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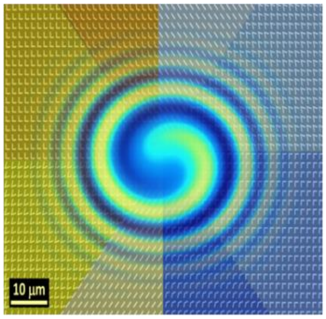

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Breakthroughs in Photonics 2013: Flat optics: wavefronts control with Huygens' interfaces

(Invited Paper)

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Abstract: Recent progress in the fields of nanophotonics and metamaterials have enabled the development of ultrathin and flat optical components, providing physicists and optical engineers a new method to control light. According to the Huygens-Fresnel principle, light gradually propagates step by step by exciting secondary waves which then reradiate to form the next wavefront; the phase and the amplitude of these secondary waves are intimately related to the incoming optical wavefront. By using the response of nano-engineered sub-wavelength optical resonators at interfaces, it is now possible to engineer Huygens' interfaces to achieve an unprecedented control of the wavefront over large bandwidths and subwavelength propagation distances.

Index Terms: Huygens-Fresnel principle, nanophotonics, surface plasmon polaritons, wavefront engineering.

Inspired by the early work of Ignace-Gaston Pardies, Christian Huygens (1629-1695) developed a universal model of propagation which sets the foundation of classical optics. In his work entitled "Traité de la Lumière", presented at the Academie des Sciences in 1678 and later published in 1690 [1], he proposed the wave theory of light, in which he assumed that the wavefront of light at time t+Δt is the envelope of spherical wavelets emanating from every single point reached by the wavefront at the prior time t. From this assumption which in fact embeds the superposition principle of waves, Fresnel added the principle of interference to explain the effect of diffraction [2]. Although the accuracy of this simple approach is limited in the sense that it neglects the backward part of the propagating waves, it provides an intuitive picture of light propagation. This intuitive picture is useful to qualitatively explain the working principle behind any conventional optical component: the wavefront of light is modified by accumulating gradual

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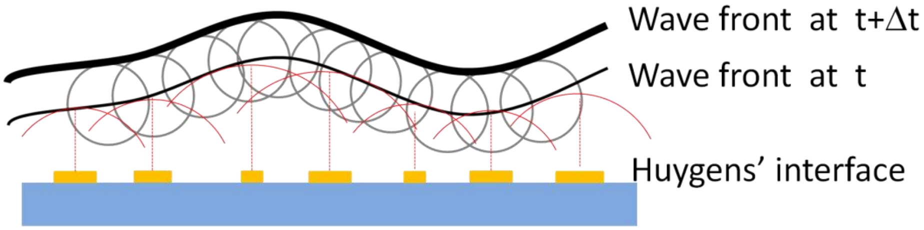
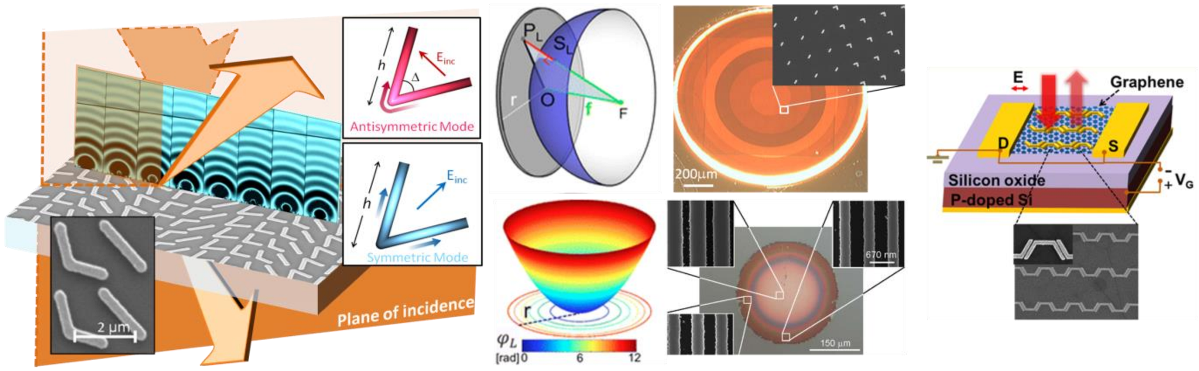
phase shifts during propagation through materials with various shapes and optical properties. New degrees of freedom in the design of optical components can be attained by introducing a sheet of subwavelength optical resonators in the path of propagation of a light beam to induce abrupt phase changes over the scale of the wavelength. It is achieved by using the large and controllable phase shift between the incident and scattered light of resonant optical scatterers, assembled and arranged with sub-wavelength separation in suitable arrays of subwavelength thickness to form a metasurface [3].





