

Reconfigurable metasurface based on plasma cylinders

Jiaruo Yan,^{1,*} Ioannis Katsantonis^{1,2}, Ioannis Draganidis¹, Konstantinos Kourtzanidis³, Alessio Monti,⁴ Stefano Vellucci^{5,6}, Mirko Barbuto^{4,6}, Filiberto Bilotti,^{4,6} and Maria Kafesaki^{1,2}

¹*Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas (FORTH), Crete, 70013 Heraklion, Greece*

²*Department of Materials Science and Engineering, University of Crete, Crete, 70013 Heraklion, Greece*

³*Chemical Process and Energy Resources Institute, Centre for Research and Technology Hellas (CERTH), 6th km Charilaou-Thermi, Thermi, 57001 Thessaloniki, Greece*

⁴*Department of Industrial, Electronic and Mechanical Engineering, Roma Tre University, Via Vito Volterra, 62, 00146 Rome, Italy*

⁵*Department of Engineering, Niccolò Cusano University, Via don Carlo Gnocchi 3, 00166 Rome, Italy*

⁶*Metamorphose-VI, 1348 Louvain-la-Neuve, Belgium*



(Received 5 October 2024; accepted 31 January 2025; published 19 March 2025)

Dynamically reconfigurable metasurfaces, offering real-time wavefront control, promise the realization of unprecedented components for the future information and communication technologies. The current reconfiguration approaches, though, suffer from certain inefficiencies, such as small tunability range and depth, slow response, complex implementation, etc. Plasma discharges promise to face some of those inefficiencies, as they exhibit a wide tunable range of electric permittivity, via simple control of the plasma source in the implementation. Here, exploiting these unique tunability properties of plasma, we design and numerically demonstrate dynamically reconfigurable metasurfaces formed as arrays of plasma cylinders. Analytical results for single-cylinder scattering properties provide initial guidelines for the realization of a generalized Kerker condition below the plasma frequency of the plasma cylinder, where both the electric dipole and quadrupole moments are excited and balanced, and Huygens response for the cylinders array is expected. This is verified by numerical investigation of arrays of identical cylinders, demonstrating tunable high transmission and a wide phase coverage. Based on those results, a phase gradient metasurface made of tunable plasma cylinders is designed, optimized, and demonstrated. The analysis is extended to practically realizable coated plasma cylinders, where both frequency tunability and dynamically controllable beam steering capabilities are demonstrated.

DOI: [10.1103/PhysRevResearch.7.013287](https://doi.org/10.1103/PhysRevResearch.7.013287)

I. INTRODUCTION

Metasurfaces, 2D structures composed of subwavelength unit cells, can be designed to achieve unconventional electromagnetic (EM) properties, and to provide full control of the transmitted and reflected EM waves [1,2]. Applications include absorption control [3–5], anomalous reflection [6,7], polarization control [8], etc. Phase-gradient metasurfaces, which are spatially modulated and locally nonperiodic, have been used for wavefront control, such as for beam steering or focusing [9]. Unlike metagrating structures [10], where a single scatterer per unit cell is tailored to reroute the incident power to a desired diffraction mode, gradient metasurfaces rely on discretizing continuous phase or impedance profiles to achieve anomalous reflection or refraction [11].

One approach to realize phase gradients along thin interfaces is to use Huygens metasurfaces [12–15], where the

designed meta-atoms exhibit overlapping balanced electric-dipole and magnetic-dipole resonances, resulting in full transmission and 2π transmitted-wave phase coverage. For a single meta-atom, the condition of balanced overlapping electric and magnetic resonances is known as Kerker condition. Exploiting the Huygens behavior, desired phase gradients can be attained, for instance through the designs of cascaded metasurfaces [16–18], or dielectric metasurfaces based on Mie scatterers [19–23].

It has been discussed in Refs. [24,25] that Huygens behavior (i.e., full transmission with 2π phase coverage) is obtained not only when a meta-atom exhibits a balanced electric-dipole and magnetic-dipole resonance, but also when it exhibits any pair of resonances with opposite scattered wave symmetry in the backward and forward direction (i.e., a resonance of even scattered fields paired with a resonance of odd scattered fields). This condition is known as the generalized Kerker condition. An example of it is, when the electric-dipole and electric-quadrupole resonant modes are excited and balanced. [As further explained in Ref. [25], modes of opposite phase symmetries in their far-field radiation are multipoles of the same nature (e.g., electric) and successive orders, or of the same order but different nature (i.e., electric versus magnetic); interactions between them can lead to the suppression of back-scattering.]

*Contact author: jiaruo.yan@iesl.forth.gr

In general, broadband efficient polarization control can be acquired by the superposition of scattering from different electric and/or magnetic multipole modes [26]. Interference effects between electric, magnetic, and toroidal higher-order multipoles are discussed in Refs. [27–29], where generalized Kerker scattering is also studied. Different scenarios, where the electric and magnetic multipoles excited in a core-shell dielectric sphere are balanced to produce directionality, are presented in Ref. [30]. A high- Q passband filter is designed in Ref. [31], by tailoring the dipole and quadrupole moments of core-shell spherical dielectric meta-atoms. In most of these studies on generalized Kerker conditions, static rather than reconfigurable structures have been explored and demonstrated. In future technologies though (e.g., communications), an essential capacity is reconfigurability, which implies reconfigurable metasurfaces.

