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Transformation Optics scheme for two-dimensional materials

Anshuman Kumar, Kin Hung Fung, M. T. Homer Reid, and Nicholas X. Fang

1Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA - 02139
2Department of Applied Physics, The Hong Kong Polytechnic University, Hong Kong
3Mathematics Department, Massachusetts Institute of Technology, Cambridge, MA - 02139

Two dimensional optical materials, such as graphene can be characterized by a surface conductivity. So far, the transformation optics schemes have focused on three dimensional properties such as permittivity \( \epsilon \) and permeability \( \mu \). In this paper, we use a scheme for transforming surface currents to highlight that the surface conductivity transforms in a way different from \( \epsilon \) and \( \mu \). We use this surface conductivity transformation to demonstrate an example problem of reducing scattering of plasmon mode from sharp protrusions in graphene.

\[ \nabla \times \mathbf{H} = \mu_0 \mu_{\text{bulk}} \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}_s}{\partial t} \nabla F(\mathbf{r}) \delta(F(\mathbf{r})) \]  \hspace{1cm} (1)

where \( F(\mathbf{r}) = 0 \) is the equation of the surface discontinuity, \( \epsilon \) is the permittivity of the surrounding three dimensional materials and \( \mathbf{P}_s \) is the surface polarization of the two dimensional material. The time derivative of this surface polarization gives rise to a surface current density:

\[ \mathbf{J}_s = \frac{\partial \mathbf{P}_s}{\partial t} = \sigma^{2D} \mathbf{E}_|| = \hat\sigma \mathbf{E} \]  \hspace{1cm} (2)

For the usual case of the interface of two bulk materials, this term is absent, however for 2D materials we need to retain this term in the derivation of the boundary conditions due to the presence of the Dirac delta function in Eq(1). Thus, in this case of a finite surface electrical conductivity \( \sigma^{2D} \), the boundary condition for the tangential magnetic field can be written in terms of a surface current:

\[ \hat\mathbf{n} \times \Delta \mathbf{H} = \mathbf{J}_s = \hat\sigma \mathbf{E} \]  \hspace{1cm} (3)

where \( \mathbf{J}_s \) is the surface current density, \( \hat\mathbf{n} \) is the unit normal to the surface and \( \hat\sigma \) is the surface conductivity.
tensor. For instance, an isotropic surface conductivity would be represented in terms of the basis \{|t_1\}, |t_2\rangle, |n\rangle}, as \(\tilde{\sigma} = \sigma^{2D}(|t_1\rangle \langle t_1| + |t_2\rangle \langle t_2|)\). Here \(|t_1\rangle\) and \(|t_2\rangle\) are the two orthonormal local tangential vectors and \(|n\rangle\) is the local normal unit vector. Our aim here is to find out the transformation rule for the \(\tilde{\sigma}\) tensor.

Based on Eq.1 and 2, the permittivity can be thought of as containing a Dirac delta function:

\[
\epsilon = \epsilon_{\text{bulk}} + i\frac{|\nabla F(r)|\delta(F(r))}{\omega \epsilon_0} \tilde{\sigma}
\]  

(4)

Now, applying the usual transformation rule for permittivity \(\epsilon' = \Lambda^T \epsilon \Lambda / \det(\Lambda)\) to Eq.1 and the standard rule for the change of variables in a delta function, we arrive at the result:

\[
\tilde{\sigma}' = \frac{\Lambda \sigma \Lambda^T}{|(\Lambda^{-1})^T \hat{n} \Lambda| \det(\Lambda)}
\]  

(5)

where \(\hat{n}(r)\) is the local surface normal given by \(\nabla F(r)/|\nabla F(r)|\) and \(\Lambda\) is the transformation matrix \(\Lambda' = \partial x'/\partial x\). The additional factor explicitly enters the surface conductivity tensor because a compression in the plane normal for the 2D material, should produce no transformation of the surface conductivity physically. But the \(\det(\Lambda)\) factor does contain this compression factor. Therefore surface conductivity further requires a multiplicative factor for the renormalization of the surface delta function. Equivalently, one could say that the normal unit vector, after transformation, does not remain a unit vector. Hence the additional factor needs to be put in to ensure that in the transformed medium, \(\hat{n}'\) is indeed a unit vector.

Taking cue from the SPP wave adapter proposed in [15, 16], we illustrate that the surface conductivity transformation indeed works, by using the transformation shown in Fig.1.

