Plasmonic planar antenna for wideband and efficient linear polarization conversion

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ABSTRACT

The design of metasurfaces able to efficiently control the polarization state of an electromagnetic wave is of importance for various applications. We demonstrate both theoretically and experimentally that plasmonic planar L-shaped antennas can induce a 90°-rotation of the linear polarization of light with a nearly total efficiency in the infrared (3-5 µm). The nanoantenna geometry is engineered so that the polarization conversion occurs over a 1 µm-wide spectral band ([3.25-4.25] µm) with a mean polarization conversion efficiency of 95 %. In order to validate a theoretical model describing the antenna behaviour, we investigate the polarization conversion effect as function of the incident and azimuthal angles.

Keywords: Plasmonic, Nano-antenna, polarization, converter

1. INTRODUCTION

The ability to control the polarization of an electromagnetic wave has a wide range of applications, like quarter wave plate\textsuperscript{1} or circular polarizers.\textsuperscript{2} This is classically done thanks to dichroic crystals or birefringent materials, but can also be achieved with plasmonic diffraction gratings\textsuperscript{3,4} or chiral structures.\textsuperscript{5} More recently, polarization conversion using plasmonic metasurfaces or metamaterials has attracted a wide attention. Demonstrations have been shown in the GHz,\textsuperscript{6-8} infrared\textsuperscript{9} and at optical frequencies.\textsuperscript{9,10} Although, a wideband circular polarizer based on a gold helix has been reported in the infrared\textsuperscript{11,12} and a wideband linear polarization converter in the THz region,\textsuperscript{13} most of these demonstrations have been restricted to narrow wavelengths ranges.

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In this paper, after a brief investigation of the resonant behaviour of a rectangular plasmonic patch antenna based on metal-insulator-metal (MIM) resonators, which are known to be spectrally tunable.\textsuperscript{14–17} We explain in a second part how a plasmonic planar L-shaped antenna, which results of a combination a rectangular antenna, can convert the linear polarization of light with a high efficiency on a wideband. Then, in a third part, the fabrication of these L-shaped antenna is described. In the fourth part, we demonstrate both theoretically and experimentally that it is possible to get an 80\%-efficient polarization converter on a 1 \(\mu\)m-wide band at wavelengths [3.25-4.25] \(\mu\)m.\textsuperscript{18} Eventually in the last part, the influence of the incident and the azimuthal angles on the polarization conversion is investigated.

2. DESCRIPTION OF THE RECTANGULAR MIM PATCH ANTENNA

We consider a rectangular MIM patch antenna, as depicted in Fig. 1. It consists in a bi-periodic pattern along \(x\) and \(y\) directions with period \(D\), made of a rectangular gold patch (width \(w\), length \(L\) and 50 nm thick) deposited on a 300 nm silicon oxide layer. The bottom gold layer is continuous and very thick compared to the skin depth of gold (25 nm in the infrared (IR) range).

The structure is illuminated by a normal incident light with a transverse electric polarization (\(i.e.\) \(E\) is along \(y\) axis). The reflectivity spectra are calculated with a Fourier modal method.\textsuperscript{19–21} At infrared wavelengths, the refractive index of silicon oxide is \(n_{SiO_2} = 1.4\). The dielectric function of gold is computed from a Drude model which fits the literature data: \(\epsilon(\lambda) = 1 - [(\lambda_p/\lambda + i\gamma)\lambda_p/\lambda]^{-1}\) with \(\lambda_p = 159\)nm and \(\gamma = 0.0077\).\textsuperscript{22} In order to investigate the influence of the in-plane parameter \(L\) and \(w\) on the reflectance, the reflectivity spectra have been computed for various values of \(L\) and \(w\) and a period set at \(D = 3\ \mu\)m respectively in Fig. 1(b) and (c). First, we can notice that in all considered structures, a very high absorption resonance appears for a specific wavelength. Out of the MIM antenna resonance, the surface appears as a metallic mirror with a nearly perfect reflection. Second, Fig. 1(b) shows that the position of the resonance is shifted from 3.5 to 5 \(\mu\)m when the length \(L\) of the antenna ranges from 1 to 1.5 \(\mu\)m. On the contrary, a shift from 100 to 300 nm of the width \(w\) slightly influences the resonance according to Fig. 1(c). These results are in agreement with a Fabry-Perot like resonance model that appears in the insulator layer of the MIM antenna.\textsuperscript{23} Indeed, following this model the resonance wavelength \(\lambda_r\) relative to the length \(L\) and the effective index of the propagation mode \(n_{eff}\) is described by the equation \(\lambda_r \approx 2Ln_{eff}\) (with \(n_{eff} \approx 1.5\)).

