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Controlling asymmetric reflection of metasurfaces with loss

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Abstract. Optical theorem, being the manifestation of the energy conservation law, relates the total scattering cross-section of a structure with its scattering in the forward direction. However, there are no fundamental restrictions on other directions. Strong asymmetric reflection and backscattering can be achieved in structures with magneto-electric coupling, taking place between constitutive elements. Here scattering properties of single meta-particles, based on near-field coupled electric and magnetic dipoles, and their arrays are analyzed. It is shown that dissipation is the key mechanism, responsible for the asymmetric backscattering behavior. While far-field scattering can serve as a sufficient loss mechanism in the case of single structures, ohmic dissipation should be added in the case of periodic arrays (metasurfaces). In this case, the practical realization is based on split-ring resonators, loaded with resistance, and wires, both printed on a PC board.

Keywords: metasurfaces, metamaterials, scattering, asymmetric responses

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Управление асимметричным отражением метаповерхностей с потерями

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Аннотация. Оптическая теорема, являющаяся частным случаем закона сохранения энергии, связывает полное сечение рассеяния структуры с ее рассеянием в направлении падающей волны. Однако для других направлений не существует фундаментальных ограничений. Здесь анализируются рассеивающие свойства одиночных метачастиц, через ближнее поле электрических и магнитных диполей, и их массивов. В частности, показано, что диссипация является ключевым механизмом, ответственным за асимметричное поведение обратного рассеяния. В то время как рассеяние в дальнем поле может служить достаточным механизмом потерь в случае одиночных структур, в случае периодических массивов (метаповерхностей) необходимо добавить омическую диссипацию. В данном случае практическая реализация основана на резонаторах с разрезным кольцом, нагруженных сопротивлением, и проводах, оба напечатаны на плате ПК.

Ключевые слова: метаповерхности, метаматериалы, рассеяние, асимметричные отклики

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Introduction

Metamaterials have gained broad interest in the past decade, as they hold the promise for delivering new types of devices [1]. The basic functionalities of metamaterials are achieved by carefully designing the constitutive elements (meta-atoms) that govern the composite's behavior. Split ring resonators (SRR) and thin wires are often employed as the building blocks in many realizations, owing both to the fact that these structures are well understood theoretically [2], as well as the relative ease of their manufacturing. In order to achieve complex properties, meta-atoms often consist of more than one structure [3]. One of the desired functionalities that could be achieved with metamaterials is an asymmetric response. For example, asymmetric properties (and especially transmission) could find use in a range of applications, such as anti-reflection coatings [4] and many others.

Scattering characteristics of individual elements could be controlled by engineering their multipolar responses. For example, the so-called Huygen's elements rely on interference between electric and magnetic dipolar responses that suppress the backward scattering [5, 6]. Properties of magnetic and electric resonances could be tailored by particle's shape, e.g. core-shell geometry [7]. Meta-particles with nonsymmetrical scattering are discussed in detail in [8, 9, 10] where a few structures were studied analytically, including the omega, omega-Tellegen, and the chiral-moving particle. It was shown that periodic structures constructed from such meta-atoms could be used to create thin films with tunable nonsymmetrical transmission and reflection, e.g. [11, 12] and references therein. Here another example of an asymmetric meta-particle is proposed, putting an emphasis on reflection characteristics and its balance with the forward scattering.

The optical theorem [13] relates the forward scattering from an object with its total radar cross-section (RCS) and is a manifestation of the fundamental principle of causality. Remarkably, the theorem favors the forward direction over all the rest and there is no simple relation between the total RCS and the backward scattering, for example. Here a special type of meta-atom, having a symmetric forward and asymmetric backward scattering is studied. The hybrid magneto-electric particle (HMEP), consisting of a SRR and a thin wire (Fig. 1, *a*) is considered analytically, numerically and experimentally. The HMEP is shown to have asymmetric backscattering when illuminated by a plane wave from opposite directions. At the next stage, arrays of HMEPs are analyzed and asymmetric reflection characteristics are studied.

Results

Single HMEP particle was analyzed first. The theoretical description is based on coupled dipole model, which addresses the scattering phenomenon self-consistently. The key mechanism for the asymmetric scattering relies on peculiar coupling dynamics, where magnetic field of electric dipole, induces currents on the SRR, and electric field of the SRR is coupled to the wire (Fig. 1, *b*) [14]. Fig. 1, *c-f,* shows the numerical values of forward and total scattering cross sections of the HMEP. Blue and red lines correspond to opposite directions of the incident plane wave. For both positive and negative incident directions the scattering remains the same. Those numerical results underline the validity of the optical theorem, relating forward scattering to the RCS. As it could be explicitly seen, the theorem is satisfied and no distinction on the propagation