Reconfigurability, or tunability, has been explored extensively for metasurfaces in recent years [32]. Various tuning mechanisms have been developed, including geometrical tuning, electronic tuning, or material tuning [33]. Mechanical movements are usually induced in geometrical tuning, for instance to reorient or move [34,35], or to reshape the unit cells [36], which generally lead to complicated implementations and relatively slow responses. Electronic tuning is to incorporate tunable lumped elements, e.g., varactor diodes with voltage-controlled capacitance [37], RF MEMS [38], or PIN diodes with switchable functions [39], into unit cell designs. Although reconfigurability rates in the GHz-range have been demonstrated, limitations arise due to high insertion losses, limited tuning ranges, or complex integrated designs. As for material tuning methods, the use of ferroelectric materials like barium-strontium-titanate (BST) [40], liquid crystals [41], and phase-change materials such as vanadium oxides [42] in metasurfaces has been investigated. Through tuning the permittivity of materials, reconfigurable metasurfaces are designed, although high insertion losses (e.g., for liquid crystals or ferroelectric materials) or low reconfigurability rates (e.g., for phase change materials) [33], if operating in the GHz frequency range, may be inevitable.

Apart from these conventional reconfiguration mechanisms, plasma discharges with tunable EM properties can also be implemented to introduce reconfigurability, promising large tunability rates and ranges. This is due to the fact that the plasma EM response is governed by the free electrons generated in a plasma discharge; with a possibility to vary the free electron density (of the plasma discharge) by a few orders of magnitude, large changes in both real and imaginary parts of the plasma permittivity can be obtained. Plasma tunability has been already investigated in photonic crystals, where tunable photonic bandgaps realized by the use of plasma columns have been demonstrated [43,44]. In the case of metamaterials there are still few explorations involving plasma discharges. Among the worth-mentioning examples are reconfigurable metamaterials with plasma discharges excited between the gaps of dielectric resonators [45] and, also, arrays of split ring resonators, in combination with highly dense plasma, exhibiting tunable double negative response [46,47]. Numerically, similar applications have also been studied with both simplified [48] and self-consistent plasma-wave simulations [49]. In the case of metasurfaces, where ultra-strong

response is desired from ultra-thin structures, e.g., for beam-steering and forming applications, the investigation of plasma is still very limited. Very recently, plasma discharges as means for realization of a reconfigurable multipolar Huygens metasurface consisting of Drude-like spherical scatterers have been investigated [50], demonstrating (numerically) the vast reconfiguration potential of plasma-based scatterers. Compared to the conventional tuning methods, plasma discharges offer the possibility to tune both the real and imaginary parts of the permittivity [51,52]; when the imaginary part (representing losses) is of low magnitude, a relatively wide tuning range of the permittivity can be attained. As discussed in Ref. [53], controllable tunability of plasma photonic crystals and plasma metamaterials is accessible through varying the experimental settings: varying the external power sources for plasma ignition controls the electron density (thus changes the plasma frequency), and regulating the gas pressure changes the losses of the plasma volume. The plasma EM properties can be tuned in the time scale of microseconds [54], depending on the electrical power supply used for igniting and sustaining the plasma.

In this work, exploiting the wide tuning range of plasma, in its most commonly and easily attainable form, i.e., that of cylindrical tubes [55], we investigate and demonstrate numerically the potential of plasma cylinders to realize highly reconfigurable transmitting metasurfaces. In particular, we demonstrate metasurfaces of both tunable frequency and refraction angle.

The permittivity of plasma is modeled based on the Drude model,

$$\varepsilon_c = 1 - \frac{\omega_p^2}{\omega^2 - j\omega\gamma}, \quad (1)$$

where ε_c is the relative permittivity, ω_p is the plasma frequency in rad/s, and γ is the collision frequency in rad/s. ω_p can be expressed as a function of the electron density n_e (in units of m^{-3} in SI) of the plasma discharge, i.e., $\omega_p = \sqrt{e^2 n_e / \varepsilon_0 m_e}$, with e being the electron charge, ε_0 the vacuum permittivity, and m_e the electron mass. Substituting these constant values gives

$$\omega_p = \sqrt{3180 n_e}. \quad (2)$$

Assuming that the collision frequency is only dependent on gas pressure p and the plasma discharge is created from air, a simplified expression for γ of air is obtained as $\gamma = 2\pi \times 5.3 \times 10^9 p$, where the unit of p is Torr [56]. For low-loss conditions, i.e., $\gamma \ll \omega_p$, when $\omega < \omega_p$, ε_c has a negative real part that can be controlled by changing ω_p . Therefore, the frequencies lower than the plasma frequency is our range of interest here, to ensure the tunability of plasma properties.

As already mentioned, in this work we investigate the possibility to achieve a reconfigurable metasurface comprising cylindrical plasma tubes, and more generally cylindrical scatterers with Drude-like behavior. Initially, the scattering properties of a single cylinder are calculated analytically, and the possibility to obtain Huygens behavior by using such cylindrical scatterers as unit cells of a metasurface is investigated and confirmed (Sec. II). This is followed by a numerical study of homogeneous arrays of Drude-like

