

# Subwavelength Polarization Control of Magnetic Fields in Plasmonic Nanocircuits

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**Abstract**—Magnetic surface plasmons (MSP) provide a strong potential for the extension of optical circuitry into the nanometer scale. This can lead to technology on a scale that rivals that of electronic devices, but operates at faster speeds. The understanding of MSP subwavelength focusing and propagation in potential circuit structures is crucial for the advancement of nano-optical circuitry. In a complex structure, MSP are produced when subjected to incident electromagnetic radiation. We show that by varying the incident light's wavelength and polarization, it is possible to control the location of magnetic field hot spots within the structure. The polarization control can provide greater contrast in magnetic field strength along each arm of the nanocircuit than the wavelength control, making the switch in direction more apparent. Varying the polarization as well as the incident light's wavelength can provide a flexible method of magnetic field control in plasmonic circuits.

## I. INTRODUCTION

Optical circuit technology demonstrates faster speeds compared to electronic circuits, and are capable of carrying more information. Unfortunately, most current optical components are much larger than their electronic counterparts. Development of optical circuitry on a smaller scale is crucial in order to create circuits that are comparable to the size of current electronic components. Circuits that utilize surface plasmons are a good option that can lead to optical technology on a nanometer scale [1].

Surface plasmons are electron oscillations on the surface of a metal that produce electromagnetic fields. Typically, the magnetic fields produced are much weaker compared to the electric fields. However, more complex structures can be used to produce surface plasmons that optimize magnetic field production; these surface plasmons are called magnetic plasmons. Magnetic plasmon propagation is most ideal for nano-optical circuits due to their lower losses compared to electric plasmons [2].

An understanding of how to control the location of magnetic field hot spots and the direction of magnetic plasmon propagation is crucial in order to be able to create nano-optical circuits. Since electric plasmons are more well-known and understood [3]–[5], a relationship between their behavior and the behavior of magnetic plasmons could provide stronger understanding that could explain the magnetic plasmon behaviors. This paper investigates the variation of the incident

light's wavelength and polarization as a method for controlling the magnetic fields in plasmonic nanocircuits.

## II. METHODS

Using *Multiple Elastic Scattering of Multipole Expansions* (MESME) the near-field excitation of a structure was calculated. MESME requires input data regarding the cluster's properties, as well as electric and magnetic properties of its surrounding medium, and calculates exact solutions to Maxwell's equations, returning far-field and near-field results. The results returned are the cluster's response to incident plane wave emissions. The incident light's wavelength, angle of incidence, and polarization are also required for the calculations.

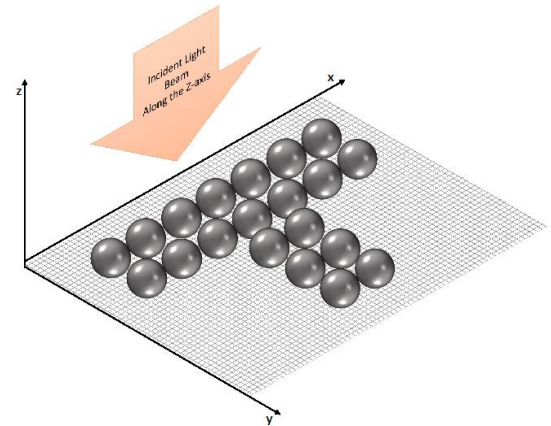


Figure 1: Plasmonic nanocircuit made of 20 silver nanospheres of 25nm radius with 10nm gaps is excited by plane waves of varying wavelength and polarization

The plasmonic nanocircuit examined consists of 20 silver spheres of radius 25nm, separated by 10nm gaps, forming a T-shape; shown in Figure 1. It was considered in a vacuum environment. The incident light was perpendicular to the plane of the structure (parallel to the z-axis). The light's wavelength was varied from 200nm to 800nm; its polarization ranged from 0 degrees (parallel to the x-axis) to 90 degrees (parallel to the y-axis). Based on these varying parameters, MESME returned the electric and magnetic near-field response.

The structure was excited by two incident beams; one polarized along the x-axis and the other polarized along the y-axis. In MESME the response for each polarization is

calculated, then the sum of the field's strength is taken. By varying the incident light's wavelength, the maximum magnetic field strength was found along the vertical-arm and horizontal-arm of the structure.

The structure was also excited by single incident beams, where the polarization was varied from 0 degrees to 90 degrees. Again, the incident wavelength was varied to find the maximum magnetic field strength along the vertical-arm and horizontal-arm.