An incident beam of light impinges on an array of metallic optical antennas deposited across an interface and excites surface electromagnetic waves propagating back and forth along the surface of each element, the so called “localized plasmon polaritons”. The oscillating charges along each element produce a radiation field, releasing the stored optical energy, with spatially varying amplitude and phase retardation which depend on the geometry of the metallic antennas [4]. Therefore, local phase and amplitude modification of the wavefront is intimately related to the dispersion of the antenna resonances. The effect of a metasurface on the wavefront of light can be reconciled with the intuitive Huygens-Fresnel’s picture by considering that the secondary waves have tailorable amplitude and phase response. Designing an interface with a distribution of antennas to impose a constant gradient of phase along the interface, i.e. elements with the same scattering amplitude but spatially varying phase retardation, it is possible to reorient the propagation of light in an arbitrary direction. Anomalous reflection and refraction phenomena are observed in this regime in optically thin arrays of metallic antennas on silicon with a linear phase variation along the interface which are in excellent agreement with generalized laws derived from Fermat’s principle [3]. An illustration of the effect is depicted in the left panel of the figure.

This approach of designer optical phase retardation –also called optical phase discontinuities (because the phase changes occurs over a distance much less than the free space wavelength)- provides great flexibility in the design of the wavefront of light and can be applied to generate various beams such as optical vortices [5], holograms [6-8], Bessel beams and perfectly spherical wavefronts [9]. The latter, obtained by imposing a hyperboloidal phase profile on the metasurface (see the top center part of the figure), is in fact equivalent to a perfectly flat lens which is also free from spherical aberrations. In this way, secondary waves emerging from the each element create a converging spherical wavefront which remains spherical as long as the incident plane wave impinges normal to the flat lenses. The secondary waves constructively interfere at the focal plane similar to the waves that emerge from conventional lenses. It is therefore straightforward to achieve high numerical-aperture focusing without spherical aberration. Experimentally, the generalized laws, vortex beams and flat lenses have been first demonstrated by using various spatial distributions of plasmonic V-shape antennas in the mid- and near-infrared spectral range. As depicted in the inset of the left panel, V-shaped metallic antennas support two different current oscillation modes (symmetric and anti-symmetric) with different resonant responses that can be combined to achieve homogeneous amplitude and tailorable phase response from 0 to 2π. Antennas with high radiation losses, i.e. low Q-factors, are essential to improve the overall scattering efficiency of the metasurfaces. It turns out that this is also beneficial for maintaining the metasurface performance over a large bandwidth [10].

Besides tuning the antenna geometry or equivalently the antenna dispersion, it is also possible to use other physical mechanisms to control phase and amplitude. In particular, the rotation of anisotropic subwavelength scatterers with the exact same geometry induces cross-polarized phase retardations equal to twice the rotation angles [11-12]. This phase retardation is also known as the Pancharatnam–Berry phase [13-14]. Combining dispersion and spatial orientation, it is possible to design metasurfaces with steering capabilities that operate as waveplates on a very large bandwidth -from 5 to 10 μm- to change a linear incident polarized beam into an anomalously refracted beam with very high degrees of circular polarization [15-16].

Incidentally, any material with a sub-wavelength size that can “catch and release” the electromagnetic field with a controllable phase shift can be a good candidate for creating phase discontinuities. The previous examples make use of plasmonic nano-antennas which have resonant behavior from the visible to the radio spectral ranges, making this approach of molding wave fronts with antennas applicable to a large part of the electromagnetic spectrum. The possibility of using other optical oscillators, such as split ring resonators, ellipsoid nano-antennas, dielectric resonators, quantum dots, nanocrystals, resonant molecules, or metamolecules is promising for creating optical phase and amplitude elements with extremely subwavelength dimensions, reduced losses, and dynamic tunability[17]. As an example, a dielectric flat lens created by sub-wavelength arrangement of non-periodic gratings has also been reported showing high reflectivity (see the bottom center of the figure) [18]. In order for this technique to be viable for real applications, new approaches which would favor high throughput power -for example by cancelling the reflected wavefronts [19, 20] - have still to be developed. Interfaces with more complex design such as those with aperiodic [21] or random arrangements of anisotropic electric and/or magnetic polarizable nanostructures could enable new devices with unexpected optical response. Today, the nascent field of ‘‘computational metamaterials’’ is regarded as another promising direction of research, announcing the development of a new class of ultrathin devices to process optical analog computing at speed of light in highly compact metamaterials [22]. The control of the optical properties of nanostructures is also desirable for many applications, including biochemical sensors, ultrafast bio-imaging, reconfigurable meta-surfaces, and compact optoelectronic devices. In particular, graphene, which has gate-voltage dependent optical properties, is emerging as a possible platform for electrically controlled plasmonic devices (see the right panel in the figure) [23-25]. The combination of metallic structures with materials with large tunable refractive index or stretchable [26]or even phase-change materials is particularly exciting and promises the development of a new class of flat optical components with fast tunability and broadband performances.

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