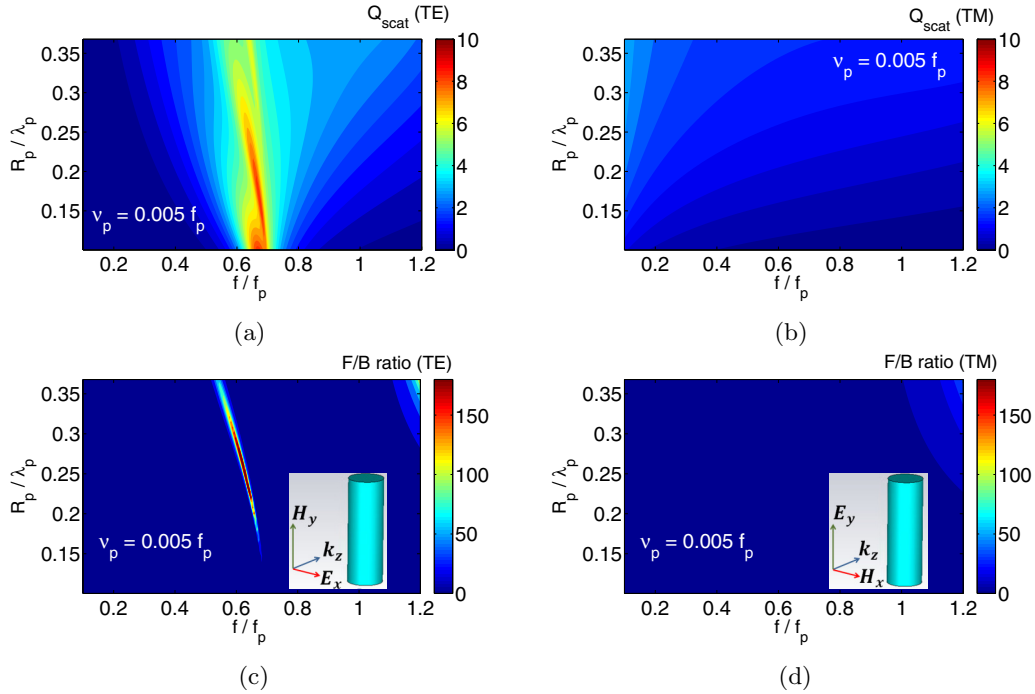


FIG. 1. Contour plots of the scattering properties from an infinitely long plasma cylinder. Panels (a) and (b) are the scattering efficiencies Q_{scat} corresponding to the TE and TM modes, respectively. Panels (c) and (d) are the forward-to-backward scattering ratio F/B for the TE and TM modes, respectively. The insets in panels (c) and (d) show the polarizations, but the cylinders are shown with finite length for illustration purposes. In all the subplots, $\nu_p \approx 0.1$ GHz, x axis is the normalized frequency f/f_p , with the plasma frequency $f_p \approx 20$ GHz, and the y axis is the normalized radius R_p/λ_p , with $\lambda_p = c/f_p \approx 15$ mm.

cylinders, demonstrating high transmission and a phase coverage of nearly 2π within a wide frequency range. Plasma cylinders can be used to implement these Drude-like scatterers, and we demonstrate that the metasurface is reconfigurable via controlling the plasma EM properties. A phase-gradient metasurface composed of tunable plasma cylinders is thus designed and analyzed (Sec. III). To take into account practical aspects, the analysis is extended to plasma cylinders contained within glass tubes (referred to as coated plasma cylinders in this paper), where a reconfigurable phase-gradient structure is designed for beam steering capabilities, and the sensitivity to losses or the angle incidence is investigated (Sec. IV).

II. SCATTERING BY A SINGLE PLASMA CYLINDER

The scattering properties of an infinitely long cylinder can be calculated analytically employing Mie theory. For TE polarization, with the magnetic field parallel to the cylinder axis, the scattering efficiency is [57]

$$Q_{\text{scat}} = \frac{2}{|kR_p|} \left[|\alpha_0|^2 + 2 \sum_{\nu=1}^{+\infty} |\alpha_\nu|^2 \right], \quad (3)$$

where α_ν are the Mie scattering coefficients of order ν , defined as

$$\alpha_\nu = \frac{z_h J_\nu(qR_p) J'_\nu(kR_p) - z_c J_\nu(kR_p) J'_\nu(qR_p)}{z_c H_\nu(kR_p) J'_\nu(qR_p) - z_h J_\nu(qR_p) H'_\nu(kR_p)}, \quad (4)$$

with R_p being the radius of the cylinder, $k = \sqrt{\epsilon_h \mu_h} \omega/c$ and $q = \sqrt{\epsilon_c \mu_c} \omega/c$ being the wave vectors in the host and in

the cylinder, respectively. Here $z_h = \sqrt{\mu_h/\epsilon_h}$, $z_c = \sqrt{\mu_c/\epsilon_c}$ are the wave impedances of the host medium (assumed to be vacuum) and of the cylinder. The subscripts h and c refer to the material properties of the host and of the cylinder, respectively. To assess the scattering properties of the cylinder, a useful quantity is the forward-to-backward scattering ratio (F/B) [57],

$$F/B = \frac{|\alpha_0 + 2 \sum_{\nu=1}^{+\infty} \alpha_\nu|^2}{|\alpha_0 + 2 \sum_{\nu=1}^{+\infty} (-1)^\nu \alpha_\nu|^2}. \quad (5)$$

Similar expressions for the scattering properties corresponding to the TM polarization can also be found in Ref. [57].

To investigate the scattering properties of a plasma cylinder with infinite length, we have assumed a low pressure condition, $p = 0.02$ Torr, and thereby low losses, with collision frequency $\nu_p = \gamma/2\pi \approx 0.1$ GHz. Taking a realistic value for electron density $n_e = 5 \times 10^{18}/\text{m}^3$ (giving a plasma frequency $f_p = \omega_p/2\pi \approx 20$ GHz and $\nu_p = 0.005f_p$), parametric contour plots of Q_{scat} and F/B ratio for both TE [magnetic field parallel to the cylinder axis, as illustrated in the inset of Fig. 1(c)] and TM [electric field parallel to the cylinder axis, illustrated in the inset of Fig. 1(d)] modes are shown in Fig. 1. The x axis (f/f_p) is the frequency normalized by the plasma frequency, and the y axis (R_p/λ_p) is the cylinder radius normalized by plasma wavelength, where $\lambda_p = c/f_p \approx 15$ mm in this case. Figures 1(a) and 1(c) on the left are for the TE case. It can be seen that, both Q_{scat} and F/B ratio reach high values for roughly $R_p/\lambda_p > 0.2$, at frequencies close to $0.6f_p \approx 12$ GHz, within the epsilon-negative regime which is