The primary responses were the z-component of the magnetic field  $B_z$ , as well as the x-component and y-component of the electric field  $E_x$  and  $E_y$ . All wavelengths and positions observed were in consideration to the response of  $B_z$ .

### III. RESULTS

When excited by both x-polarized and y-polarized light, the structure produced its strongest magnetic response along the vertical-arm at 392nm wavelength. At 428nm wavelength, the strongest magnetic response was observed on the horizontal-arm. Figure 2 (a) and (b) show the  $B_z$  responses at 392nm and 428nm wavelengths, respectively. The field strength at the hot spot locations were plotted against varying wavelengths in Figure 2 (c). At 392nm, it shows the magnetic field amplitude on the vertical-arm is 3.77 times stronger than on the horizontal-arm. At 428nm, it shows the magnetic field amplitude on the horizontal-arm is 1.14 times stronger than on the vertical-arm.

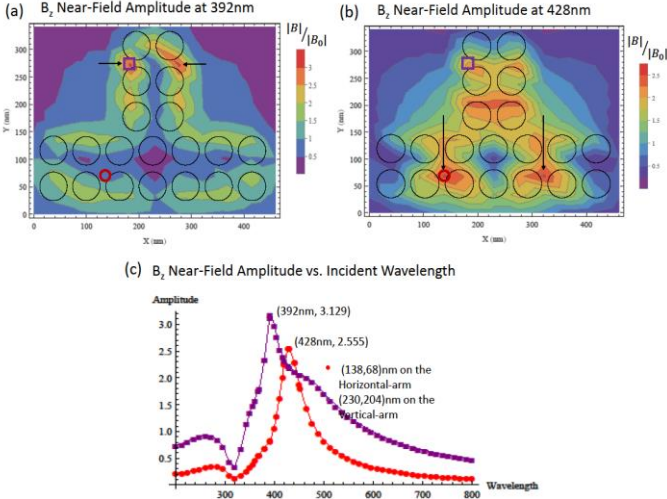


Figure 2: (a) and (b) show the out-of-plane magnetic field  $B_z$  for the structure excited by incident light polarized in both the x-direction and y-direction, at 392nm and 428nm wavelengths, respectively. (c) is the comparison of  $B_z$  at the positions indicated by the purple square (vertical-arm) and red circle (horizontal-arm) in (a) and (b).

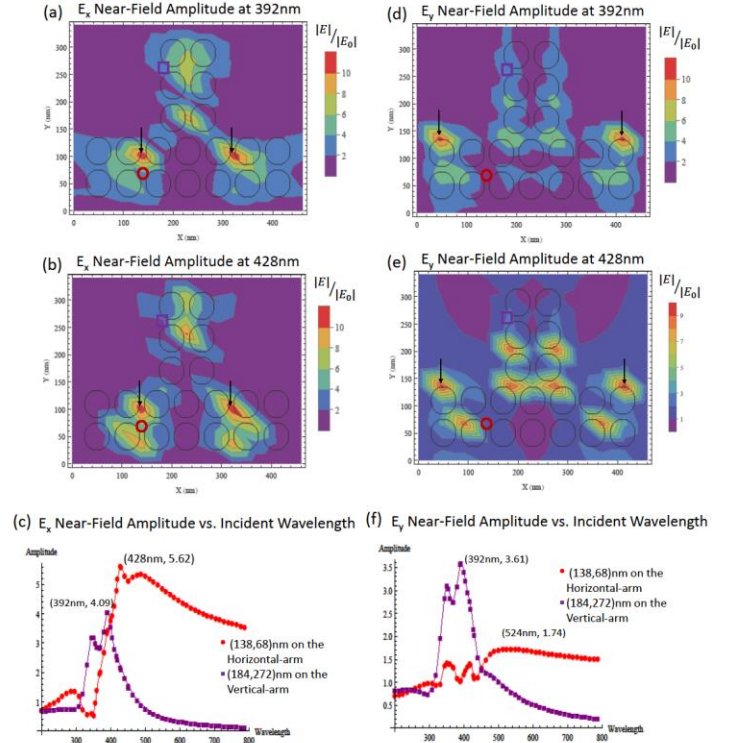


Figure 3: (a) and (b) show the electric field  $E_x$  for the structure excited by incident light polarized in both the x-direction and y-direction, at 392nm and 428nm wavelengths, respectively. (c) is the comparison of  $E_x$  at the positions indicated by the purple square (vertical-arm) and red circle (horizontal-arm) in (a) and (b). (d) and (e) show the electric field  $E_y$  for the structure excited by incident light polarized in both the x-direction and y-direction, at 392nm and 428nm wavelengths, respectively. (f) is the comparison of  $E_y$  at the positions indicated by the purple square (vertical-arm) and red circle (horizontal-arm) in (d) and (e).

