diabolo antenna arrays of different waist widths and periods: (a) Relative reflectivity of different waist width with the same period 2.7 µm, (b) Transmittance of different waist width with the same period 2.7 µm, (c) Relative reflectivity of different period but with the same waist width 60 nm, (d) Transmittance of different period but with the same waist width 60 nm. The insert in (a) and (b) shows the variation of the resonance peak wavelength with the waist width. The insert in (c) and (d) shows the variation of the resonance peak wavelength with period.

only on observing the resonant wavelength shift caused by changing waist width and changing the array period. The measured reflectivity and transmittance are shown in Fig. 2, with the resonance wavelengths in reflection (R) and transmission (T) summarized in Table I. The inserts in Fig. 2 show the variation of the measured resonance peak wavelength with the waist width of the diabolo antenna bars. With diabolo waist decreasing from 260 nm to 60 nm, the resonance wavelength has a red-shift of 661 nm in reflection and a red-shift of 787 nm in transmission. However, while the array period changes from 2.6 µm to 2.9 µm, the resonance wavelength shift is 146 nm in reflection and 167 nm in transmission. We noticed that reducing the waist width is much more effective to than increasing the period for tuning the resonance wavelength.

To understand the resonance behavior of diabolo antennas, we analyzed the transmittance and reflectance by using a commercial finite difference time domain (FDTD) software developed by Lumerical Solution, Inc. In the simulation, periodic boundary condition is used for the x and y boundaries. Perfectly matched layer (PML) boundary conditions are used in the z direction above and below the antenna structure. A plane wave with x polarization propagates in the z direction.

<table>
<thead>
<tr>
<th>Device</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
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</thead>
<tbody>
<tr>
<td>P (µm)</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.6</td>
<td>2.7</td>
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<tr>
<td>w (nm)</td>
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<td>80</td>
<td>140</td>
<td>200</td>
<td>260</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>λ_{res} (µm) in R</td>
<td>5.088</td>
<td>5.026</td>
<td>4.719</td>
<td>4.577</td>
<td>4.427</td>
<td>5.042</td>
<td>5.088</td>
<td>5.144</td>
<td>5.188</td>
</tr>
<tr>
<td>λ_{res} (µm) in T</td>
<td>5.108</td>
<td>4.961</td>
<td>4.663</td>
<td>4.539</td>
<td>4.321</td>
<td>5.034</td>
<td>5.108</td>
<td>5.146</td>
<td>5.201</td>
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</tbody>
</table>
FIG. 3. (a) Reflectance of diabolo antenna arrays with different waist widths but a fixed array period 2.7 µm. (b) Transmittance of diabolo antenna arrays with different waist widths but a fixed period 2.7 µm. (c) Reflectance of diabolo antennas with different array periods but a same waist width (w) of 60 nm. (d) Transmittance of diabolo antenna arrays with different periods but a same waist width of 60 nm.

Two 2D optical power monitors were used to capture the transmittance and reflectance. A near field monitor was placed in the middle of the gold metal bars at z = 16.5 nm to analyze the near electric field and magnetic field distributions. Electric permitivities of gold (Au) and chromium (Cr) in numerical simulations were taken from Palik’s Handbook of Optical Constants. The simulated optical reflection and transmission of diabolo antenna arrays with different array periods and waist widths are shown in Fig. 3, with the resonance wavelengths in reflection (R) and transmission (T) summarized in Table II. From Fig. 3, it can be observed that the resonance wavelength red-shifts while decreasing waist width and increasing array period in approximately same amount as the experimental results. From Table II, it can be seen that as increasing the waist width from 60 nm to 260 nm (A-E), the resonance wavelengths for R and T shift to shorter wavelength: 5.113 µm to 4.497 µm for reflection and 5.137 µm to 4.492 µm for transmission. Meanwhile, from device F to device I, as the period increasing from 2.6 µm to 2.9 µm the resonance wavelengths for R and T increase from 5.062 µm to 5.216 µm and from 5.116 µm to 5.211 µm, respectively. In Fig. 2, the reflectance and transmittance from experimental results show obvious spectrum broadening with decreasing the waist width. However, we do not observe the same phenomenon in simulation results

<table>
<thead>
<tr>
<th>Device</th>
<th>A</th>
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<th>F</th>
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<td>$\lambda_{res}$ (µm) in R</td>
<td>5.113</td>
<td>4.988</td>
<td>4.755</td>
<td>4.565</td>
<td>4.497</td>
<td>5.062</td>
<td>5.113</td>
<td>5.169</td>
<td>5.216</td>
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<tr>
<td>$\lambda_{res}$ (µm) in T</td>
<td>5.137</td>
<td>4.993</td>
<td>4.765</td>
<td>4.561</td>
<td>4.492</td>
<td>5.116</td>
<td>5.137</td>
<td>5.168</td>
<td>5.211</td>
</tr>
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</table>
in Fig. 3. This can be explained as fabrication defect. In the SEM images in Fig. 1, it is observed that the shape of fabricated diabolo antennas does not follow our design exactly. This is due to the uncertainty of the electron beam lithography process. The fabrication uncertainty can cause rounding corners at both side of the antenna and rounding corners at the apex of the waist width. Also the uncertainties of material properties should also be taken into account. However, the rounding corners can be modified during the simulations. After taking the rounding corners issue into account in simulations, it can be seen from the inserts in Fig. 3 that the spectral resonance peak positions are in excellent agreement with the experimental results.