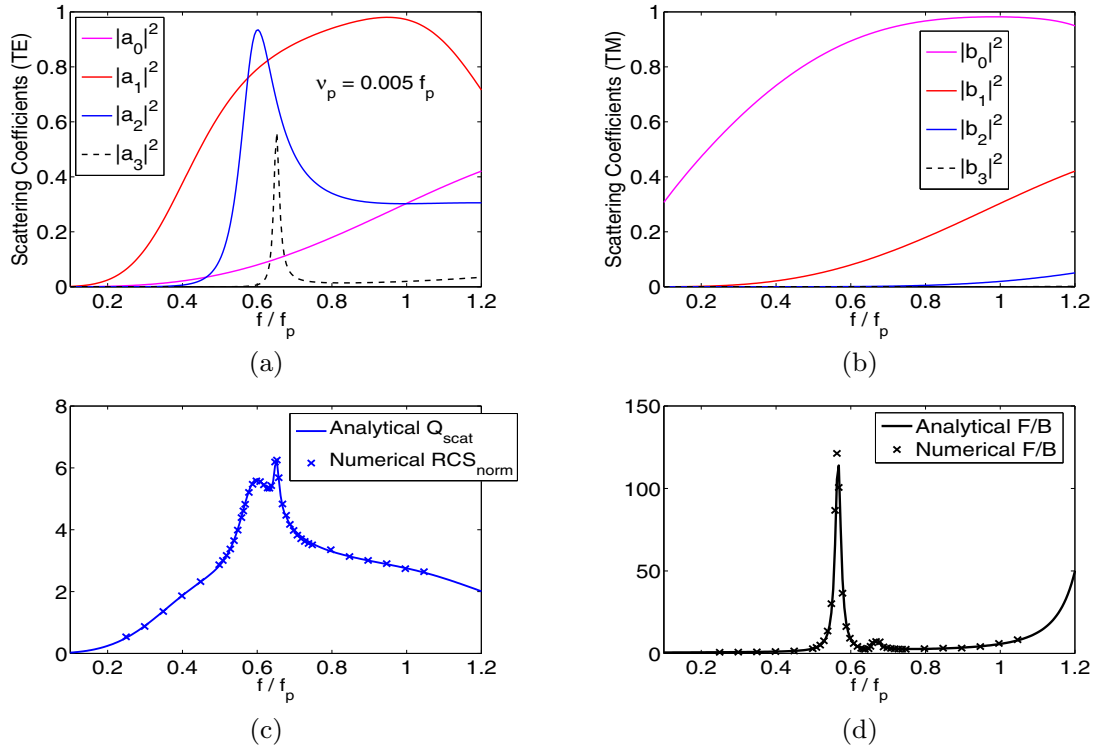


FIG. 2. Scattering properties of an infinitely long plasma cylinder with radius $R_p = 5$ mm. Plasma properties are the same as those of Fig. 1: $f_p = 20$ GHz, $v_p = 0.1$ GHz. Panels (a) and (b) are the magnitude-squared of the scattering coefficients over normalized frequency f/f_p , corresponding to the TE and TM polarizations, respectively. Panels (c) and (d) are the TE scattering efficiency and forward-backward ratio over the normalized frequency, respectively. Solid curves are from analytical calculations, and crosses are from numerical calculations.

the range of interest as explained in Sec. I. This is not the case for the TM-polarized case though [Figs. 1(b) and 1(d)]. Note here that high values for Q_{Scat} and F/B ratio are both fundamental requirements to implement Huygens metasurfaces [58,59]. The F/B ratio in Fig. 1(c) exhibits a slightly wider frequency bandwidth as the plasma radius increases. Results on phase-gradient structures are to be shown in Sec. III, where the radius of the plasma cylinders has been optimized to be $R_p \approx 5$ mm through numerical calculations. Figure 2 shows the scattering properties of an infinitely long plasma cylinder of $R_p = 5$ mm. The plasma properties of the cylinder are the same as those for Fig. 1 ($f_p = 20$ GHz, $v_p = 0.1$ GHz). Figure 2(a) shows the magnitude squared of the scattering coefficients for the TE-polarized case, demonstrating that the generalized Kerker condition is met near $f/f_p = 0.6$, where both the electric dipole and the electric quadrupole are excited. The same phenomenon is, as expected, not seen in Fig. 2(b) for the TM polarization. The analytically calculated scattering efficiency Q_{Scat} and F/B ratio, for TE-polarized plane waves, versus the normalized frequency are shown in Figs. 2(c) and 2(d), respectively, both showing good agreements with numerical results. The numerical calculations have been performed in CST microwave studio for a single cylinder, with boundaries in the x and z directions set to “open (add space)” to accommodate the space required for far-field monitors, while the boundaries have been set to “periodic” in the y direction (parallel to the cylinder axis) to model an infinitely long cylinder. The radar cross section (RCS) has been

normalized by the rectangular cross-sectional area of the cylinder enclosed by the boundary set ($A = 2R_ph$, where h is the height of the boundary box). So far, we have verified that high Q_{Scat} and high F/B ratio can be achieved at the same time using an infinitely long plasma cylinder of $R_p = 5$ mm, with the plasma electromagnetic properties listed in Fig. 2 as reference values. Numerical and analytical results of the corresponding forward and backward scattered power from the cylinder are discussed in the Appendix, where we show that near $f/f_p = 0.6$, the power is largely scattered to the forward direction; therefore, we expect that in the case of metasurfaces formed by arrays of cylinders (as the ones discussed in the next sections,) the multiple scattering effects will not significantly alter the single scattering picture, and the single-cylinder scattering properties are able to provide a sufficient guidance for selecting the suitable parameters for a Huygens response; this is confirmed by the numerical results presented in the next sections.