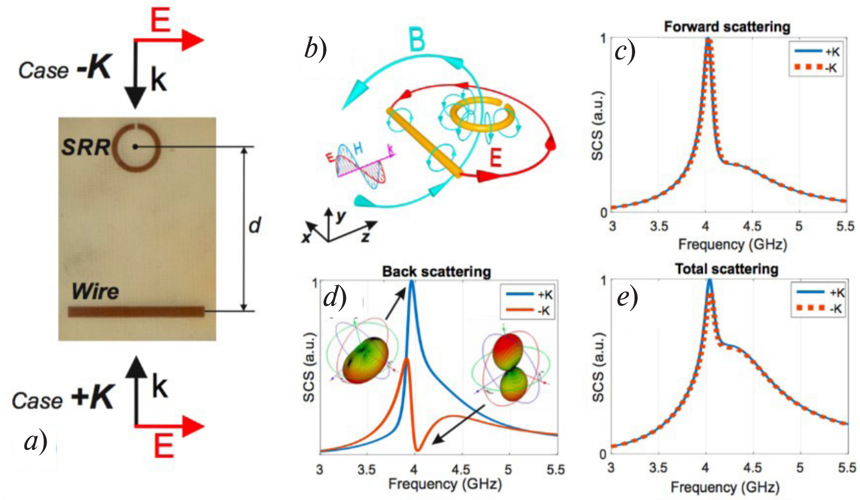

Fig. 1. Work [14], Fig. 1 (*b*), Fig. 3: Photograph of the HMEP particle (*a*). Schematics of magneto-electric coupling (*b*). Total and forward scattering spectra (*c*), (*e*). Asymmetric backscattering spectra (*d*)

direction could be made. Fig. 1, *d* is the main result, showing that the backscattering on the z-axis at a large distance away from the HMEP, strongly depends on the direction of incident field propagation. In the forward direction (+k) the field is strongly reflected around 4GHz while in the backward direction (-k) there is almost no backscattering at all in the same frequency range. To satisfy optical theorem, the scattered radiation should be redistributed along other directions in space. It is worth noting, that retarded Green's functions should be used for the accurate description of the asymmetric backscattering phenomenon. As the result, the relation to the radiation losses can be traced back.

To underline the impact of the loss mechanism on the asymmetric backscattering phenomenon, arrays of HMEPs were analyzed. In periodically structured subwavelength surfaces the diffraction losses plays a minor role, hence true Joule losses should be incorporated. This was done by attaching lumped resistive elements within the split rings. Chrematistics of the arrays with different resistive loads were analyzed and the results appear in Fig. 2. Panel (*a*) shows the forward scattering (transmission) of the structure. It can be seen that exactly the same spectra are obtained for both incident directions, as it is expected from the reciprocity theorem. The backward scattering (reflection), on the other hand, strongly depends on the value of the lumped resistors.

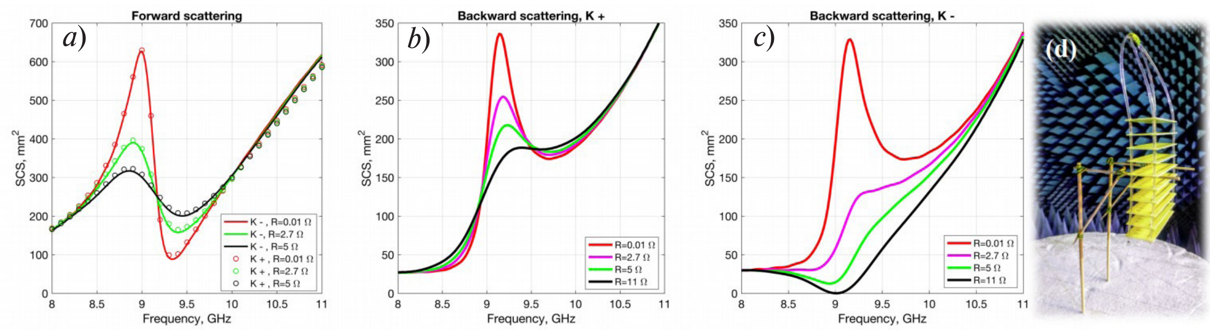

Fig. 2. Scattering cross-section of HMEP array (transmission) spectra (*a*). Reflection spectra for opposite directions of the incidence (*b*), (*c*). Colored lines correspond to different values of lumped resistors. (*d*) Photograph of the fabricated HMEP array

Fig. 2, *b* and *c* show the reflection spectra, obtained for opposite incident directions. While for the small value of the resistors the spectra are almost identical, strong asymmetry develops with the increase of the values. This behavior clearly demonstrates the nature of the effect – dissipation-inspired asymmetric reflection. Fig. 2, *d* shows the photograph of the fabricated HMEP array.

Conclusion

The effect of asymmetric backscattering and reflection was demonstrated analytically and numerically. It was shown that the radiation loss is responsible for the effect in the case of single meta-particle with a sufficient level of magneto-electric coupling between two constitutive elements. In the case of the array, composed of such particles, the effect of asymmetric reflection is inspired by Joule losses, which were implemented via inclusion of additional resistive elements within the split rings, forming the array.

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