4^{th} URSI AT-RASC, Gran Canaria, 19-24 May 2024

Design of Reconfigurable Refractive Metasurfaces based on Drude-like Scatterers

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Abstract

In this contribution, we describe a novel route for designing reconfigurable refractive metasurfaces. The proposed approach leverages on Drude-like scatterers, engineered in terms of both geometry and electromagnetic characteristics, to establish robust interaction with the incident field while ensuring complete forward transmission at a specified frequency. Through a combination of theoretical analysis and extensive full-wave simulations, we demonstrate the efficacy of employing Drude-like scatterers in the epsilon-negative regime for the realization of reconfigurable refractive metasurfaces. A possible implementation in the microwave spectrum, based on plasma discharges, is finally discussed.

1. Introduction

In recent years, the burgeoning research field of metamaterials has paved the way for unprecedented advances in controlling and manipulating electromagnetic waves. Among the innovative developments, refractive metasurfaces, often referred to as beam-steering metasurfaces [1], have emerged as a cutting-edge technology with relevant implications for wavefront engineering throughout the whole electromagnetic spectrum [2].

Unlike conventional optical components that rely on bulk materials, in fact, refractive metasurfaces consists of subwavelength structures designed to impart tailored phase shifts across the wavefront and modify either the propagation direction of the wave [2] or its amplitude pattern [3].

The phase-shifted transmission required for refractive metasurfaces can be realized through various structures, with the most established one relying on dipolar meta-atoms. These meta-atoms, when stimulated by a properly electromagnetic field, support the concurrent excitation of both electric and magnetic dipole moments [3]-[5]. More recently, it has been also shown how multipolar metasurfaces, which harness the interaction between higher-order multipoles, enable even additional degrees of freedom and allows achieving improved control over the amplitude, phase, and polarization of refracted waves [6]-[9].

Building upon these earlier works, this contribution introduces an alternative method for crafting multipolar refractive metasurfaces, utilizing Drude-like scatterers. Specifically, we illustrate how Drude-like scatterers, operating within the epsilon-negative regime, can be tailored to exhibit a generalized Kerker's condition over a moderately wide frequency range. This phenomenon is then exploited to engineer metasurfaces with full-phase coverage, making them well-suited for the implementation of beam-steering devices. The proposed approach, that can be considered alternative to the ones based on dipolar meta-atoms or core-shell structures, features an easier integration of reconfigurability strategies.

2. Scattering analysis of the individual particle

The individual particle considered in this work is shown in the inset of Fig. 1 and consists of a sphere made by a Drude-like material, whose permittivity function is:

$$\varepsilon_s = 1 - \frac{\omega_p^2}{\omega^2 - j\omega\gamma}, \qquad (1).$$

being ω_p and γ the plasma and collision frequency, respectively. In Fig. 1, we report the magnitude of the relevant scattering coefficients of this particle evaluated through the Mie theory. The scattering coefficients are shown *vs.* the normalized frequency parameter x, defined by the equation $\omega = x\omega_p$.

The radius of the sphere, that has been chosen after extensive analysis of the forward and total scattering cross sections of the particle, is set to $a = \lambda_p/2$, being λ_p the wavelength at the plasma frequency. As it can be appreciated, there is a frequency range around half of the plasma frequency (*e.g.,* $x = 0.50$), within the epsilon-negative regime, for which the magnitudes of the electric dipole and quadrupole overlap and hit their maximum values. As a consequence, the particle is expected to exhibit a full-forward scattering as well as a strong interaction with the impinging field. These two characteristics are necessary for designing effective refractive metasurface.

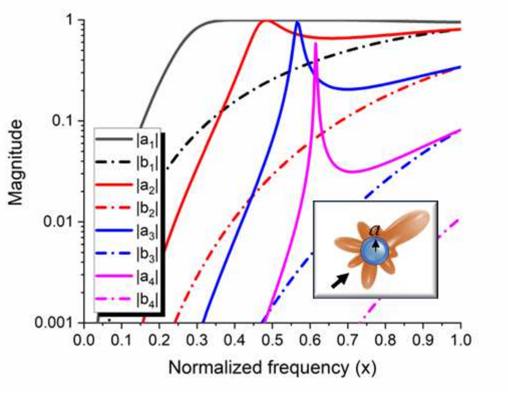

Figure 1. Magnitude of the scattering coefficients vs. the normalized frequency of a sphere made by a Drude-like material. The radius of the sphere is set to $a = \lambda_p/2$.

