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Extended summary

# Light Propagation Control with Flat Plasmonic Metasurfaces

*Curriculum: Ingegneria dei Materiali, delle Acque e dei Terreni*

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**Abstract**. Conventional optical components such as lenses, prisms, and waveplates, involve engineering of the wavefront as it propagates through an optically thick medium. One can instead exploit abrupt phase and polarization changes associated with scattered light from optical resonators to control light propagation. This work is about the optical responses of anisotropic plasmonic antennas and a new class of planar optical components ("metasurfaces") based on arrays of these antennas. To demonstrate the versatility of metasurfaces, the design and experimental realization of a number of flat optical components are proposed: metasurfaces with a constant interfacial phase gradient that deflect light into arbitrary directions; planar lenses and axicons that generate spherical wavefronts and non-diffracting Bessel beams, respectively; metasurfaces with spiral phase distributions that create optical vortex beams of well-defined orbital angular momentum; and metasurfaces with anisotropic optical responses that create light beams of arbitrary polarization over a wide wavelength range.

**Keywords.** Metasurfaces, Antenna phased array, Generalized law of refraction, Flat Lens.

## 1 Problem statement and objectives

The general function of most optical devices can be described as the modification of the wavefront of light by altering its phase, amplitude, and polarization in a desired manner. A new way to control the propagation of light that can attain new degrees of freedom in molding the wavefront is obtained by introducing abrupt phase changes over the scale of the wavelength into the optical path. An intuitive picture for understanding the mechanism behind the wavefront modification can be given by recalling the Huygens Principle. Huygens expressed the intuitive concept that if each point of an electromagnetic wavefront was considered to be a new source of a secondary spherical disturbance, then the wavefront at a later instant could be seen as the envelope of the secondary wavelets [1]. Figures 1(a) and (b) show the propagation of a plane wave travelling in a conventional medium along the direction z: the phase is gradually accumulated and the secondary wavelets propagating at an interface placed at z = 0 are all in phase. The envelope produces a plane wave. If now we introduce a phase jump (or phase discontinuity) in the propagation path, as shown in Figure 1(c), the effect will be different. We consider a distribution of phase discontinuities with different values along the interface. Intuitively, the wavefront is no longer a single plane, but a distorted envelope is obtained (Figure 1(d)). If we manage to control reciprocal delays between adjacent wavelets, we can shape the light wavefront at the immediate output of the interface.

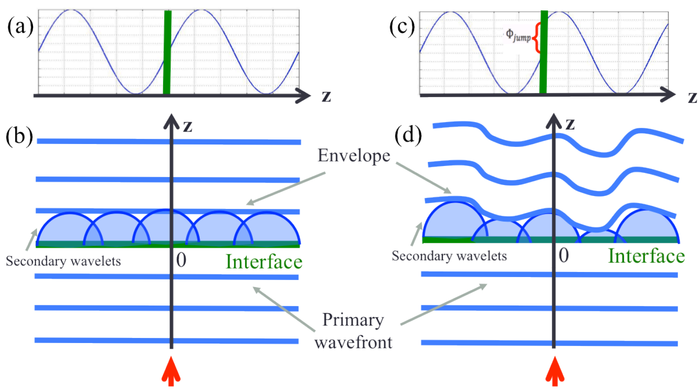


Figure 1. Huygens envelope reconstruction for a conventional interface (a and b), and for an interface with a spatial distribution of phase jumps (c and d).

The introduction of such abrupt phase changes can be achieved by using the large and controllable phase shift between the incident and scattered light of resonant optical scatterers, designed with suitable geometry and assembled in arrays as proposed in Reference [2].

A systematic study of the properties of plasmonic antennas, optical analogues of radio wave antennas, in changing the phase and polarization of the scattered light is reported. The applications of plasmonic antenna arrays in flat optical components ("metasurfaces") are investigated and demonstrated. Optical antennas have a wide range of potential applications [3-15]. Previous research efforts have primarily focused on the capability of optical antennas in capturing and concentrating optical power into subwavelength regions [16-21].

However, their phase and polarization responses and their implications in controlling the propagation of light have not been systematically investigated.

## 2 Research planning and activities

To gain full control over an optical wavefront, we need a subwavelength optical element able to span the phase of the scattered light relative to that of the incident light from 0 to $2\pi$ and able to control the polarization of the scattered light. A plasmonic element consisting of two independent and orthogonally oriented oscillator modes is sufficient to provide complete control of the amplitude, phase, and polarization response, and is therefore suitable for the creation of designer metasurfaces as described in detail in References [21] and [22].