III. INFINITE ARRAYS OF PLASMA CYLINDERS

To design a phase-gradient array for beam steering, the local transmission phase of each cylinder in a supercell can be estimated based on the locally periodic approximation [60], by simulating the transmission through homogeneous arrays of infinitely long plasma cylinders. Unit cell boundaries in both x and y directions have been adopted in the simulation model to model an infinite array of plasma cylinders, with

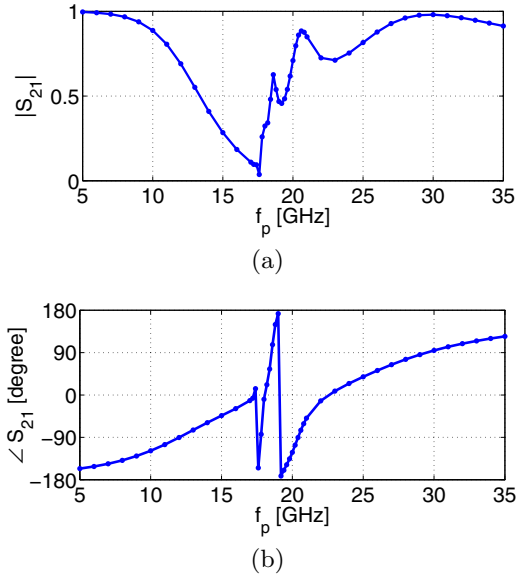


FIG. 3. Simulated TE-mode transmission coefficient evaluated at 12 GHz over varying plasma frequency f_p , for a homogeneous array of plasma cylinders ($R_p = 5$ mm, period $a_x = 11.5$ mm). Panel (a) is the magnitude of S_{21} , and panel (b) is the phase of S_{21} in degrees.

Floquet boundaries set in the z direction. As discussed previously, the generalized Kerker condition is met near $f = 0.6f_p = 12$ GHz for the TE polarization, therefore an operational frequency of $f_{op} = 12$ GHz has been chosen. The unit cell period here is $a_x = 11.5$ mm, which has been optimized for the gradient array. The S_{21} evaluated at 12 GHz for a homogeneous array, with f_p of each cylinder in the array changed from 5 to 35 GHz, is plotted in Fig. 3. Figure 3(a) is the magnitude of the transmission, and Fig. 3(b) is the transmission phase in degrees. $|S_{21}|$ remains above 0.5 for $f_p < 13$ GHz, $18.5 < f_p < 18.9$ GHz, and $f_p > 19.5$ GHz. It can be seen that within these ranges of f_p , a wide S_{21} phase coverage of nearly 2π is achieved.

For a phase-gradient array, we have designed a simple structure with three plasma cylinders per supercell. As discussed in Ref. [61], a linear periodic phase gradient profile exhibited by a gradient metasurface, spanning a 2π -range, resembles that of a blazed diffraction grating. The incident wave can be designed to couple to a desired diffraction order, and steered in the corresponding direction. This allows us to apply the diffraction formula to a gradient metasurface

$$\sin \theta_t - \sin \theta_i = m \frac{\lambda_{op}}{P_{super}}, \quad (6)$$

where θ_t is the refraction angle corresponding to the m th mode (here $m = 1$ is of interest), $\theta_i = 0^\circ$ is the incident angle, corresponding to normal incidence of our concern, $\lambda_{op} = c/f_{op} \approx 25$ mm is the operational wavelength, and $P_{super} = 3a_x$ is the supercell period.

The steering performance of the phase-gradient structure has been optimized in CST. The dimensional parameters a_x and R_p , as well as the f_p of each cylinder, have been set as variables in the optimizer. The plasma properties of the three cylinders initially selected based on similar recon-

figurability analysis to those shown in Fig. 3, have been corrected by full-wave optimizations using CST. The analytical calculations of the single-cylinder scattering properties in Fig. 1 provided a guidance for an optimization range of R_p (roughly $5.25 > R_p > 3$ mm, and higher R_p within the range might be desirable due to slightly wider bandwidths), with the necessary condition of $a_x > 2R_p$. The algorithm “particle swarm optimization” has been selected in CST. Although local optimization algorithms usually would result in a faster convergence, a global algorithm has been chosen to avoid reaching a local optimum since multiple parameters have been varied simultaneously. The goals of the optimization have been set to increasing the S parameter corresponding to the desired first-order Floquet mode of transmission, while suppressing the other modes at the design frequency f_{op} . With the local transmission phases of the plasma cylinders forming a discretized linear phase gradient, expanding a range of 2π across one supercell, the zeroth- or higher-order transmission modes are suppressed. TE-polarized waves are normally incident onto the gradient structure, as illustrated in the schematic of Fig. 4(a). The optimized transmission coefficients are shown in Fig. 4(b). Around 45% of the incident power is coupled to the desired $m = 1$ transmitted mode at 12 GHz, while the remaining power is distributed among the different reflection [not shown in Fig. 4(b)], 25% of incident power is coupled to the reflected zeroth mode, which is in the normal direction and transmission modes (since $P_{super} < 2\lambda_{op}$, we consider up to the first-order modes in the calculations) rather than absorbed by the low-loss plasma cylinder array. As shown in Fig. 3, while a transmission phase coverage of 2π can be achieved, the transmission magnitude is not always equal to 1 as we vary f_p . Imperfect local transmission provided by the individual plasma cylinders within a supercell array, as well as impedance mismatch of the phase-gradient array to incident and refracted waves, may have led to reflections from the metasurface, reducing its beam steering efficiency.