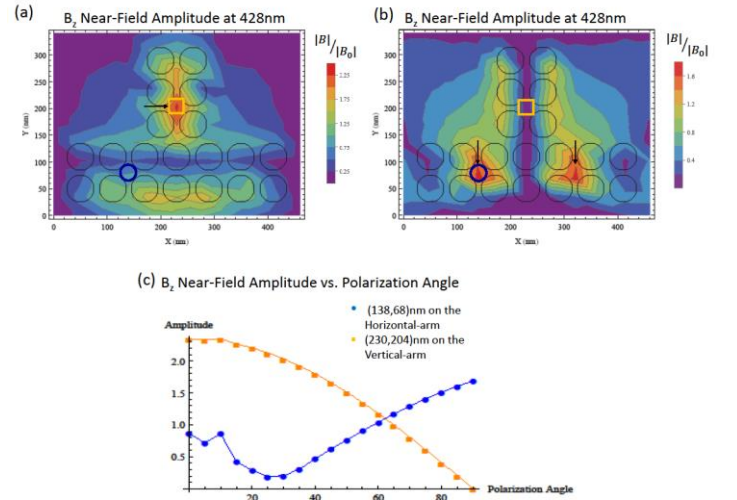


Figure 4: (a) and (b) shows the out-of-plane magnetic field  $B_z$  for the structure excited by 428nm wavelength light at 0 degree and 90 degree polarization, respectively. (c) is the comparison of  $B_z$  at the positions indicated by the orange square (vertical-arm) and blue circle (horizontal-arm) in (a) and (b). X-polarized light is equal to a 0 degree polarization angle. Y-polarized is equal to 90 degrees.

The x-component of the electric field at the magnetic hot spot

positions demonstrated similar behavior. Figure 3 (c) shows at 392nm the strength of  $E_x$  on the vertical-arm is 1.18 times stronger than the horizontal-arm. At 428nm, the strength of  $E_x$  on the horizontal arm is 2.53 times stronger than the vertical-arm. The y-component of the electric field at the magnetic hot spot positions does not demonstrate switching between 392nm and 428nm wavelengths, as seen in Figure 3 (f). However, the position of the electric hot spots does not changed between 392nm and 428nm wavelengths, as seen in Figure 3 (a), (b), (d), (e).

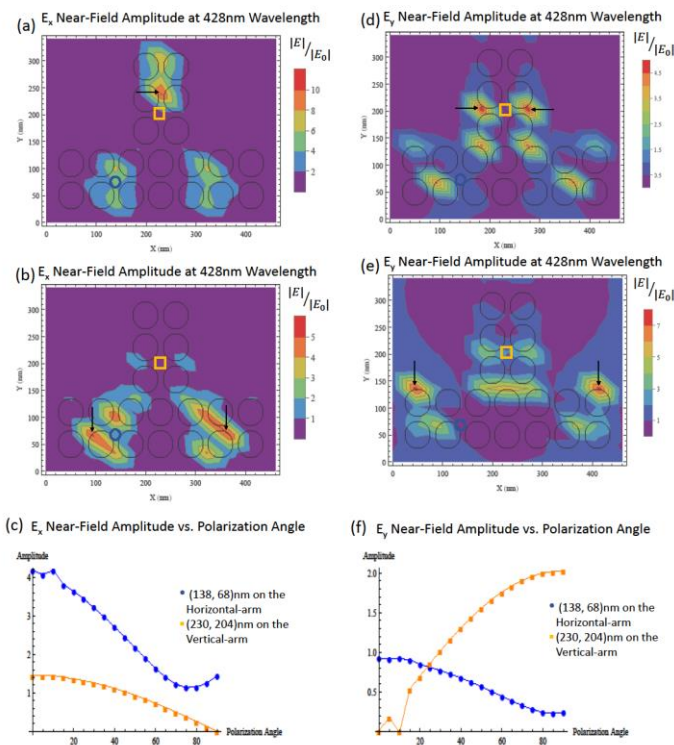


Figure 5: (a) and (b) shows electric field  $E_x$  for the structure excited by 428nm wavelength light at 0 degree and 90 degree polarization, respectively. (c) is the comparison of  $E_x$  at the positions indicated by the orange square (vertical-arm) and blue circle (horizontal-arm) in (a) and (b). X-polarized light is equal to a 0 degree polarization angle, Y-polarized is equal to 90 degrees. (d) and (e) shows electric field  $E_y$  for the structure excited by 428nm wavelength light at 0 degree and 90 degree polarization, respectively. (f) is the comparison of  $E_y$  at the positions indicated by the orange square

When excited a single plane wave, the structure produced its strongest magnetic response along the vertical-arm at a polarization of 0 degrees (x-polarized). With a polarization of 90 degrees (y-polarized), the strongest magnetic response occurred on the horizontal-arm; as shown in Figure 4 (c). For x-polarized light, the magnetic field along the vertical-arm is 2.7 times stronger than along the horizontal-arm. For y-polarized light, the magnetic field along the vertical-arm is negligible.