The MIM antenna reacts as a nano-resonator, which at the resonance radiates waves with a similar amplitudes of the incident field, and also polarized along \(y\)-axis. Therefore, in the case of a rectangular MIM antenna the resonant wave interferes destructively with the directly reflected wave explaining the nearly total absorption.
Figure 1. (a) Scheme of the array of the rectangular MIM antenna, which consists of a gold ribbon of 50 nm thickness, width $w$, length $L$ and period $D$ deposited on a 300 nm silicon oxide layer. The incoming plane wave is y-polarized (the electric field $E$ is along $y$), with an angle $\theta$ with respect to the $z$-axis. (b) Reflectivity spectra for a rectangular MIM antenna for $w = 100$ nm and $L$ ranges from 1 to 1.5 $\mu$m. (c) Reflectivity spectra for a rectangular MIM antenna for $L = 1$ $\mu$m and $w$ ranges from 100 to 300 nm. In both cases, the period $D$ is set at 3 $\mu$m.

3. DESCRIPTION OF THE L-SHAPED MIM ANTENNA

Now we consider a L-shaped MIM antenna as described in Fig. 2. The stick of layers is similar than previously, apart for the antenna top layer. The light impinging on the structure is in the incident plane which made an azimuthal angle $\delta$ with respect to the $xz$-plane, with a transverse electric polarization (i.e. $E$ perpendicular to the incident plane), and incident with an angle $\theta$ with respect to the $z$-axis.

This L-shaped antenna can be seen as the combination of two rectangular antennas placed orthogonally and coupled to each other. As for single rectangular antenna, the L-shaped antennas behave as resonator and thus at resonance wavelengths, they radiate waves polarized along each arm. Therefore this antenna is excited by an
incident light polarized along one of its arm, there are destructive interferences only along this direction. The wave radiated by the second arm (i.e. in the polarization perpendicular to the incident polarization) does not interfere and the resulting reflected wave is cross-polarized.

Figure 2. Scheme of the array of L-shaped MIM antenna, which consists of a gold L-shaped ribbon of 50 nm thickness (width $w$ and length $L$ are described in Fig. 1(a)) in each period $D = 1.5 \mu m$ deposited on a 300 nm silicon oxide layer. The incoming plane wave is y-polarized (the electric field $E$ is along $y$), with an incident angle $\theta$ with respect to the $z$-axis and an azimuthal angle $\delta$ with respect to the $x$-axis. A polarizer is placed on the optical path of the reflected wave and rotated either along $y$-axis (position $p_{||}$) or in the reflected-plane (position $p_{\perp}$).

4. FABRICATION OF AN EXPERIMENTAL SAMPLE

The sample was fabricated by first depositing a 200 nm gold layer on a silicon wafer using an e-beam evaporator (step 1 in Fig. 3(a)). Then a layer of 300 nm of SiO$_2$ was deposited by pulverisation. Next, a PMMA resist was spin-coated on the wafer (step 2 in Fig. 3(a)) and patterned by electron beam lithography with a Vistec Leica at 100kV. Eventually, the patterned top gold layer was obtained by a lift-off, after depositing 50 nm of gold, with a 3 nm adhesion layer of titanium (step 3 in Fig. 3(a)). A scanning electron microscope (SEM) image of the sample is shown in Fig. 3(b). The period was set at $D = 1.5 \mu m$, the dimensions of the antenna are $w = 430$ nm and $L = 930$ nm. The roughness on the edges was measured below 9 nm, which is small compared to the infrared wavelengths. The dimensions of the total sample array is 5x5 mm$^2$.

5. WIDEBAND AND EFFICIENT POLARIZATION CONVERTER

The reflectivity spectra of the sample were measured inside a Brucker Vertex 70v Fourier Transform Infrared Spectrometer (FTIR) under vacuum, with a polarized angularly resolved reflection module A513.
Figure 3. (a) Fabrication process of the L-shaped MIM antenna described in Fig. 2. (b) 45° tilted SEM image of a fabricated L-shaped MIM antenna array with \( w = 430 \) nm, \( L = 930 \) nm.

