Non-reciprocal space-time gratings

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Reciprocity is a desired property in many wave applications. Nevertheless, sometimes we would like to be able to violate reciprocity, and in the extreme case design devices such as isolators or circulators. This ability is rather mature at radio-frequencies, where one usually utilizes the gyrotropic property of rare-earth materials in order to break reciprocity. Unfortunately, an extension of such techniques into the optical regime is challenging if not impossible due to changes in the properties of gyrotropic materials at these frequencies. Therefore, a different methodology should be followed. According to Lorentz reciprocity theorem, a structure is reciprocal if it is linear, time-invariant structure and if it is made of symmetric materials ($\epsilon = \epsilon^T, \mu = \mu^T$). Thus, in order to break reciprocity, except for using gyrotropic materials, one may use either non-linear or time dependent materials.

In this work we follow the latter approach and explore diffraction by spatially and temporally modulated gratings as a way to obtain non-reciprocal transmission/diffraction. The grating, which is designed to be resonant, is opaque in the absence of modulation. However, when we add spatial modulation it becomes transparent in a narrow angular and frequency window, based on a phenomenon associated to Wood's anomaly. When we also add temporal modulation, the grating becomes non-reciprocal: it is fully transparent at a given angle of incidence and for a particular frequency, while it is almost fully opaque when the incident wave with the same frequency impinges from the complementary direction.

We begin the analysis with an analytic continuous model for the time dependent surface impedance operator, expand the solution in terms of space-time Floquet harmonics and show that, under certain conditions, full transmission can take place even though the surface is opaque in the absence of modulation. We also propose an implementation in terms of a two dimensional array of electrically small split ring resonators loaded with varactors. Using a full-wave solver, we simulate the proposed structure and show that we indeed obtain the phenomenon as predicted by our analytic model.