Invisibility Cloak Scheme with Composite Plasmonic Waveguides and Metsurface Overlayers

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Abstract— Here, we report on an invisibility cloak scheme with composite plasmonic waveguide and metsurface overlayers. Designated structures create a 'black hole' which conceal a nano-scale object placed on a waveguide. Using the calculated effective permittivity of plasmonic overlayer on waveguide, we analyze the mode using Finite-difference time-domain method (FTDT) based Maxwell solver of Lumerical. We show that evanescent fields of composite plasmonic waveguide structure do not interact with the object, i.e., resulting in object's invisibility.

1. INTRODUCTION

Invisibility cloaks have been a concept of interest over the last few centuries. With the recent developments in metamaterial science [1] and nanotechnology [2, 3], the possibility of cloaking an object became a technological reality. Two primary approaches to cloaking are available: transformation optics [4] and mantle cloaking [5]. Transformation optics [4, 6] was introduced as a technique to control and manipulate interaction between electromagnetic fields and materials. This material interpretation [7] is based on the form invariance of Maxwells equations under coordinate transformations. The exact medium parameters that will physically realize the new phenomena in the transformed space are completely specified by the coordinates transformation definitions.

One of the most appealing applications of the metamaterials is achieving invisibility cloaks by tailoring evanescent fields. This can be allowed in controllable manner using an integrated photonics platform. Composite plasmonic waveguides [8] provide large confinement of light in sub-wavelength scale and the control of the surface plasmons excited on the thin overlayer. Here, we show that by reducing the scattering of an object at the interaction length L of the evanescent field with an object, we distort an interaction of evanescent field with an object which results in object's invisibility.

2. SYSTEM AND METHODS

We consider a guided wave system shown in Figure 1 which is constructed from a composite plasmonic waveguide structure. Silicon nitride (Si_3N_4) ridge waveguide is modeled on a silicon dioxide (SiO_2) substrate. The thin gold layer of 40 nm covered by 10 nm Si is designed to confine the optical mode in vicinity with the gold-waveguide interface for efficient coupling to the surface plasmon modes.

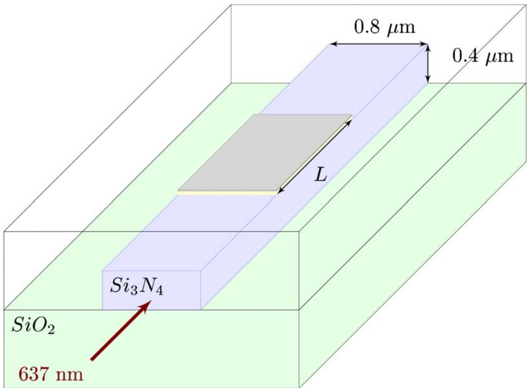
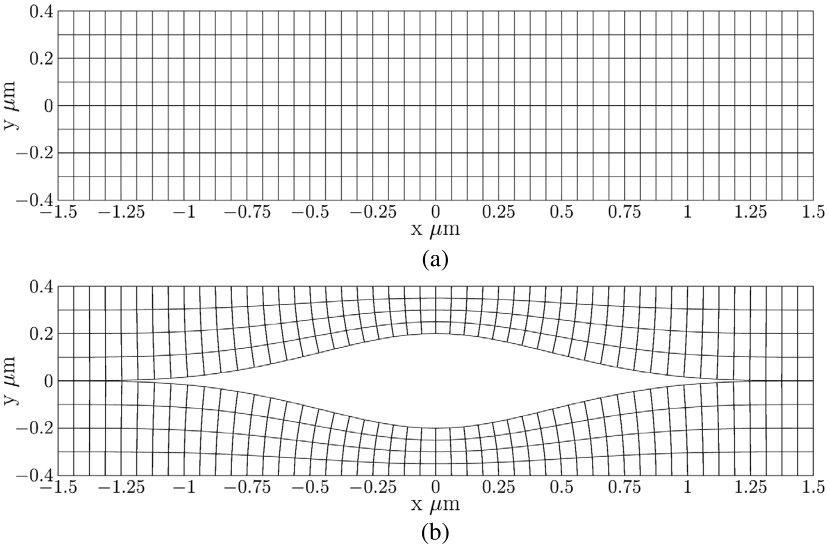


Figure 1. Composite plasmonic waveguide structure and materials.

Since Maxwells equations are form-invariant under coordinate transformations, the thin gold layer coordinates can be transformed into a new system. The surface is divided into a grid and converted into the desired mapping as illustrated in Figure 2.