Although previous studies indicated that reducing the width of waist in a diabolo shape optical antenna increases the magnetic field near the waist and shifts the resonance to longer wavelengths.\textsuperscript{29} However, the quantitative relation between magnetic field enhancement and resonance wavelength shift was not investigated. Fig. 4 shows the near field enhancement distributions at the resonance wavelengths of optical antennas with waist width of $w = 60$ nm and $260$ nm, plotted in the logarithmic scale. We calculated near field distributions in one unit cell in x-y plane in the middle of the gold layer at $z=16.5$ nm. We observed from figure 4(b) and 4(d) that the near magnetic field for waist width 60 nm are greatly enhanced than the diabolo antenna with waist width 260 nm at their respective resonance wavelengths. The magnetic field is enhanced 52 times greater than the initial value at the resonant wavelength for diabolo antenna with $w=60$ nm, while the magnetic field is enhanced 28 times greater than the initial value for the antenna with $w=260$ nm. We also observed that the near electric field enhancement changes only a very small amount for these waist sizes. According the Ampere’s law, the tapered waist in the center of metal bar causes the current density to increase and induces a strong magnetic field distribution around the narrow waist. For diabolo antenna with smaller waist width, the current density in the waist increases more than the antenna with lager waist width. In the traditional diabolo antenna, the enhanced magnetic field is azimuthally polarized around the central metal strip.\textsuperscript{28} For the diabolo antenna in this paper, it is

![FIG. 4.](image_url)

(a) Electric field enhancement profile of diabolo metal bar antenna $w=60$ nm. (b) Magnetic field enhancement profile of a diabolo metal bar antenna array ($w=60$ nm). (c) Electric field enhancement distribution of a rectangular metal bar antenna array ($w=260$ nm). (d) Magnetic field enhancement distribution of rectangular metal bar antenna $w=260$ nm.
found that the enhanced magnetic field is around the narrow waist of metal bar and the maximum enhancement is at the apex of the waist width.

To further understand the resonance wavelength shift caused by reduction of the waist width of the diabolo antennas, a point monitor was placed close to the diabolo antenna waist where the maximum of magnetic field enhancement is located. Fig. 5 shows the calculated magnetic enhancement varying with waist widths and periods. In Fig. 5(a), it shows the magnetic field enhancement of diabolo antenna arrays with different waist widths, but a fixed period of 2.7 µm. It can be seen that the magnetic field of diabolo antenna array of 60 nm waist width is enhanced 52 times larger than the magnetic field of the incident optical wave. The magnetic field of rectangular metal bar antenna array with 260 nm waist width is 28 times of the magnetic field of incident wave. Then the waist width is kept at 60 nm and the period is changed from 2.6 µm to 2.9 µm. In Fig. 5(b), we found that the magnetic field enhancement difference between periods from 2.6 µm to 2.9 µm is relatively small. The magnetic field enhancements for diabolo antenna array with 2.9 µm period and 2.6 µm period is enhanced 54 times and 50 times than the value of incidence, respectively. It also can be seen that stronger the magnetic field enhancement corresponds to a longer resonance wavelength. The magnetic field enhancement is strongly correlated to the shift of the resonance wavelength.

In summary, optical resonance spectra of diabolo antenna arrays with varied waist width and array period were investigated through experiment and numerical simulations. A complete set of diabolo optical antenna arrays with different waist widths and array periods was fabricated on a sapphire substrate using a standard e-beam lithography and liftoff process. Fabricated optical antenna arrays were characterized by measuring the transmittance and reflectance spectra with microscope-coupled a FTIR optical spectrometer. Finite difference time-domain (FDTD) numerical simulations were carried out for investigating the relationship between near magnetic field enhancement and the resonance wavelength shift. It was found that reducing the waist width shifts the resonance wavelength significantly to longer wavelength and greatly enhances the near magnetic field, while changing the antenna array period also changes the resonance wavelength but has less effect. We noticed that the magnetic field enhancement in the diabolo antenna waist is strongly correlated to the resonance wavelength shift.

This work was partially supported by National Science Foundation (NSF) (1158862). Hong Guo acknowledges the support from the Alabama Graduate Research Scholars Program. Authors acknowledge Dr. Jeffrey C. Owreutsky and Dr. James P. Long for insightful discussions on optical antennas. Correspondence should be sent to guoj@uah.edu.