The optimized electric field pattern $|E_x|$ at 12 GHz is shown in Fig. 4(c). Refraction is clearly demonstrated, and the angle of refraction is estimated to be around 46.8° from Fig. 4(c). Based on Eq. (6), with $P_{super} = 34.5$ mm, the expected refraction angle is $\theta_t \approx 46^\circ$, very close to what is observed.

IV. COATED PLASMA CYLINDERS

The numerical investigations so far are based on free-standing plasma cylinders, with the main aim to achieve a reconfigurable metasurface employing an array of such cylinders. For practical implementations of such a reconfigurable array, plasma sources such as plasma tubes with DC or AC/RF excitation [62] can be adopted. Such tubes confine plasma in a dielectric container which may affect the plasma electromagnetic response (as it alters its dielectric environment) and restricts the close proximity of the neighboring tubes. The effects of such a typical dielectric container, i.e., a glass coating, are discussed in this section. The thickness of the cylindrical container has been chosen to be 1 mm. The relative permittivity of the coating, $\epsilon_r = 4.6$, is a value for borosilicate tubes that are typically used to confine plasma discharges. The dimension of the cylindrical plasma volume has been kept to be of $R_p = 5$ mm (the outer radius is then

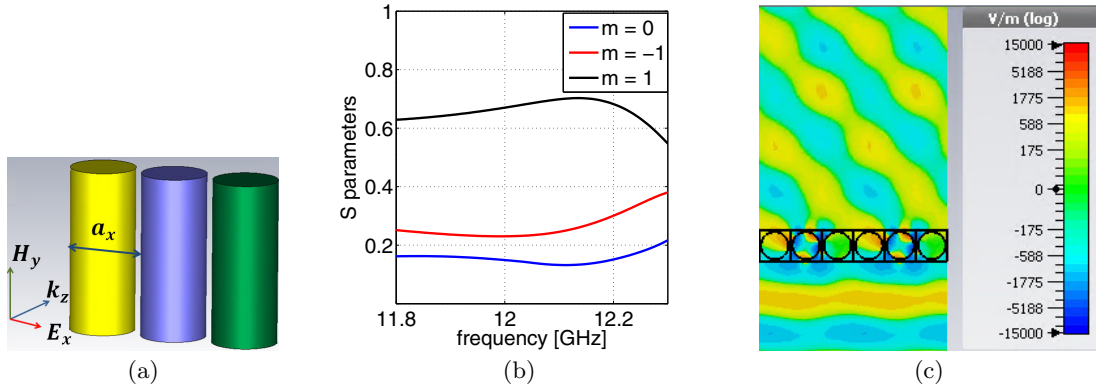


FIG. 4. Simulated magnitude of the transmission coefficients (TE mode) of a phase-gradient structure of three plasma cylinders per supercell, with $R_p = 5$ mm, $\nu_p = 0.1$ GHz, $a_x = 11.5$ mm, and with plasma frequency of each cylinder being $f_p = 5.7, 18.8, 35$ GHz. Panel (a) shows one supercell of the simulated model, with the direction of TE polarized incident plane waves shown. The cylinders are shown with finite lengths for illustration purposes, but they are modeled as infinitely long cylinders by setting unit cell boundaries along the vertical axis. Panel (b) is the simulated magnitude of the transmission coefficients corresponding to the zeroth mode (blue), and the first mode (the negative mode is red, the positive mode is black). Panel (c) is the optimized E -field (the x -component) distribution shown across two supercell periods at 12 GHz.

$R_{\text{out}} = 6$ mm), assuming a collision frequency of 0.1 GHz, the same as in the previous section.

A. Scattering by a single plasma cylinder

The scattering properties of a coated plasma cylinder (plasma frequency $f_p \approx 20$ GHz) are plotted in Fig. 5. For the

coated cylinder case, generalized Kerker condition is met for the TE polarization [Fig. 5(a)] near frequency $f \approx 0.45f_p = 9$ GHz, where the electric dipole and quadrupole modes are almost balanced, and strong forward scattering of the cylindrical scatterer is expected. Recall that the same condition is met near 12 GHz for a single plasma cylinder as shown in Fig. 2. This frequency shift to a lower range can be

