Nonmagnetic transformation optics for two-dimensional photonic devices

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In the past decade, some extraordinary devices, e.g., invisibility cloaks, perfect lenses and beam manipulators, have been realized thanks to a new design tool called transformation optics. This technique leads to unprecedented control of optical fields through complex material structures designed according to a predefined coordinate transformation. In order to achieve the intended flow of light without unwanted side-effects, transformation-optical devices must be impedance-matched. Often this leads to designs of sophisticated materials with inhomogeneous and anisotropic permeability and permittivity. In this contribution, we investigate how it is possible to relax the impedance-matching condition in realistic 2D transformation-optical systems.

Transformation optics

The control of macroscopic material parameters, such as the permittivity ε and the permeability μ, is of utmost importance in the manipulation of the propagation of light. This is illustrated by Fermat's principle. Observable light trajectories extremize a new measure of length, the optical path length, which is determined by the refractive index profile of the medium through which light is propagating. Therefore, complex materials affect the propagation of light by imposing a new geometry within which light follows an extremal path.

Transformation Optics (TO) extends Fermat's principle to describe the effect of inhomogeneous and anisotropic material parameters on wave propagation [1]. Transformation-optical devices explicitly introduce a nontrivial geometry starting from a metric tensor G, which transforms the perceived distances for light. Light propagates along trajectories of extremal length, called geodesics, which are completely determined by this metric. Thus, a device whose electromagnetic interactions are described by macroscopic Maxwell equations, manipulates light in the same way as an empty space, called physical space, with a geometry G.

To design a metric G and its corresponding device, an auxiliary electromagnetic space is introduced. The electromagnetic space is equipped with its own metric G' and material parameters $\tilde{\varepsilon}$ and $\tilde{\mu}$. A coordinate transformation between both spaces links geometries G and G' and maps the fundamental behaviour of light in electromagnetic space to physical space. If electromagnetic space is simply vacuum, the coordinate transformation ensures light will also propagate throughout physical space as if it were in vacuum. This approach is used in cylindrical cloak design [2] to avoid reflections from an object hidden within the device. Even more impressively, if both electromagnetic and physical space contain a metal sheet, which is flat in electromagnetic space and irregularily curved in physical space, light reflects of this irregular sheet in physical space as if it really encouters a planar metal sheet. In this way a ground plane cloak is constructed, capable of hiding bumps and irregularities in a metal surface [3]. Next to determining fundamental behaviour of light within physical space, form invariance of the macroscopic Maxwell equations under coordinate transformations also predicts the material parameters ε and μ of the device

$$\varepsilon = \frac{\sqrt{det G'}}{\sqrt{det\Gamma}} \frac{\Lambda^T\ G'\ \tilde{\varepsilon}\ \Lambda}{det\Lambda}, \tag{1}$$

$$\mu = \frac{\sqrt{det G'}}{\sqrt{det\Gamma}} \frac{\Lambda^T\ G'\ \tilde{\mu}\ \Lambda}{det\Lambda}, \tag{2}$$

where the Jacobian of the transformation Λ, the metric G' and electromagnetic space material parameters $\tilde{\varepsilon}$ and $\tilde{\mu}$ clearly influence the design.[1] The remainder of this contribution considers two-dimensional transformation-optical devices. These devices have one normal coordinate that does not mix with the remaining planar coordinates during the transformation, as for beam bends, beam splitters and the cylindrical cloak.

Two-dimensional transformation-optical devices

The field of photonic circuitry [4] has led to innovative two-dimensional waveguiding schemes and surface plasmon optical devices. Two-dimensional circuits require structures capable of sustaining surface waves, such as metal-dielectric interfaces or graphene sheets. Transformation optics (TO) is a valuable tool to guide and optimize component designs. In particular, TO might reduce decoupling losses of conventional beam benders and beam splitters inherent to confined waveguides. To our knowledge, two interesting developments ([5] and [6]) extend TO to two-dimensional systems.

Huidobro *et al.* [5] applied the TO framework to a metal-dielectric interface to investigate the relative importance of metals and dielectrics on material parameters. Because TO predicts bulk, three-dimensional permittivity and permeability distributions, an ideal design includes metamaterials both in the dielectric and the metal side of the interface. These regions include several decay lengths of the evanescent surface wave in order to capture all electromagnetic energy. Since form-invariance of macroscopic Maxwell equations is required for TO to be applicable, the dimensions of metamaterial structures in the metal need to be much smaller than its skin depth. To simplify fabrication, the authors limit manipulation of material parameters to the dielectric side of the interface (Figure 1) and compare the resulting wave propagation with full TO simulations.
Both the geometry and the decay length in the dielectric affect the efficiency of the device. Long decay lengths yield very good results since the energy mostly resides within the dielectric and the metal's contribution is neglegible. Functionalities are excellently conserved in the telecommunication window ($\lambda \approx 1.5\,\mu$m), but not very good at optical wavelengths ($\lambda \approx 600$ nm). Some geometries that naturally require a metal interface in order to function, e.g, the ground plane cloak, do not suffer from the restricted implementation while others, such as the cylindrical cloak, suffer greatly from the discontinuous

[1] Additionally, the metric Γ is introduced to correct for coordinates used to describe the device in physical space.