The strength of  $E_x$  along the vertical-arm doesn't surpass the strength of  $E_x$  along the horizontal-arm at any polarization angle. The strength of  $E_y$  along the vertical-arm is negligible for x-polarized incident light. The strength of  $E_y$  along the

vertical-arm is 8.4 times stronger than along the horizontal-arm. Figure 5 (a), (b), (d), (e) show the position of the electric hot spots change for x-polarized and y-polarized light.

When the wavelength of light is changed to 392nm for x-polarized light, the strength of the magnetic field along the vertical-arm is 12 times stronger than along horizontal-arm. The strength of  $E_x$  is 1.97 times greater on the vertical-arm than along the horizontal-arm for x-polarized light at 392nm wavelength. The strength of  $E_y$  along the vertical-arm is negligible.

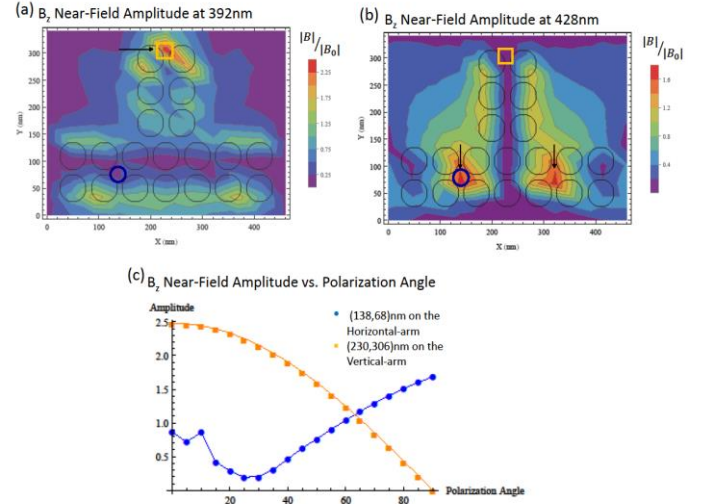


Figure 6: (a) shows the out-of-plane magnetic field  $B_z$  for the structure excited by 392nm wavelength light at 0 degree polarization. (b) shows the out-of-plane magnetic field  $B_z$  for the structure excited by 428nm wavelength light at 90 degree polarization (c) is the comparison of  $B_z$  at the positions indicated by the orange square (vertical-arm) and blue circle (horizontal-arm) in (a) and (b). X-polarized light is equal to a 0 degree polarization angle, Y-polarized is equal to 90 degrees.