A polarizer is placed in a plane orthogonal to the optical axis of the reflected wave, and is used to measure the reflected intensities in both polarizations. Thus, we define the reflectivity coefficients \( R_\parallel \) when the polarizer is set in position \( p_\parallel \) and \( R_\perp \) when it is rotated of \( 90^\circ \) and is in \( p_\perp \) position.

The reflectivity coefficients \( R_\parallel \) (red lines) and \( R_\perp \) (blue lines) were measured for two configurations of the polarizer (respectively \( p_\parallel \) and \( p_\perp \)) at an incidence of \( 13^\circ \) and an azimuth of \( 0^\circ \) and plotted in Fig. 4(a) (solid lines). First, there is a nearly total extinction of the reflectivity \( R_\parallel \) between \( 3.25 \) µm and \( 4.25 \) µm with two resonances at \( \lambda_1 = 3.4 \) µm and \( \lambda_2 = 4.2 \) µm. Second, the cross-polarized reflectivity \( R_\perp \) in this wavelength range is nearly constant and higher than 70%. The polarization conversion ratio (PCR), defined as:

\[
P_{\text{CR}} = \frac{R_\perp}{R_\perp + R_\parallel}
\]

is plotted on the same figure (green lines). The PCR is greater than 95% on this 1 µm band, which indicates that there is a nearly total conversion of the polarization of the reflected light. However, it must be emphasized
Figure 4. (a) Reflectivity spectra of a y-polarized plane wave impinging on at an incidence $\theta$ of $13^\circ$ measured (solid lines) and computed (dashed lines). (b) Maps of the losses $\Im(\epsilon)E^2$ integrated on the thickness of the considered metallic layer (red area described in the central scheme) at $\lambda_1 = 3.4 \mu m$. (b) Maps of the losses $\Im(\epsilon)E^2$ integrated on the thickness of the considered metallic layer (red area described in the central scheme) at $\lambda_2 = 4.2 \mu m$.

that nearly 20% of the incident light is dissipated in the metal (which is lossy in the IR). This is higher than on a plane surface due to the resonance in the MIM antenna. In order to investigate the dissipation mechanisms at stake, maps of the electromagnetic dissipation losses occurring in metallic layers (i.e. in the top L-shaped gold antenna and the bottom gold mirror) are plotted at both wavelengths $\lambda_1$ and $\lambda_2$ respectively in Fig.4(b) and Fig.4(c).

First, it must be noticed that the dissipation maps are quiet similar for both resonance wavelength. Second,
the spatial distribution of dissipation is different according to the gold layer considered. Indeed, in the top layer of antenna, the presence of sharp edges involves a local strong enhancement of the electric field. Third, remarkably, the dissipation amplitude in the antenna is nearly 100 times more important than in the bottom gold mirror. Indeed, the loss in the L-shaped patch represents nearly 85% of the losses.

The two resonances wavelengths do not depend in the same manner on the in-plane dimensions of the antenna. These two resonances are balanced by the choice of the geometric parameters which has permitted to design this wideband converter. The structure was theoretically investigated with the Fourier modal method used above. The corresponding computed spectra are also plotted in Fig. 4(a) (dashed lines), there is a rather fair agreement between experiments and computations.

6. INCIDENCE AND AZIMUTHAL ANGLE DEPENDENCES

Figure 5. (a) Polar plot of experimental values (red crosses) and computed values (solid line) of the mean PCR on the band [3.25-4.25] µm as a function of the incident angle for an azimuthal angle set at 0°. (b) Computed values (solid lines) and theoretical values following Eqs. (4-3) (dashed lines) of the mean reflectivity $R_\parallel$ and $R_\perp$ on the band [3.25-4.25] µm as a function of the azimuthal angle for a incident angle set at 0°.

The angular dependence of the L-shaped antenna is now considered. Both resonance wavelengths $\lambda_1^r$ and $\lambda_2^r$ appear independent of the incidence angle (not show here).

