Non-reciprocal Metamaterials with Angular Momentum Biasing

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Non-reciprocity is an asymmetry of a medium's response to waves propagating in opposite directions. Non-reciprocal devices, such as isolators, circulators and phase shifters, are essential in electronic systems, for instance to isolate a receiver from a transmitter, protect a source from undesired reflections or shield a receiver from interfering signals. A structure can be non-reciprocal when biased with a vector that is odd under time reversal, i.e. the magnetic field, the current, the linear momentum and the angular momentum [J. D. Jackson, Classical Electrodynamics, John Wiley & Sons, Inc., 1999]. Since the 1950's, the most common way to achieve non-reciprocity at microwaves has been through biasing ferrites with a static magnetic field. Although ferrite-based devices are excellent in terms of performance (high isolation, low loss, broad bandwidth, weak nonlinearity, and operation in extreme temperature conditions), the requirement for magnetic biasing, usually obtained via permanent magnets, makes them heavy, bulky and difficult to integrate. Recently, two other types of biasing schemes were devised: direct current and linear momentum. The former cocnerns metamaterials based on transistor-loaded ring resonators [T. Kodera, D. L. Sounas, and C. Caloz, Appl. Phys. Lett. 99, 031114 (2011)], while the latter concerns optical isolators consisting of spatially-temporarily modulated waveguides [Z. Yu and S. Fan, Nature Photon. 3, 91 (2009)]. Although such structures overcome the drawbacks of ferrites, either they suffer from power consumption (nonreciprocal metamaterial) or they are limited to specific applications (optical isolator).

Here we propose a novel class of metamaterials which exhibit nonreciprocity through angular momentum biasing. The constituent element of theses metamaterials is a ring resonator with biasing provided by an external electromagnetic field. At microwaves, biasing may be achieved by inserting non-uniformly biased varactors at equidistant points along the rings, with modulated voltages $V_i = V_0 + \Delta V \cos(\omega_B t - \varphi_i)$. At optical frequencies, biasing may be achieved by placing the rings on a material with second-order nonlinearities and illuminating the structure with a strong circularly-polarized field. Then, the response to a weak incident wave is similar to that of a ring with a spatially-temporarily modulated permittivity, $\varepsilon_r = \varepsilon_{r0} + \Delta\varepsilon \cos(\omega_B t - \varphi)$. Our theoretical analysis and numerical simulations show that a slab of the proposed metamaterial rotates the polarization of an incident wave in a nonreciprocal way, exactly as a magnetically biased ferrite slab. Contrary to non-reciprocal metamaterials [T. Kodera, D. L. Sounas, and C. Caloz, Appl. Phys. Lett., 99, 031114, (2011)], the biasing of the new metamaterial does not involve any power consumption.