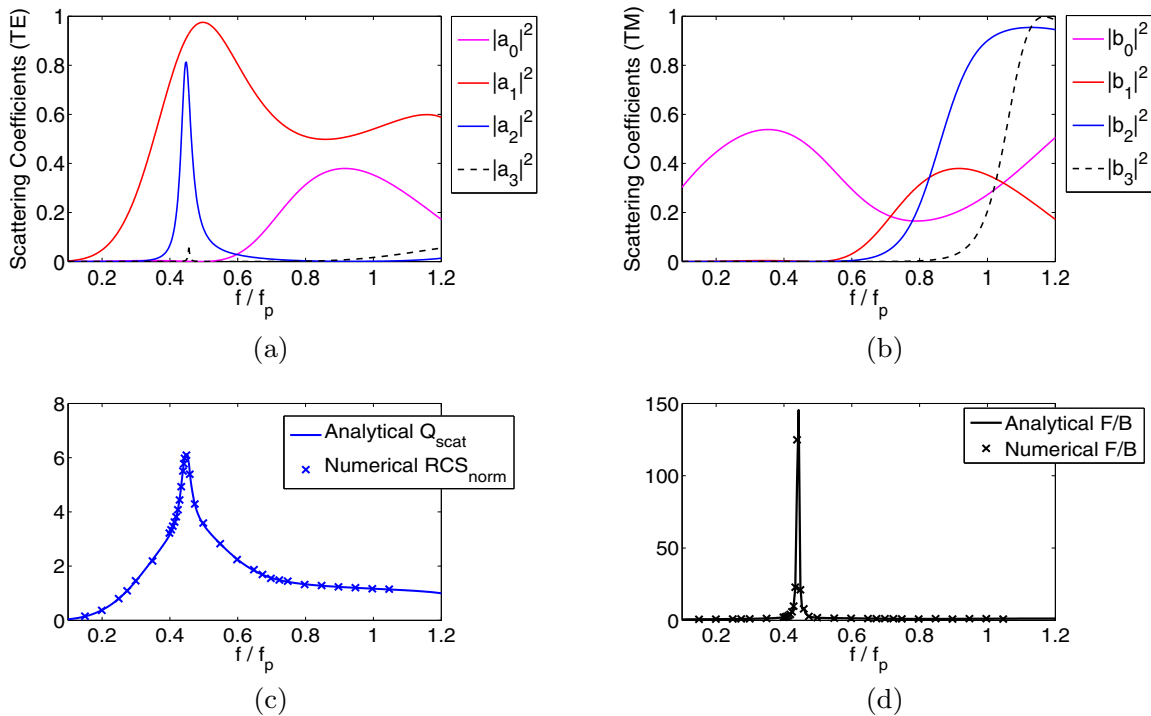


FIG. 5. Scattering properties of an infinitely long coated plasma cylinder, with properties of the plasma content the same as in the previous analysis $R_p = 5$ mm, $f_p = 20$ GHz, $\nu_p = 0.1$ GHz, and with an additional 1 mm coating ($R_{\text{out}} = 6$ mm). Dielectric constant of the coating is $\epsilon_r = 4.6$. Panels (a) and (b) are the magnitude squared of the scattering coefficients over normalized frequency, corresponding to the TE and TM cases, respectively. Panels (c) and (d) are the TE scattering efficiency and forward-backward ratio over the normalized frequency, respectively. Solid curves are from analytical calculations, and crosses are from numerical calculations.

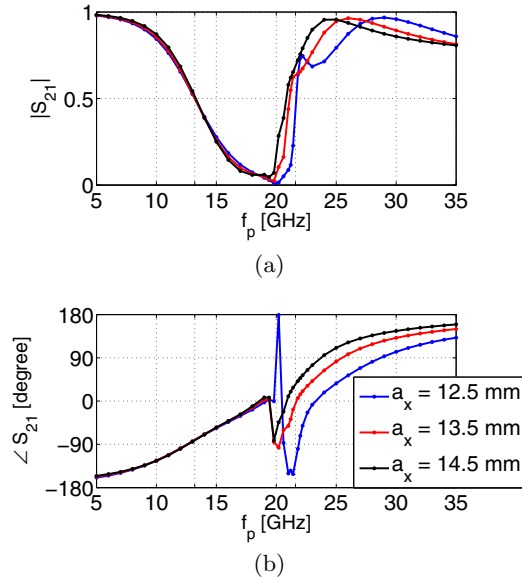


FIG. 6. Simulated S_{21} evaluated at 9 GHz for homogeneous coated plasma cylinder arrays, $R_p = 5$ mm, $R_{out} = 6$ mm, $\nu_p = 0.1$ GHz, with plasma frequency f_p varied from 5 to 35 GHz. Results are shown for three different unit cell sizes: $a_x = 12.5$ mm (blue), $a_x = 13.5$ mm (red), and $a_x = 14.5$ mm (black). Panel (a) is the magnitude $|S_{21}|$, and panel (b) is the phase of S_{21} in degrees.

attributed to the presence of the dielectric coating. Similar to the case of a pure plasma cylinder, there is no sharp resonances below the plasma frequency for the TM-polarized case, as seen in Fig. 5(b). Figures 5(c) and 5(d) are the TE scattering efficiency and forward-backward ratio, respectively, matching well with the numerical results. Here the RCS from CST is normalized by $A' = 2R_{out}h$, the area of the coated cylinder enclosed by the boundary box. Both Q_{Scat} and F/B ratio reach maximum values near $f/f_p = 0.45$. As a consequence, similar to the plasma cylinder without coating, the coated cylinder may be used as a composite unit cell of a Huygens metasurface.

B. Infinite arrays of coated plasma cylinders

A homogeneous array of coated plasma cylinders has been modeled in CST, and the transmission of normally incident TE waves has been simulated. With the physical dimensions of the cylinders, $R_p = 5$ mm, $R_{out} = 6$ mm kept constant, the plasma frequency of the plasma content has been swept from 5 to 35 GHz, evaluating S_{21} at 9 GHz in the simulations. Although a_x has been optimized to be 11.5 mm for the gradient structure consisting of plasma cylinders in the previous section, here a larger value of a_x would be required to accommodate the coated cylinders. The results corresponding to three different values of a_x are shown in Fig. 6: $a_x = 12.5$ mm (blue), 13.5 mm (red), 14.5 mm (black). For the case $a_x = 12.5$, $|S_{21}|$ [Fig. 6(a)] remains above 0.5 for $f_p < 13$ and $f_p > 21.6$ GHz, and within these ranges, $-160^\circ < \angle S_{21} < -90^\circ$ and $-130^\circ < \angle S_{21} < 135^\circ$ are achieved. The overlapping phase ranges means that a continuous range of phases is accessible while keeping a relatively high transmission. As a_x

