Metamaterials and Flow of Photons and Electrons

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Abstract

In this paper, I give an overview of our recent efforts in my group in the areas of optical metamaterials and their roles in taming photons and electrons. I discuss our recent progress on design of building blocks of optical metamaterials with specific bulk properties, optical metatronics, extreme-parameter metamaterials, one-way flow of photons, graphene metamaterials and transformation optics, and nonlinear phenomena in certain metamaterial nanostructures. Physical insights into these results are given and future directions are speculated.

1. Summary

As is well known, metamaterials are engineered composite media formed by collections of properly designed subwavelength elements and inclusions. Since one can tailor and design the electromagnetic parameters of metamaterials to desired values, such materials may manipulate and control flow of photons and electrons in the microwave, THz, IR and optical signals at various length scales. In particular, when we merge the concept of extreme-parameter metamaterials with the fields of nanooptics and nanoelectronics, various interesting possibilities may arise. Among these, one can mention the metamaterial-inspired optical nanocircuitry, for which we have coined the term “metatronics” [1-3], graphene-based metamaterials and transformation optics and electronics for controlling photons and electrons on ‘flatland’ structures [4], and control of one-way flow of photons and electrons in desired directions. In this past year, we have obtained interesting results, a sample of which will be presented in this talk.

In the presentation, we will discuss our recent efforts in developing design rules for the building blocks of optical metamaterials when certain bulk properties of the materials are desired. This effort can be efficiently linked to the concept of metatronics, providing a useful tool in developing metamaterials with specific desired spectral properties, starting from the basic principles and from the unit elements.

We will present our most recent results on the development of the concepts of metatronics and the unifying paradigm of metatronics, in which the three fields of “electronics”, “photonics” and “magnetics” can be brought together seamlessly under one umbrella. (See Fig. 1, when the two paradigms of metatronics and electronics are compared.) Nonlinearity in metatronics can also provide us with novel optical nonlinear lumped elements. We have investigated the concept of metatronics through extensive analytical and numerical studies, computer simulations, and in a set of experiments at the IR wavelengths. We will show our experimental results using the nanorods made of low-stressed Si_3N_4 with properly designed cross sectional dimensions, functioning as lumped circuit elements at the IR wavelengths between 8 to 14 microns [5]. We have now planned to extend this finding into the near-IR regime, by using transparent conducting oxides (e.g., indium tin oxides) as the materials for lumped circuits elements for the near-IR metatronics.

We have been exploring how metamaterials can be exploited to control the flow of photons, analogous to what semiconductors do for electrons, providing the possibility of one-way flow of photons. (See Fig. 2, where two conduits, one for electrons and one for photons are sketched.) We have been inves-

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tigating this phenomenon in the non-reciprocal metamaterials. We will present our recent results on this finding.

We have extended the concept of metatronics to other platforms such as graphene, providing one-atom-thick metamaterials and transformation optics [4]. This concept can be expanded to embrace various optical devices and component on the flatland graphene structures.

In this talk, we will present a sample of our recent results on these topics.

References

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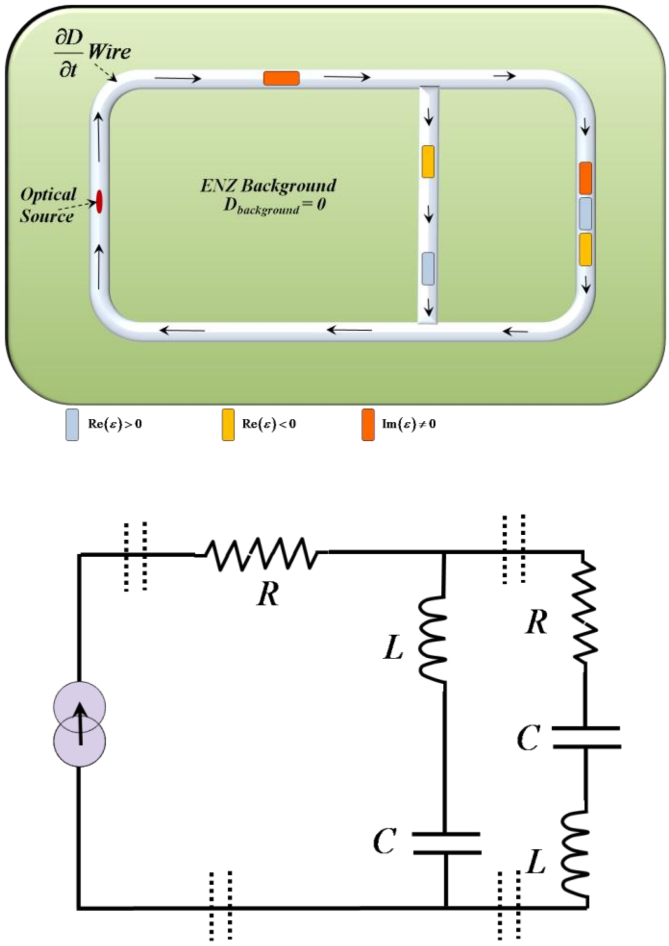