First, in order to quantify the angular dependency of the efficiency of conversion, Fig.5(a) represents the mean value of the reflectivity PCR on the [3.25-4.25] µm band in function of the incident angle $\theta$, the azimuthal angle set at 0°. There is still a fair agreement between experimental and computed values. Besides, the mean PCR remains higher than 80% up to 45°. These results demonstrate that the polarization conversion in the L-shaped antenna does not depend on the incidence angle due to the localized nature of the resonances at stake.\textsuperscript{15,17}

Now, we investigate the angular dependency of the structure on the azimuthal angle $\delta$ with a normal incident angle (i.e. $\theta = 0^\circ$). Fig. 5 (solid line) represents the evolution of the mean values of the reflectivity $R_\parallel$ and
$R_\perp$ computed on the [3.25-4.25] µm band for the azimuthal angle $\delta$ ranges from 0° to 90° (i.e. respectively for $xz$ to $yz$-plane incidence). We can notice that the reflectivity $R_\parallel$ and $R_\perp$ evolve sinusoidally with $\delta$ and in quadrature. Indeed, the maximum of $R_\parallel$ corresponds to the minimum of the $R_\perp$. Besides, the absorption in the L-shaped antenna stays constant with the azimuthal angle. In order to describe this evolution of the reflectivity, we propose an analytical model based on the Jones formalism. Indeed, following the argument described in the first part, the radiation properties of the L-shaped antenna at the resonance can be described by the Jones matrix $R_{\text{radiate}}$, such as:

$$R_{\text{radiate}} = -\begin{pmatrix} 1 & \eta \\ \eta & 1 \end{pmatrix}$$ (1)

where $\eta$ is the efficiency in amplitude of the cross-conversion polarization (in our case, $\eta^2 = 0.8$).

Thus, considering a normalized incident TE-polarized wave, its related Jones vector is $\vec{E}_{\text{inc}} = (-\sin(\delta), \cos(\delta))$ in the $xy$-plane. The total reflected field $\vec{E}_{\text{reflected}}$ results from the interferences between the incident and the radiate electric fields:

$$\vec{E}_{\text{reflected}} = (I_2 + R_{\text{radiate}}) \vec{E}_{\text{inc}}$$

$$= \begin{pmatrix} -\eta \cos(\delta) \\ \eta \sin(\delta) \end{pmatrix}$$ (2)

with $I_2$ represents the Jones matrix of the incident medium (i.e. the identity matrix in the case of air). Finally, the reflectivity $R_\parallel$ and $R_\perp$ can be expressed as:

$$R_\parallel = \left(\vec{E}_{\text{reflected}} \cdot \vec{E}_{\text{inc}}\right)^2 = 4\eta^2 \cos(\delta)^2 \sin(\delta)^2$$ (3)

$$R_\perp = \left(\vec{E}_{\text{reflected}} \times \vec{E}_{\text{inc}}\right)^2 = \eta^2 \cos(2\delta)^2$$ (4)

Equations (3-4) are plotted in Fig. 5(b)(dashed curve). The good agreement between the theoretical and the computed results demonstrates the coherence of our model in order to describe the L-shaped antenna behaviour in the resonance [3.25-4.25] µm band.

7. CONCLUSION

In conclusion we have demonstrated, both theoretically and experimentally, that array of L-shaped antennas can induce a 90°-rotation of the linear polarization of light with a nearly total efficiency (PCR ≥ 95%). This
was demonstrated over a 1 µm-wide spectral range in the IR. According to the study described in the first part and in Ref., we have demonstrated that this effect is due to two resonances, which are tunable with the in-plane geometry of the antenna. Besides, other spectral shape can be obtained, like a dual-band polarization converter. Furthermore, we have demonstrated that this effect is independent of the incident angle. The study of the influence of the azimuthal angle on the reflectivity has validated our theoretical model based on the Jones formalism. The bandwidth could be further increased by exploiting recent advances on the MIM antenna: the possibility to engineer the quality factor of the resonances and to combine several resonators. Pioneer works have recently demonstrated the possibility of using planar antennas for designing optical components. In these devices, only a small fraction of the incoming wave is transmitted in the cross-polarization by V-shaped antennas. Nevertheless, the efficiency of this devices is a pending issue that limits their applications. Results presented in this paper should pave the way to the design of efficient planar optical components in the infrared, in a similar way as in the THz domain.

REFERENCES


