Plasmonic wormholes

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Abstract

We describe two types of toroidal metamaterials which are invisible for surface plasmon polaritons (SPPs) propagating on a metal surface. The former is a toroidal handlebody bridging remote holes on the surface: it essentially works as a plasmonic counterpart of electromagnetic wormholes. The latter is a toroidal ring lying on the metal surface: this bridges two disconnected metal surfaces i.e. it connects a thin metal cylinder to a at metal surface with a hole. Full-wave numerical simulations demonstrate that an electromagnetic field propagating inside these metamaterials does not disturb the propagation of SPPs at the metal surface. A multilayered design of these devices is proposed, based on effective medium theory for a set of reduced parameters: The former metamaterial requires homogeneous isotropic magnetic layers, while the latter requires dielectric layers.

1. Introduction

Five years ago, two groups of physicists [1, 2] unveiled independent paths towards electromagnetic invisibility. The transformational optics proposal by Pendry et al. leads to singular tensors on the frontier of the invisibility region [3, 4] that require an extreme electromagnetic response achieved upon resonance of split ring resonators. In this letter, we introduce two types of plasmonic wormholes. Our main contribution is an explicit design of a toroidal handle-body to control SPPs propagating at a metal surface with two holes: The main ingredient in the wormhole recipe is to blow up a curve, rather than a point as is used in a typical invisibility cloak[5]. We further numerically demonstrate the validity of our theoretical approach with 3D finite element computations for SPPs propagating in a toroidal heterogeneous anisotropic wormhole. We finally derive some reduced set of parameters allowing for the design of a multi-layered toroidal tunnel consisting of an alternation of isotropic homogeneous layers approximating the ideal wormhole in the homogenization limit. This brings plasmonic wormholes a step closer to an experimental setup. Potential applications in plasmonics range from invisible Plasmonic waveguides (which could be useful in making measurements of electromagnetic fields without disturbing them, or as new types of endoscopes in medical applications), to hard discs for optical computers.

2. Topological description of the wormholes

We start by describing the mathematical construction of a magnetic wormhole, which involves an invisible handlebody and two holes on a metal plate. Such a wormhole can be implemented for electromagnetic fields by deriving the required tensors of permittivity and permeability for a toroidal region of R^3 (the invisible tunnel) connecting two regions of a metal surface, using the tools of transformational plasmonics.

The main ingredients of our wormhole construction are as follows: We start by making two identical holes in a metal plate, for instance two discs D_1 and D_2 separated on a plane. We denote by M the region so obtained: $M = R^2 \setminus (D_1 \cup D_2)$. Topologically, M is a two-dimensional manifold with

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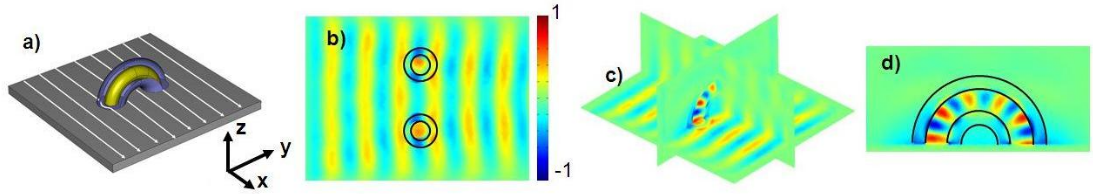

Fig. 1: Principle of the undetectable tunnel bridging two distant regions on a metal surface. The electromagnetic waveguide is shown in yellow and the coating in blue. It is coated with a transformed dielectric plasmonic wormhole with reduced parameters: in principle, the handlebody is acting as a waveguide for electromagnetic waves launched from the metal dielectric interface where we set $\mathbf{H} = (H_{x2}, 0, 0)\exp(-i\omega t)$ with $H_{x2} = \exp(-i\sqrt{2}z)$ (a); (b) Two dimensional plot (view from above) of the real part of the magnetic field; (c) 3D plot validating the guiding and invisibility properties; (d) Two-dimensional plot of the real part of the magnetic field in the vertical plane showing the inner structure of the wormhole with a dielectric in the middle region which is surrounded by two regions of transformed medium. Note that the interfaces between the regions consist of a thin, infinitely conducting layer of thickness 70 nm. These computations are for a wavelength of 700 nm.

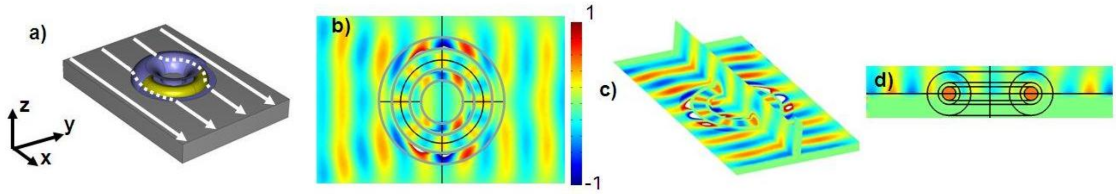

Fig. 2: (a) Principle of the undetectable toroidal ring. Ray trajectories are drawn for illustrative purpose only. Full wave simulations validate the theoretical proposal: (b) Top view; (c) 3D plot; (d) Side view; Here, all plots are for the real part of the magnetic field and we set $\mathbf{H} = (0, 0, H_{z2})\exp(-i\omega t)$ with $H_{x2} = \exp(-i\sqrt{2}z)$ on the waveguide cross-section in the vertical plane $y = 0$.

boundary, the boundary of M being $\partial M = \partial D_1 \cup \partial D_2$. We note that ∂M is the disjoint union of two discs on the plane.