Fig. 1. Top Panel shows a sketch of the concept of Metatronics: Properly arranged nanostructures embedded in a groove (or a tube) carved within an epsilon-near-zero (ENZ) metamaterial substrate. When this structure is excited by an optical signal (e.g., from an optical source also embedded in the groove (or tube)), the electric field and electric displacement current distributions resemble the distributions of voltage and current in an analogous electronic circuit shown in the bottom panel.

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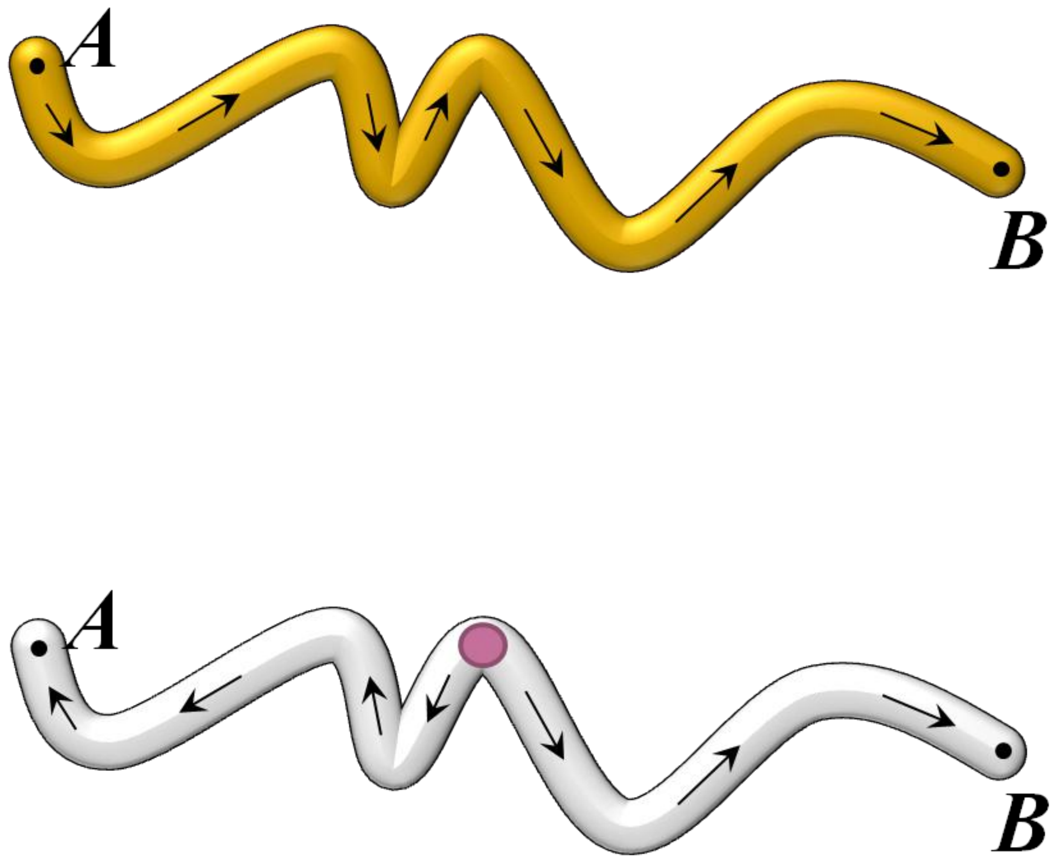

Fig. 2. Similarity and differences between the electronics and the photonics regarding the flow of electrons and photons: Top panel shows a sketch of a standard metallic wire that is a useful conduit for the flow of charged particles. The direction of motion of such charged particles and their general paths can be estimated from the polarity of voltage source and the geometry of the metallic wire. Bottom panel shows a structure as a conduit for photons. If a source of photons is introduced in the middle of this structure, the flow of photons would usually be in both directions. However, we are exploring the possibility of designing metamaterials that would provide one-way flow of photons, i.e., 1-way waveguide, which would make this "photon conduit" more analogous to the electronic metallic wires.