3. Uniform metasurface

The particle described in the previous Section shows all the features needed to be employed in refractive reconfigurable metasurfaces. To prove this point, in Fig. 2 we report the magnitude and phase of the transmission coefficient of a uniform metasurface made by spherical Drude-like scatterers. The results have been evaluated at $x = 0.50$ and are shown *vs*. the plasma frequency normalized to its original value (*i.e.,* the value for which the radius of the sphere satisfies the condition $a = \lambda_p/2$). The separation distance between the particles, and consequently their interaction level, has been optimized to maximize the transmission bandwidth. This optimization approach aligns with the methodology discussed in [8] for dielectric multipolar particles.

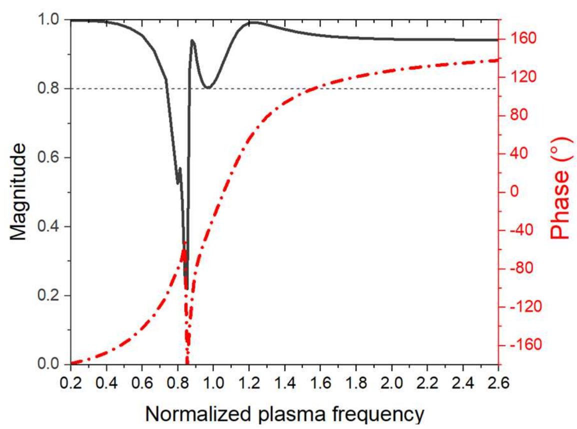

Figure 2. Magnitude and phase of the transmission coefficient of an uniform metasurface consisting of Drude-like scatterers. Results have been obtained through full-wave simulations once fixed a small amount of losses.

As it can be appreciated, by changing the plasma frequency between 100% and 260% of its original values, the phase of transmission coefficient almost covers the entire 2π. At the same time, the magnitude of the transmission coefficient keeps almost always higher than 0.8, which is a reasonable threshold for meta-atoms of refractive metasurfaces.

4. Reconfigurable gradient metasurface

To confirm the suitability of the proposed particles for beam-steering purposes, we have designed a 4-element refractive metasurfaces. The macro-period of the gradient structure has been chosen to achieve a steering angle $\vartheta_t = 25°$ when the phase profile across the transverse direction sweeps from -π to +π.

In Fig. 3, we report the magnitude of the transmission coefficient of the most significant Floquet mode excited by the grating. The red line refers to the uniform case (*i.e.*, all the elements have the same plasma frequency), whereas the black line refers to the gradient scenario. In this latter case, the optimal plasma frequencies of the scatterers have been derived by Fig. 2 and, then, refined with full-wave simulations. As it can be appreciated (and confirmed also by the E-field profile in the inset), the proposed gradient structure is able to couple most of the impinging energy to the Floquet mode aligned with the desired ϑ_t. Conversely, in the uniform case, all the energy is transmitted to the fundamental mode, without any relevant refractive effect.

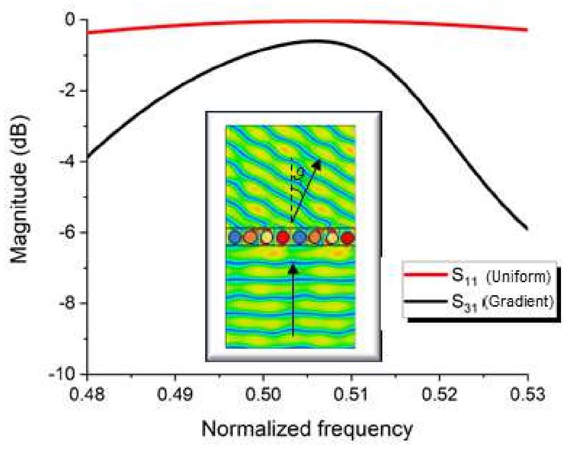

Figure 3. Magnitude of the transmission coefficient of the most significant Floquet mode of a 4-element reconfigurable metasurface. Red line refers to the uniform metasurface, whereas black line refers to the gradient design. In the inset, it is shown the E-field profile in the latter case.

Regarding the possible implementations of such devices, there are several possibilities that could be explored. As a relevant example, at microwave frequencies, such a behavior can be obtained through plasma discharges, whose effectiveness for electromagnetic applications has

been demonstrated in several earlier publications about waveguides [10] or antennas [10].
More details about the theoretical analysis of the individual scatterer, the modelling and design of the reconfigurable metasurface as well as about its robustness towards realistic Ohmic losses will be provided at the Conference.

6. Acknowledgements

This work has been developed in the frame of the activities of the Project PULSE, funded by the European Innovation Council under the EIC Pathfinder Open 2022 program (protocol number 10109931). Project website is: https://www.pulse-pathfinder.eu/.

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