Chapter 1

Introductory Chapter: Plasmonics

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1. Introduction

The optical interaction with nanostructures is studied by the field of plasmonics. Recently, the potential of subwavelength confinement and the enhancement of optical fields close to the appropriately designed nanoscale objects have opened a gateway to extensive investigations of plasmonic optical phenomena.

Consequently, the outstanding field of plasmonics has spread over different disciplines, providing the wide avenues for the promising applications in material science, biology, and engineering. Furthermore, the field of metamaterials has been enriched and enhanced by the plasmonic optics, for example, metasurfaces. The former concept is based on the collective electromagnetic behavior of many subwavelength inclusions and building blocks as "meta-atoms." Doing so, novel tunable composite materials, i.e., near-zero material parameters, and extreme-value material parameters, characterized by unconventional bulk and surface properties, have been proposed and applied.

Surface waves open a gateway to a wide spectrum of physical phenomena providing a fertile ground for a number of applications [1–3]. The discovery of metamaterials with tunable electric and magnetic features [4] has allowed for a rich phenomenon, i.e., expansion of the wide spectrum of structures capable of supporting surface waves. Surface plasmon polaritons (SPPs) are electromagnetic excitations occurring at the interface between a conductor and dielectric. These are evanescently confined in the perpendicular direction [5–8]. It is possible to imitate the properties of confined SPPs by geometrical-induced SPPs, named as spoof SPPs. The proposed phenomenon may take place at lower frequencies. It might be concluded that surface structure may open a gateway to spoof surface plasmons. The former serves as a perfect prototype for structured surfaces [9].

Thus, metasurfaces, a class of planar metamaterials possessing the outstanding functionality, i.e., capabilities to mold light flow, have recently attracted intensive attention. The main goal of the metasurfaces is to achieve the anticipated phase profile by designing subwavelength structures at the interface between two ordinary materials. Abilities to fully engineer the properties of the propagating waves are gained thanks to the rationally designed phase. It should be mentioned that anomalous reflection and refraction have been verified in the infrared range.

Metasurface-based optical devices, such as vortex plates, wave plates, and ultra-thin focusing lenses have also been proposed for various types of incident light, i.e., linearly polarized light or vertex beams. Now is the time that the fundamental research in the field is giving rise to the first promising applications for industry.

For centuries, the control of optical properties has been limited to altering material compositions, relying on light propagation through naturally occurring materials to impart phase shifts and tailor the desired wavefronts. The introduction of metamaterials allows control over optical wavefronts to deviate from the usual propagation methods and rely instead on its carefully engineered internal structure. This was first theorized 20 years ago by Pendry et al. [10], and since then, the development in the field of artificially designed materials has only accelerated. Metamaterials offer an extensive range of novel electromagnetic phenomena, which do not occur in natural materials, but whose existence is not restricted by physical laws. These artificially created "materials" are made up of a series of composite unit elements, which although are a few orders of magnitude larger than the molecular unit cells of regular materials. This allows the metamaterials to provide descriptions of its interactions with electromagnetic waves in terms of its effective "material" parameters. Metamaterials can, therefore, still be viewed as a homogenous material at their desired operational wavelengths, typically within the optical regime. With careful structuring of the elements within the metamaterial, unusual material properties such as a negative refractive index can be achieved. The refractive index η of a material is governed by its macroscopic electromagnetic permittivity e and permeability μ, where $\eta = \pm\sqrt{e\mu}$.

The development of such negative index material could lead to novel applications especially within the optical regime, such as creating the perfect lens, which images beyond the diffraction limit, or an optical cloaking device. The initial realization of a negative refractive index metamaterial uses a pattern of metallic wires and split-ring resonators to form its unit cells, which have been experimentally demonstrated in the microwave regime and later at optical wavelengths as the elemental array is reduced into the nanoscale. Bulk metamaterials, however, are usually susceptible to high losses and strong dispersive effects due to the resonant responses of metallic structures used. Additionally, the complex structures required in a 3D metamaterial is challenging to build using the existing micro- and nanofabrication methods. Thus, recent studies have been focusing on the development of 2D metamaterials, or metasurfaces. These planar materials allow for the combined advantages of the ability to engineer electromagnetic responses with low losses associated with thin layer structures. The introduction of surfaces with subwavelength thicknesses results in minimal propagation phase; this shifts the focus from developing materials with negative permittivity and permeability to engineering surface structures to adjust surface reflection and transmissions. This is made possible by exploiting abrupt phase jumps and polarization changes from scattering effects, which can be realized and subsequently fine-tuned through designing spatially varying phase responses over the metasurface, through using either metallic or dielectric surface

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structures. In solid state physics, materials can be classified according to their electronic band structure. While metals have overlapping conduction and valence bands, which allows the free movement of electrons through the material, dielectric insulators have a large band gap between the two. Both types of materials are still able to interact with incident electromagnetic fields, although through different physical methods and result in light scattering effects. Thus, both materials have, therefore, been employed in the realization of the vast potential of metasurfaces.

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