A large class of plasmonic elements can support two orthogonally-orientated modes. Let us focus on lithographically-defined nanoscale V-shaped plasmonic antennas as examples of two-oscillator systems [2,21,22,23]. The antennas consist of two arms of equal length $h$ connected at one end at an angle $\Delta$. They support "symmetric" and "antisymmetric" modes (Figure 2(a)), which are excited by electric fields parallel and perpendicular to the antenna symmetry axes, respectively. In the symmetric mode, the current and charge distributions in the two arms are mirror images of each other with respect to the antenna's symmetry plane, and the current vanishes at the corner formed by the two arms (Figure 2(a) left panel). This means that, in the symmetric mode, each arm behaves similarly to an isolated rod antenna of length $h$, and therefore the first-order antenna resonance occurs at $h \approx \lambda_{sp}/2$ (where $\lambda_{sp}$ is surface plasmon wavelength [24]). In the antisymmetric mode, antenna current flows across the joint (Figure 2(a) right panel). The current and charge distributions in the two arms have the same amplitudes but opposite signs, and they approximate those in the two halves of a straight rod antenna of length $2h$. The condition for the first-order resonance of this mode is therefore $2h \approx \lambda_{sp}/2$. Experiments and calculations indeed show that the two modes differ by about a factor of two in resonant wavelength. Most importantly the phase response of the scattered light from a V antenna covers the range from 0 to $2\pi$, as opposed to the $\pi$ range of a linear antenna, since it results from the excitation of a linear combination of the two antenna modes for arbitrarily oriented incident polarization [2,21,22]. This full angular coverage makes it possible to shape the wavefront of the scattered light in practically arbitrary ways.

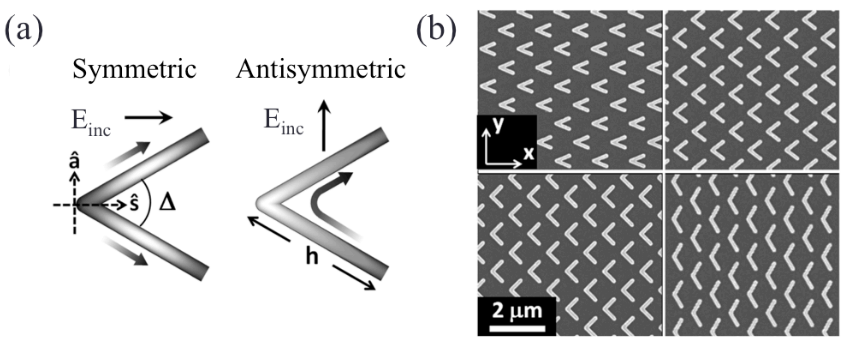


Figure 2 (a) V-shaped optical antenna and its two orthogonal modes, i.e., symmetric and antisymmetric modes, shown respectively in the left and right panels. (b) SEM images of gold V-shaped antennas fabricated on a silicon substrate.

The essence of metasurfaces is to use spatially inhomogeneous arrays of anisotropic optical antennas to control optical wavefronts. As an example, we designed a set of eight different V-antennas, which provide phase shifts over the entire 0-to-2 $\pi$ range in increments of $\pi$ /4 and are used as basic elements for constructing metasurfaces. The first four antennas in the array have their symmetry axes oriented along the same direction. The last four antennas are obtained by rotating the first four antennas in the clock-wise direction by 90º. This coordinate transformation introduces a $\pi$ phase shift in the scattered light of the last four antennas. We follow three steps to calculate the scattered light from the antennas: first, the incident field with an arbitrary linear polarization is decomposed into components along the $\hat{\mathbf{s}}$ and $\hat{\mathbf{a}}$ axes, which will excite the two eigenmodes, respectively. Second, we calculate the complex scattered fields of the eigenmodes ($\mathbf{S}_i\,\hat{\mathbf{s}}$ and $\mathbf{A}_i\,\hat{\mathbf{a}}$, *i*=1-4), which can be obtained by analytical calculations or simulations [2,21,22]. Third, the scattered field of each antenna and its rotated counterpart is expressed as a linear combination of the field components radiated by the symmetric and antisymmetric modes, in the x-y reference frame. This process, allows to extend the range of amplitudes and phase achievable from the scattering of a single antenna, creating the building blocks for a metasurface able to control the propagation of light.

