Metasurface Non-Reciprocity Engineering

Mohamed A. Salem and Christophe Caloz*
Department of Electrical Engineering, Polytechnique Montréal,
Montréal, QC H2T 1J3, Canada

Metasurfaces are thin planar electromagnetic structures that are capable of controlling electromagnetic field behavior beyond the capabilities of frequency selective surfaces or analogous structures composed of a uniform material. Metasurfaces have several advantages over volumetric metamaterials, such as compactness, low losses and ease of fabrication (C. L. Holloway, E. F. Kuester, J. A. Gordon, J. O'Hara, J. Booth, and D. R. Smith, *IEEE Antennas Propag. Mag.*, **54**, 2012, pp. 10-35). Recently, and for these particular reasons, metasurfaces have been steadily replacing volumetric metamaterials and are thus gaining wide attention in the literature.

Non-reciprocal metasurfaces are nevertheless less explored, even though they may become instrumental in numerous engineering applications, such as electromagnetic switches, gyrators, circulators, and non-reciprocal communication links. A non-reciprocal metasurface may be engineered following various physical principles. Among the most common principles followed is injecting external quantities, such as current, linear or angular momentum, or magnetic field, to achieve non-reciprocity in the structures. Alternatively, non-linear elements, such as diodes and transistors, may be incorporated in the metasurface design for same purpose. In this work, a non-reciprocal metasurface design approach is outlined, that is inherently linear and does not require external quantities. Considering a metasurface as an array of sub-wavelength scattering elements, the radiating current $\mathbf{J}$ on the elements may thus be written in terms of the incident field $\mathbf{E}$ as

$$\mathbf{J} = -\frac{i}{\omega}\left[\left(\nabla\times\bar{\bar{\mu}}^{-1}\nabla\times\right) - \omega^2\bar{\bar{\varepsilon}}\right]\mathbf{E}, \tag{1}$$

where $\bar{\bar{\varepsilon}}$ and $\bar{\bar{\mu}}$ are respectively the electric permittivity and the magnetic permeability of the element in matrix form, and a time dependence of $\exp(-i\omega t)$ is assumed. It will be shown that by engineering scattering elements with complex non-symmetric permittivity and/or permeability, a linear non-reciprocal metasurface may designed. Moreover, the metasurface can be designed to be passive and lossless by further imposing the appropriate conditions on the electric and magnetic properties of its elements. The absence of external quantities and the linearity of this proposed design reduce the overall complexity of the analysis, fabrication and implementation of non-reciprocal metasurfaces. The existence and the physical bounds of such designs will be discussed.