The second component of the wormhole W is a curved toroidal cylinder, $T = \partial M \times [0; L]$, where L denotes the arc-length which connects points of circle ∂D_1 to ∂D_2. As the boundaries of M and T are topologically the same ($\partial M = \partial T = \partial D_1 \cup \partial D_2$), we can glue these boundaries together. The resulting domain W no longer lies on the metal surface R^2, but rather has the topology of Euclidean space R^3 with a handle attached, see Fig. 1(a). W is in fact a 3D manifold (without boundary) that is the connected sum of the components M (metal surface with two distant holes) and T (toroidal cylinder).

Regarding the construction of the dielectric wormhole, see Fig. 2, the previous construction repeats mutatis mutandis with the noticeable difference that the manifold M should be replaced by a manifold M_1 with a single hole: $M_1 = R^2 \setminus D_1$. Moreover, the disc D_2 is now located inside D_1: $D_2 \subset D_1$.

We now wish to apply tools of transformational plasmonics to design a device in R^3 which controls the propagation of SPPs in the same way as the presence of the handle T in the wormhole manifold W. On W we shall use the Riemannian metric that is the Euclidean metric on M and the product metric on T. We emphasize that we are not actually tearing and gluing plasmonic space, but instead prescribing a metamaterial which makes the SPPs propagating on the metal plate behave as if they were propagating on the wormhole manifold W. In other words, adopting the viewpoint of a SPP, it appears that the topology of plasmonic space has been changed.

For simplicity, we construct a device has rotational symmetry about a line in R^3, and moreover we assume that the radii of D_1 and D_2 are equal. We use toroidal coordinates (r, u, v) corresponding to a point $((R + r \sin u) \cos v; (R + r \sin u) \sin v; r \cos u)$ in R^3, where $2R$ is the center-to-center spacing between D_1 and D_2. We then blowup the centerline of the toroid onto a toroidal coating using the transformation $r' = a + r(b - a)/b, u' = u$ and $v' = v$. Here, a and b are the radii of the circles that form the inner and outer boundaries of the cloaking region, respectively.

In order to simplify the design of the wormhole, we proceed in a way similar to what was done to obtain a reduced set of material parameters for cylindrical cloaks in. Using the transformational plasmonics tools, we obtain the set of reduced parameters:

$$\epsilon_{rr} = \mu_{rr} = \left(\frac{r - a}{r}\right)^2, \; \epsilon_{uu} = \mu_{uu} = 1, \; \epsilon_{vv} = \mu_{vv} = \frac{b^2}{(b - a)^2} \tag{1}$$

that preserve the wave trajectories, but induce a slight impedance mismatch on the wormhole boundary.

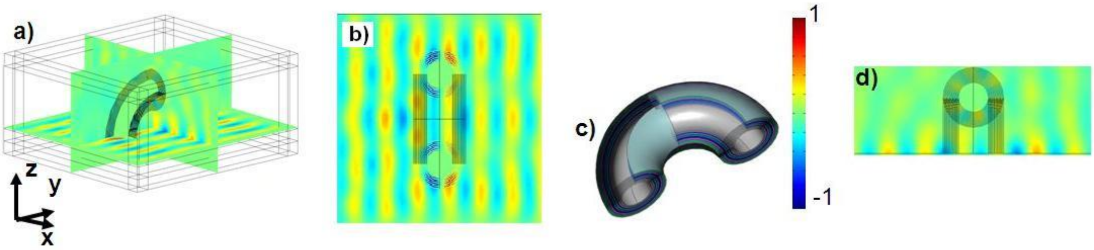

Fig. 3: Structured magnetic wormhole: SPP Gaussian beam with a waist of 2100 nm incident upon a wormhole at 700 nm smoothly bent around a metal toroidal obstacle; (a) 3D plot of the real part of the magnetic field; (b) Top view; (c) Diagrammatic view; (d) Side view. The color scale has been normalized.

4. Conclusion

Wormholes introduced by Greenleaf et al. represent a fascinating electromagnetic paradigm, but were initially thought as an abstract metamaterial bridging two spherical holes, thereby requiring a further dimension for the invisible tunnel, and moreover no permeability and permeability tensors were derived for a specific design. In the present letter, we have transposed this idea to the area of surface plasmon polaritons, with two illustrative examples of invisible handlebody and ring over surfaces, and further proposed a multi-layered version of these metamaterials to foster applications in the emerging field of transformational plasmonics. Potential applications might be in safer communications and intra-ship technologies.

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