(a)

(b)

Figure 2. Coordinate mapping of the transformed medium: (a) physical space and (b) virtual space.

The transformation can be described by the Jacobian matrix. Here, we considered a 2D transformation in the xy plane, where the coordinates are invariant in the z-direction. Under these conditions, the Jacobian matrix reduces to the form given in Eq. (1).

$$\mathbf{A} = \begin{bmatrix} \frac{\partial x'}{\partial x} & \frac{\partial x'}{\partial y} & 0 \\ \frac{\partial y'}{\partial x} & \frac{\partial y'}{\partial y} & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Based on the general transformation optics design equations provided above, the resulting permittivity and tensors become as described in Eq. (2).

$$\epsilon' = \frac{\epsilon_0}{|\mathbf{A}|} \begin{bmatrix} \left(\frac{\partial x'}{\partial x}\right)^2 + \left(\frac{\partial x'}{\partial y}\right)^2 & \frac{\partial x'}{\partial x}\frac{\partial y'}{\partial x} + \frac{\partial x'}{\partial y}\frac{\partial y'}{\partial y} & 0 \\ \frac{\partial y'}{\partial x}\frac{\partial x'}{\partial x} + \frac{\partial x'}{\partial y}\frac{\partial y'}{\partial y} & \left(\frac{\partial y'}{\partial x}\right)^2 + \left(\frac{\partial y'}{\partial y}\right)^2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

To minimize the anisotropy factor, the mesh has to be approximately orthogonal in both the physical and virtual spaces [9]. Thus, it must satisfy the Cauchy-Reimann conditions (3).

$$\frac{\partial x'}{\partial x} = \frac{\partial y'}{\partial y}; \quad \frac{\partial y'}{\partial x} = -\frac{\partial x'}{\partial y} \tag{3}$$

3. RESULTS

The composite plasmonic waveguide is illuminated by the dielectric mode (DM) shown on Figure 3. Three hybrid plasmonic modes are excited in the region covered by gold overlayer with Si, which are hybrid plasmonic/dielectric mode (HDM), SPP symmetric (SPP-s) mode and SPP asymmetric (SPP-a) mode as studied elswhere [8].

Transformation optics was used to calculate the effective permittivity of the gold using MATLAB. These parameters were then exported into the Maxwell solver, here (FTDT) of Lumerical. A Teflon ($\epsilon_r = 1.3$) cylinder with $r = 0.3\,\mu\text{m}$ is placed on top of the plasmonic layer in the center to represent the concealed object. Figure 4 shows the surface intensity on the gold layer. Figure 3(b) shows the effects of the scattering by the object compared to the plain waveguide (Figure 3(a)). The transformed surface was introduced in Figure 3(c) and after placing the cylinder on the transformed surface (Figure 3(d)) one can see that the difference is negligible. Thus, the object is concealed.