## 3 Analysis and discussion of main results

To demonstrate the versatility of metasurfaces, the design and experimental realization of a number of flat optical components are proposed.

A linear phase variation along an interface introduced by an array of phased optical antennas leads to anomalously reflected and refracted beams in accordance with generalized laws of reflection and refraction. The general form of the Principle of Fermat known as the principle of stationary phase, states that the derivative of the phase accumulated along the actual light path, is zero with respect to infinitesimal variations of the path [25]. Now, let us consider a ray of light with wave vector $k_i$ incident on a interface that introduces a constant phase gradient $\boldsymbol{\nabla}\Phi$ oriented along an arbitrary direction along the interface, and separates two media of indices $n_i$ and $n_t$, respectively. The direction of the refracted ray with wave vector $k_t$ can be derived using the principle of stationary phase. Consider the situation where the phase gradient $d\Phi/dy$ lies in the plane of incidence. Wavevector conservation states that the sum of the tangential component of the incident wavevector, $n_i \mathrm{k}_0 \sin\vartheta_\mathrm{i}$, and $d\Phi/dy$ should equal the tangential component of the wavevector of the refracted light, $n_t \mathrm{k}_0 \sin\vartheta_\mathrm{t}$. From this simple relation one can derive the generalized Snell's law:

$$n_t \sin\vartheta_\mathrm{t} - n_i \sin\vartheta_\mathrm{i} = \frac{1}{k_0}\frac{d\Phi}{dy} \qquad (1)$$

Equation (1) implies that the refracted beam can have an arbitrary direction in the plane of incidence, provided that a suitable constant gradient of phase discontinuity along the interface $d\Phi/dy$ is introduced [2].

Similarly, for the reflected light:

$$\sin\vartheta_r - \sin\vartheta_i = \frac{1}{n_i k_0}\frac{d\Phi}{dy} \qquad (2)$$

By using eight V-antennas as building blocks, metasurfaces that imprint a linear distribution of phase shifts to the optical wavefronts are created (Figure 3(a)).

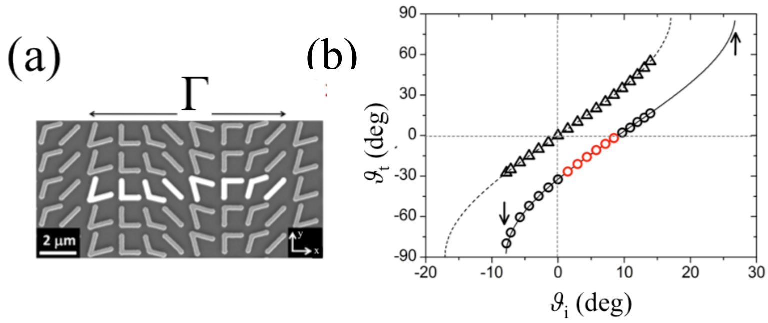


Figure 3 (a) SEM image of a metasurface with linear phase gradient (b) Angle of refraction versus angle of incidence for the ordinary (dashed line) and extraordinary (solid line) refraction for the sample with periodicity Γ = 15 µm. The curves are theoretical calculations using the generalized Snell's law (Eq. (1)) and the symbols are experimental data.

Figures 3(b) shows the angles of refraction as a function of incident angle $\vartheta_i$ for both the silicon-air interface and the metasurface with linear interfacial phase gradient. The experimental data match with the analytical curves predicted from the generalized law. In the range of $\vartheta_i$ = 0-9°, the cross-polarized extraordinary beams exhibit negative angle of refraction and reflection (red circles). The critical angle for total internal reflection is modified to about -8° and +27° for the metasurface compared to ±17° for the silicon-air interface; the anomalous reflection does not exist beyond $\vartheta_i$ = -57°.

The concept of optical phase discontinuities provides a different path for designing flat lenses. An experimental demonstration of light focusing in free space at telecom wavelength ($\lambda$ = 1.55 µm) using 60 nm thick gold metasurfaces is reported. Two flat lenses of focal distances 3 cm and 6 cm and a flat axicon with an angle $\beta = 0.5°$ (which correspond to a glass plano-convex axicon with base angle 1°) were fabricated.

In order to focus a plane wave to a single point at distance $f$ from the metasurface, a hyperboloidal phase profile must be imparted onto the incident wavefront. In this way, secondary waves emerging from the metasurface constructively interfere at the focal plane similar to the waves that emerge from conventional lenses [25].