In the absence of any transformation optics, the plasmon mode propagating along the graphene sheet from the far left, would suffer substantial scattering into the free space modes. Such radiative loss is typically dependent on the radius of curvature of the bump. For instance, if the graphene plasmon mode is highly confined compared to the radius of curvature of the bump, then it is possible to achieve smaller radiative loss of the plasmon mode[17]. In our current formalism however, we are able to tackle arbitrary radii of curvatures. To subvert this scattering one can employ the well known technique of transformation optics. This scheme would require us to modify the permittivity and permeability tensors in the region surrounding the sharp bump. However, just this would not be enough to prevent scattering since as we mentioned earlier, the surface conductivity also needs to be transformed in a way which depends on the details of the transformation we wish to carry out.

Hence we consider three cases: A) protrusion in graphene with no transformation optics employed, B) transformation optics employed but surface conductivity is not transformed and C) transformation optics employed for the surface conductivity as well as the bulk parameters. The results are shown in Fig.2

Finite element simulations in Fig.2 were carried out using COMSOL MULTIPHYSICS by employing a surface current boundary condition to represent the graphene. The surrounding media in the un-transformed case is assumed to be vacuum, for this example. But we have performed tests, which are not presented here with substrates of non-uniform refractive indices as well. For simplicity we use only the imaginary part of the surface conductivity of graphene at a doping level of \(25\ eV\), so the numerical value of the in-plane untransformed surface conductivity is \(\sigma = i \times 10^{-4}\ S\).

Mathematically, the transformation in the four regions shown in Fig.1 is given as follows:

\[
\begin{align*}
x' &= x \\
y' &= y - \frac{\tan \beta}{\tan \alpha} |y| + (a - |x|) \tan \beta \\
z' &= z
\end{align*}
\]  

(6)

Everywhere outside the four regions, there is no change. Note that we have chosen a linear map only for the purpose of demonstration of the main idea of surface conductivity transformation. The transformation we provided in Eq.5 is valid in general, beyond the linear approximation. In principle, other transformations can be employed keeping in mind the material constraints. For
Two things are apparent from the form of \( \hat{\sigma} \) in a particular, for the untransformed case, the components involved in the transformed conductivity tensor. In particular, for the untransformed case, the components \( [\hat{\sigma}]_{tt} \) and \( [\hat{\sigma}]_{zz} \) should both equal \( \sigma^{2D} \). These geometrical factors can be understood in terms of surface current conservation, as pointed out in [21]. The surface current density in the tangential direction prior to the transformation is \( J_{s,x} = \sigma^{2D} E_x \). After the transformation it becomes \( J'_{s,t} = \sigma^{2D} \sec \beta (E'_x \cos \beta - \text{sgn}(x) E'_y \sin \beta) = \sigma^{2D} \sec \beta (E_x \cos \beta) = J_{s,x} \). For the \( z \)-direction, we note that it is the surface current that needs to be preserved across the region \(-a < x < a\). So we have, \( I'_{s,z} = \int_{-a}^{a} \frac{\cos \beta}{\cos \beta} J'_{s,z} dx' = \int_{-a}^{a} J'_{s,z} dx' / \cos \beta = \int_{-a}^{a} (\sigma^{2D} \cos \beta) E'_z dx' / \cos \beta = \int_{-a}^{a} \sigma^{2D} E_z dx = I_{s,z} \). Secondly, it appears here that the given transformation requires us to somehow make the graphene conductivity anisotropic, that is, \( \hat{\sigma}'_{tt} \) and \( \hat{\sigma}'_{zz} \) need to be different. Although it might be possible to achieve such anisotropic effects using strained graphene [22, 23], yet in the present case of TM modes, \( \hat{\sigma}'_{zz} \) component does not matter since the boundary condition for \( H'_z \) only involves the surface current in the \( |t| \) direction. Hence this conductivity change can be easily implemented via electrostatic [26] or chemical doping. As far as the bulk parameters, namely \( \epsilon' \), \( \mu' \) are concerned, there have been numerous demonstrations of natural and artificial anisotropic materials in the THz range [27, 30].

We have demonstrated the transformation rule for surface conductivity under arbitrary coordinate transformations. An additional factor related to the renormalization of the surface current needs to be included.
transformation optics, B) protrusion in graphene with transformation optics applied only to surrounding $\hat{\epsilon}$ and $\hat{\mu}$ and C) protrusion in graphene with the full transformation optics scheme applied to $\sigma$, $\hat{\epsilon}$ and $\hat{\mu}$. In this example, $\alpha = \tan^{-1} 3$ and $\beta = \tan^{-1} 2$. In this example, the surrounding media in the untransformed case are assumed to be vacuum.

to maintain the form invariance of the Maxwell’s equations. We then presented an example problem of reducing scattering from a triangular protrusion in graphene, using the proposed method of surface conductivity transformation. This kind of conductivity transformation would be useful for transformation optics applications involving two dimensional materials.

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