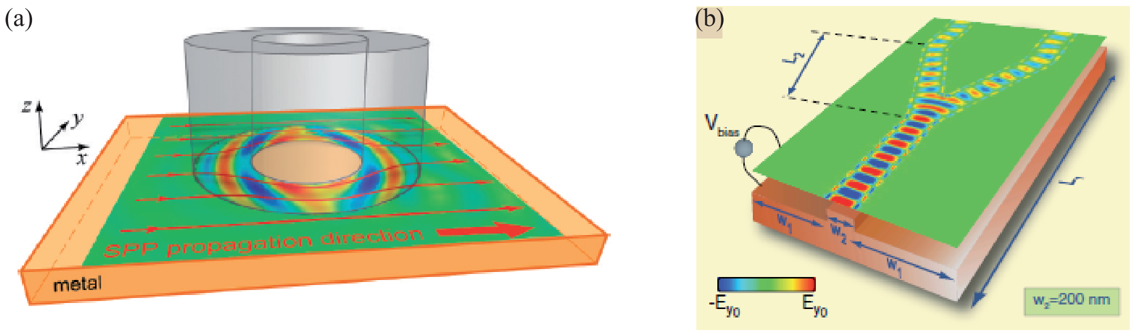

Figure 1: (a) A two-dimensional cylindrical cloak for surface plasmon polaritons on a metal-dielectric interface. Figure reproduced from reference [5]. (b) A two-dimensional beam splitter on graphene. Figure reproduced from reference [6].

metal interface.

A second interesting contribution concerns propagation manipulation of TE or TM on a graphene sheet [6]. The conductivity $\sigma = \sigma_r + i\sigma_i$ of graphene is spatially modulated by an externally applied field through changes in the chemical potential. A spatially varying external voltage or a constant voltage applied to a substrate with inhomogeneous permittivity distribution, induces a designed conductivity distribution to manipulate light propagation with high accuracy (Figure 1). More specifically, the imaginary part σ_i might be positive, acting as a dielectric sustaining a TM mode, or negative, acting as a metal and prohibiting a TM mode on the sheet. The conductivity pattern selects those regions where TM waves are allowed to propagate, leading to many applications such as TM beam splitters, perfect TM mirrors or subwavelength lenses. Next to the design of macroscopic devices, conductivity distributions are also useful to construct two-dimensional IR metamaterials. Instead of conventional resonating circuits or nanoparticle equivalents of lumped circuits [7], local fields are tuned by conductivity variations. Patches of negative σ_i might, for example, act as scatterers, similar to metallic nanoparticles.

Nonmagnetic two-dimensional systems

The fundamental trade-off between confinement and propagation length of surface waves implies that not every material is capable of sustaining longe-range surface waves. Despite desirable properties, such as conductivity tunability and confinement of graphene, its propagation length at terahertz frequencies is too small for propagating applications [8]. Those applications require metal-dielectric or purely dielectric devices with long decay constants. In addition, equation (2) shows that TO devices inherently need magnetic response to satisfy material parameters linked to a coordinate transformation. Since materials are mostly nonmagnetic at high frequencies, metamaterials need to have resonating structures [9], such as Split Ring Resonators or Fishnet Structures, to obtain the desired magnetic response. The dispersion associated to these resonators leads to significant losses and limits operating frequencies.

Omitting magnetic responses has serious consequences. For a cylindrical cloak, impedance-matched parameters ensure waves propagate throughout the device without reflections despite inhomogeneous permittivity and permeability variations. Without magnetic response, impedance-matching is violated and reflections would indicate the presence of an object hidden inside. Still, there are several approaches to relax relations (1) and (2).

Coordinate transformations are often optimized to decrease material parameter anisotropy. If optimization results in (quasi)conformal coordinate transformations, a single refractive index distribution describes all responses of the device. This approach is frequently used at optical frequenties, e.g, for a planar cloak [10], because magnetic responses of resonators saturate at optical frequencies. However, two-dimensional devices are inherently anisotropic because of the distinction between normal and planar coordinates. Another way to simplify material parameters, consists of choosing a polarization, TE or TM, for which the device is optimized. In the case of a cylindrical cloak [2], all electric field components different from the normal coordinate are set to zero. Six independent material parameters reduce to three, namely one permittivity component and two magnetic susceptibility components. Finally, the ray approximation regime uses slow variations in material parameters with respect to the wavelength to simplify the TO device in two ways. From a theoretical point of view, matching dispersion relations between the simplified device and the TO device is sufficient to match ray trajectories of both devices. From a practical point of view, slow material variations enable stacked homogeneous slices to approximate the continuous distribution inducing minor reflections and maintaining functionalities.

Acknowledgments

Work at VUB was supported by the Belgian Science Policy Office (IAP-Photonics@be, grant IAP P7-35) and by the FWO-Vlaanderen. V.G. is a Ph.D. Fellow of the Research Foundation-Flanders (FWO-Vlaanderen).

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