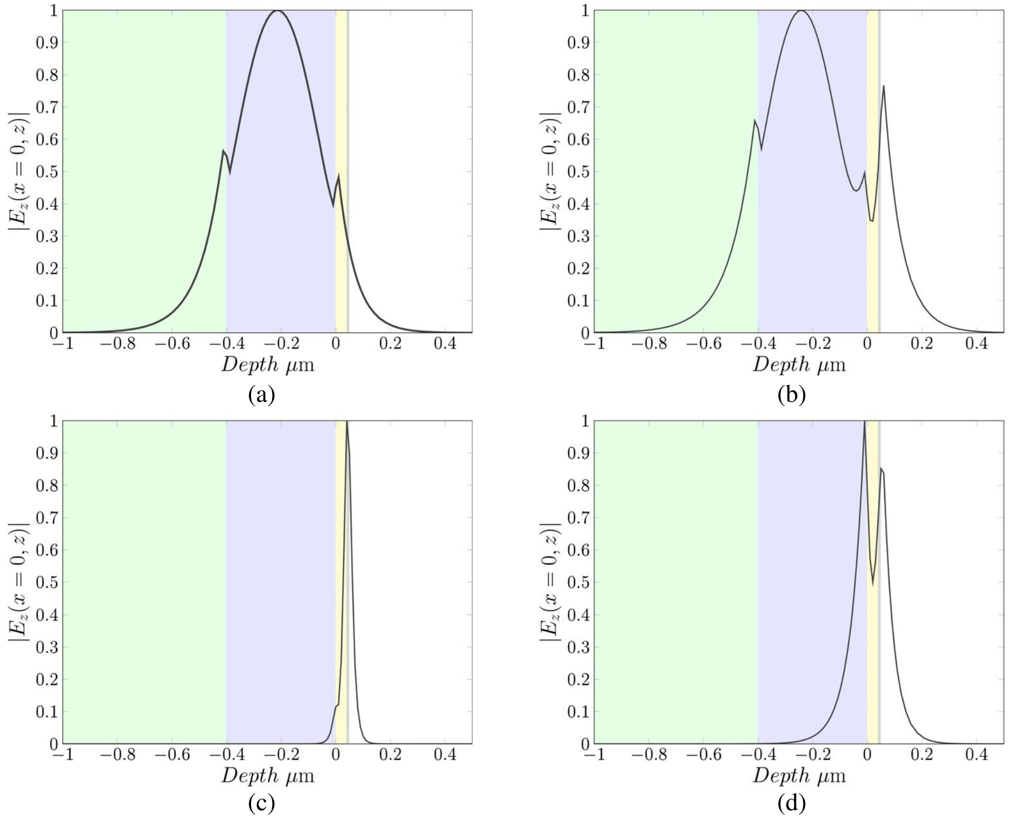


Figure 3. Cross section of modes in the hybrid plasmonic waveguide: (a) dielectric mode (DM), (b) hybrid plasmonic/dielectric mode (HDM), (c) SPP symmetric (SPP-s) and (d) SPP asymmetric (SPP-a).

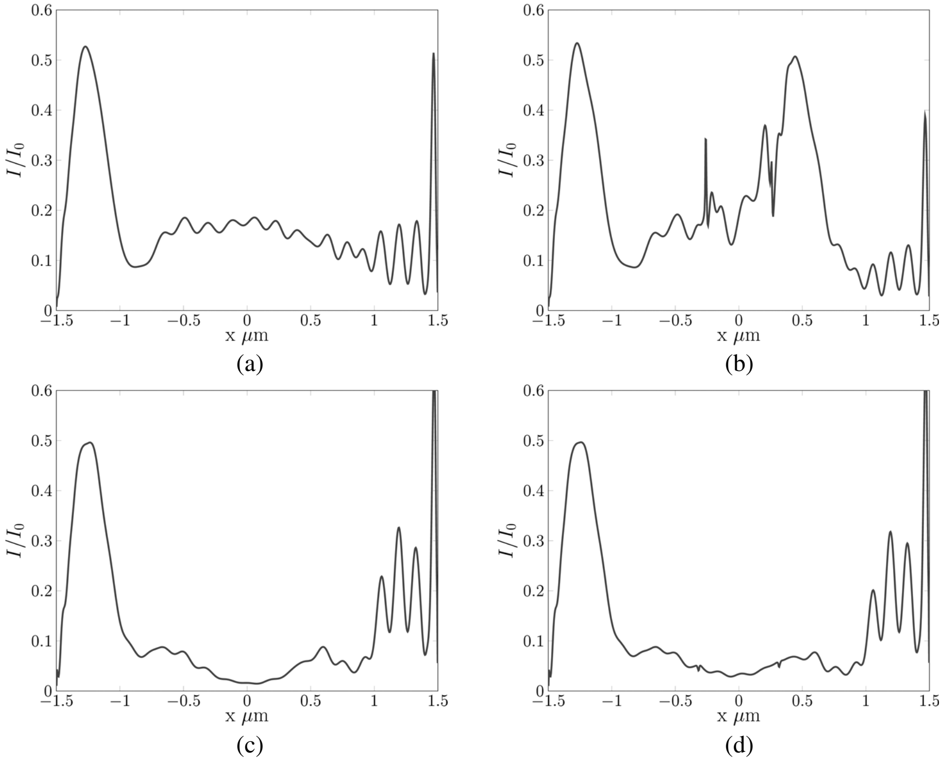


Figure 4. Cross section of the surface intensity in the hybrid plasmonic waveguide: (a) plain waveguide, (b) plain waveguide with a Teflon cylinder, (c) waveguide with transformed surface and (d) waveguide with transformed surface and a Teflon cylinder.

4. CONCLUSION

An invisibility cloak scheme with composite plasmonic waveguide and metasurface overlayer was introduced. Designated structures create a 'black hole' which in fact, distort an interaction between evanescent field and an object, or stickily speaking conceal a nano-scale object placed on a waveguide. Transformation optics were used to calculate the effective permittivity of a plasmonic overlayer on waveguide using MATLAB. The optical modes and surface intensity were analyzed using a commercial Maxwell solver.

We show that an object invisibility can be realized by using the tools provided by transformation optics. By applying these methods, we showed that the evanescent fields of composite plasmonic waveguide structure does not interact with the object.

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