The axicon images a point source onto a line segment along the optical axis; the length of the segment is the depth of focus (DOF). The phase in point on the flat axicon is proportional to the distance between the point and its corresponding point on the surface of a cone with the apex at the intersection of the metasurface with the optical axis and base angle $\beta = \tan^{-1}(r/DOF)$, where r is the radius of the metasurface.

To facilitate the design of the metasurfaces, a simple analytical model based on the dipolar emitters is used. By comparing calculations based on this model and the experimental data, it can be determined whether the phase discretization and the slight variations in the scattering amplitudes of the 8 elements create substantial deviations from the operation of ideal devices. The measured far-field for the lens with 3 cm focal distance and the corresponding analytical calculations are presented in Figures 4(a,b). The results for an ideal axicon and for the axicon metasurface are presented in Figures 4(c,d).

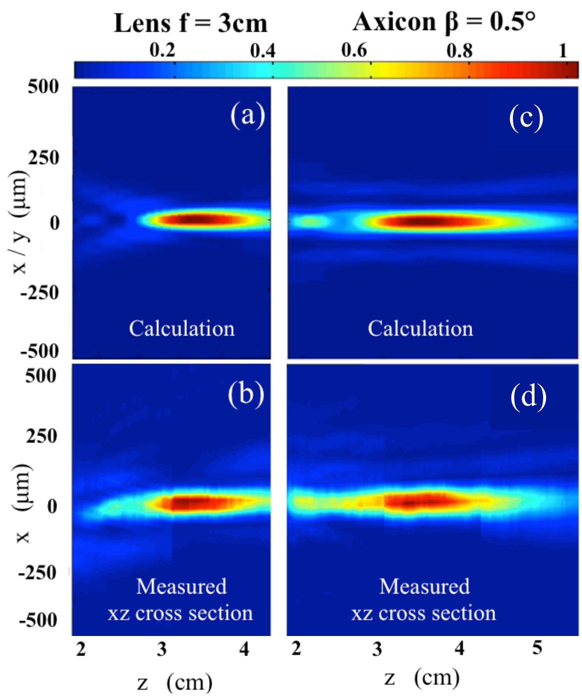


Figure 4 (a,b) Theoretical calculations and experimental results of the intensity distribution in the focal region for the flat lens with f =3cm. c-d) Theoretical calculations and experimental results of the intensity distribution for the planar axicon with $\beta$ =0.5°.

## 4 Conclusions

A new class of optical components is studied based on a recently discovered phenomenon, i.e. phase discontinuities. The scattering properties of plasmonic antennas are discussed with an emphasis on their ability to change the phase and polarization of the scattered light. The former is controlled by tuning the geometries of an antenna for a fix wavelength so different phase shifts between the scattered and incident light are selected on the antenna resonance curve. The polarization of the scattered light is instead controlled by designing antenna spectral responses in two orthogonal directions so the resulting two orthogonal scattered waves can create arbitrary polarization states. The most important feature of the metasurfaces is that they comprise arrays of antennas with subwavelength spacing and with spatially tailored phase and polarization responses. Extraordinary beams with controllable propagation direction, state of polarization, and orbital angular momentum are created using such metasurfaces.

A generalization of the laws of reflection and refraction is made possible thanks to the deeply subwavelength thickness of the optical antenna arrays and their associated abrupt phase changes, with no contribution from propagation effects. These generalized laws apply to the whole optical spectrum for suitable designer interfaces.

Different devices such as phased antenna arrays able to beam light into arbitrary directions and flat lenses that create converging spherical waves were demonstrated.

The efficiency of the flat optical components is limited by the antenna scattering amplitude and optical losses due to plasmonic absorption. The scattering amplitude is limited primarily because we only use part of the scattered waves to synthesize the extraordinary beams, while the rest of the scattered light is wasted. In order to address these problems, the following approaches are proposed: antennas that allow for control of the phase of the total scattered waves; antennas able to scatter a large percentage of optical power into the cross-polarization direction; and dielectric scatterers with controllable phase and polarization responses and with negligible absorption losses.

The concept of phase discontinuity opens the door to the development of ultra thin and integrated photonics devices. Reconfigurable spatial light modulators can be envisioned by using materials whose optical properties can be tuned by means of external excitations [26,27]. Finally, it should be mentioned that such interface can combine in a single ultra thin layer the effects of multiple and thick optical devices, which is promising for applications such as aberration correction and integrated optics.

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