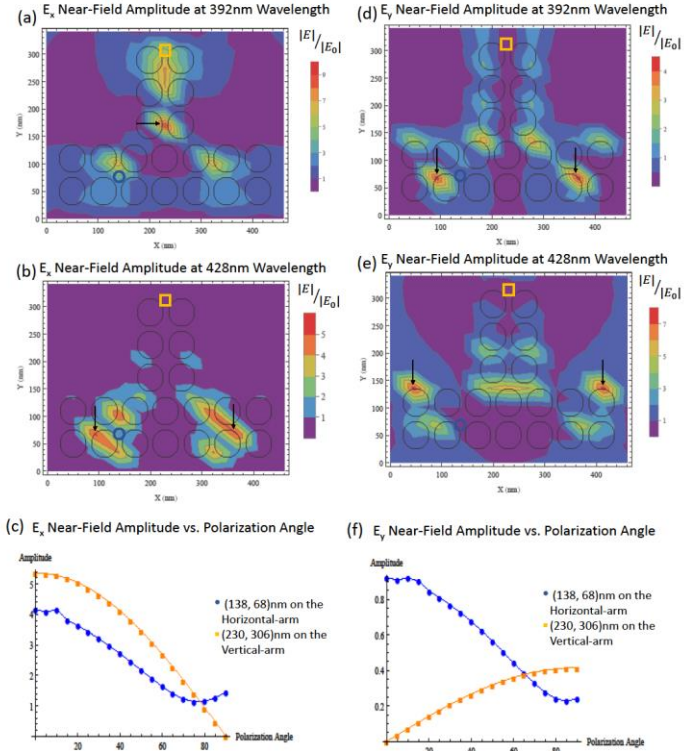


Figure 7: (a) shows the electric field  $E_x$  for the structure excited by 392nm wavelength light at 0 degree polarization. (b) shows the electric field  $E_x$  for the structure excited by 428nm wavelength light at 90 degree polarization (c) is the comparison of  $E_x$  at the positions indicated by the orange square (vertical-arm) and blue circle (horizontal-arm) in (a) and (b). X-polarized light is equal to a 0 degree polarization angle, Y-polarized is equal to 90 degrees. (d) shows the electric field  $E_y$  for the structure excited by 392nm wavelength light at 0 degree polarization. (e) shows the electric field  $E_y$  for the structure excited by 428nm wavelength light at 90 degree polarization (f) is the comparison of  $E_y$  at the positions indicated by the orange square (vertical-arm) and blue circle (horizontal-arm) in (d) and (e). X-polarized light is equal to a 0 degree polarization angle, Y-polarized is equal to 90 degrees.

#### IV. DISCUSSION

When excited by two incident plane waves, the structure had a stronger response along the vertical-arm at 392nm wavelength, and a stronger response along the horizontal-arm at 428nm wavelength. Figure 2 shows the control of magnetic field as the wavelength is varied. However, by solely varying the wavelength, provides a smaller difference in enhancement at the positions along the vertical and horizontal-arms.

At the positions where the magnetic hot spots occur, the behavior of the electric field doesn't exhibit a similar behavior to the magnetic field. Although  $E_x$  demonstrated switch between 392nm and 428nm wavelength, Figure 2 (c) and Figure 3 (c) show that the overall behavior isn't similar to the magnetic field. Also, Figure 3 (a), (b) and Figure 3 (d), (e) show that between these two wavelengths, there is no switching of the electric hot spot locations, regardless of the switch for the magnetic field hot spots.

When excited by a single incident beam at a constant wavelength, the structure had a stronger response along the vertical-arm for x-polarized light, and a stronger response along

the horizontal-arm for y-polarized light. Figure 4 shows the control of the magnetic field as the polarization angle is varied. This method showed a larger difference in enhancement at the positions along the vertical and horizontal-arms; especially for y-polarized light, where the field strength along the vertical-arm was negligible.

At the position where the magnetic hot spots occur, there are no relationships between the electric field and magnetic field.  $E_x$  doesn't exhibit any switch over all polarizations, as shown in Figure 5 (c), and although  $E_y$  shows switching in Figure 5 (e), the polarizations at which it occurs doesn't show any relation to the magnetic field in Figure 4 (c). However, when changed from x-polarized to y-polarized light, both  $E_x$  and  $E_y$  hot spots switch from a position along the vertical-arm to a position along the horizontal-arm.

Combining both methods provided the greatest contrast in field strengths for the structure. For x-polarized, 392nm wavelength light, the magnetic field strength was 12 times stronger along the vertical-arm. For y-polarized, 428nm wavelength light, the magnetic field strength along the vertical-arm was negligible. For the positions along the vertical and horizontal-arms, their respective wavelengths and polarizations provided a strong enhancement, while also suppressing the field strength at the position along the opposite arm.

For  $E_x$  the overall structure of the near-field seems to exhibit similar behavior to the magnetic field when the incident light's polarization is varied, but there is no explicit relationship between the two, and further investigation would be required.

#### V. CONCLUSION

In this paper, the magnetic plasmon behaviors based on the incident light's wavelength and polarization were explored. Directional control based on the light's wavelength was observed, although contrast of its strength along each arm wasn't great. When polarization was varied, the contrast of the magnetic field strength was greater. Ultimately, when both wavelength and polarization were varied, the strongest contrast in field strength was achieved. These methods show insight into the manipulation of magnetic plasmons in nanostructures, which can lead to a greater understand on how to approach nano-optical circuitry.

Also, a potential relationship between electric plasmon and magnetic plasmon behaviors was examined. The results of this paper didn't provide conclusive evidence of a relationship in this structure, but a possible one was noted. Further investigation is required to determine whether some relation between electric and magnetic plasmons is present.

In the future, laser pulse shaping techniques similar to in Ref. [5] and [6] may be found that can provide even greater propagation control for magnetic plasmons, leading to stronger enhancement at desired locations and greater field suppression at others.

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