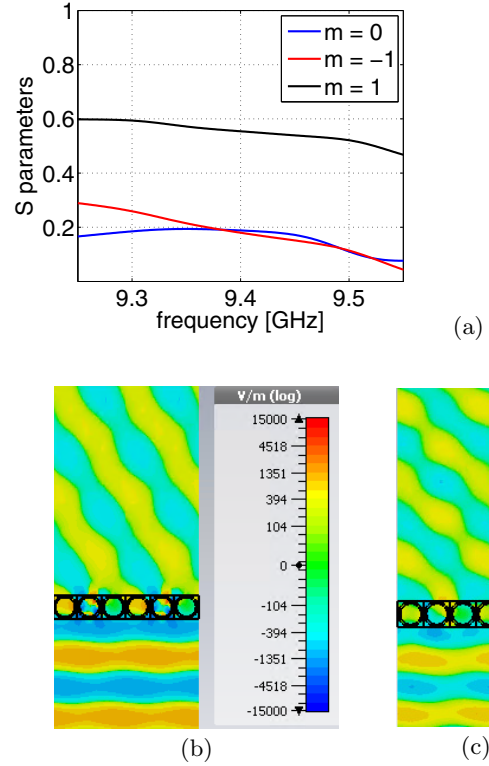


FIG. 7. Simulated magnitude of the transmission coefficients (TE mode) of a phase-gradient structure of three coated plasma cylinders per supercell, with $R_p = 5$ mm, $R_{out} = 6$ mm, $\nu_p = 0.1$ GHz, $a_x = 12.5$ mm. For panels (a) and (b), the optimization has been performed at 9.5 GHz, and the plasma frequency of the plasma volume in each cylinder is $f_p = 4.9, 22, 39.6$ GHz. Panel (a) shows magnitude of the transmission coefficients corresponding to the zeroth mode (blue) and the first mode (negative is red, positive is black). Panel (b) is the optimized E -field distribution at 9.5 GHz. Panel (c) is the E -field at 11.6 GHz when the properties of the plasma cylinders are $f_p = 5.4, 28.4, 41.1$ GHz, here the optimization has been performed at 11.6 GHz instead.

increases gradually, there is barely any change to the S_{21} for lower values of f_p , in terms of both its magnitude and phase. However, the phase range $-90^\circ < \angle S_{21} < -30^\circ$ corresponds to a range of values of f_p that give $|S_{21}| < 0.5$ for $a_x = 13.5$ mm. Similarly for $a_x = 14.5$ mm, $-90^\circ < \angle S_{21} < 0^\circ$ correspond to values of f_p that give $|S_{21}| < 0.5$, which is expected to deteriorate the efficiency of a phase-gradient metasurface even more. Consequently, $a_x = 12.5$ mm has been selected to construct a phase-gradient metasurface. Results of the TE mode refraction through a gradient structure of three coated plasma cylinders per supercell are shown in Fig. 7. The transmission coefficients corresponding to the three calculated modes are shown in Fig. 7(a), with $m = 0$ (blue), $m = -1$ (red), $m = 1$ (black). The plasma frequencies of each cylinder have been optimized using CST to be of $f_p = 4.9, 22, 39.6$ GHz, with the aim of suppressing the transmitted modes except for the desired first mode, $m = 1$. A relatively smooth E -field (x component) distribution at 9.5 GHz, slightly higher than the design frequency $f_{op} = 9$ GHz, is shown in Fig. 7(b). The refraction angle is

estimated to be around 56° based on the field distribution. The expected angle from Eq. (6) is 57.4° .

This difference in operation frequency can be explained by the local periodic approximation, as we selected the f_{op} based on a reference case with $f_p = 20$ GHz, whereas the EM environment of a cylinder in a supercell affects its transmission properties, which cannot be modeled accurately. In addition, as we initially selected the f_p of each cylinder based on the results in Fig. 6, the beam deflection efficiency of the phase-gradient structure has been affected by the locally imperfect transmissions of the individual cylinders within the supercell period [$|S_{21}|$ varies over f_p and is not always equal to 1 in Fig. 6(b)]. Impedance mismatch of the array to the incident and refracted waves may also lead to reflections, lowering the beam steering efficiency.

C. Frequency tunability and steering angle tunability

With a different design frequency of 11.6 GHz for the phase-gradient structure, the corresponding E_x -field distribution is shown at this higher operation frequency in Fig. 7(c). Here the plasma properties have been varied so that we have $f_p = 5.4, 28.4, 41.1$ GHz, while other parameters remain unchanged. The refraction angle is approximately 42.5° from Fig. 7(c), very close to the estimated value of 43.7° based on Eq. (6), resulting to a change in the steering angle of around 14° compared to Fig. 7(b). What we have shown here is that, by simply tailoring the plasma frequencies, the operational frequency of beam steering can be tuned, which in turn moderately changes the steering angle. Larger frequency tuning ranges might be achievable, but this is beyond the scope of this paper.

It is also possible to dynamically control the steering angle, without changing the dimensions of the coated plasma cylinders or the distance between the cylinders. This can again be achieved merely by controlling the plasma properties of each cylinder - essentially changing the period of the supercell. Results demonstrating beam-steering for a gradient structure of four coated cylinders per supercell are shown in Fig. 8. The f_p of each cylinder has been optimized to be 10, 21.9, 23, and 31.7 GHz, respectively, with the aim to couple the normally incident waves to the desired transmitted mode ($m = 1$) while suppressing other transmitted modes. Figure 8(a) is the transmission coefficients of a four-cylinder gradient structure. The transmission coupled to the first Floquet mode is slightly above 0.4, which is of an acceptable magnitude, while the undesired modes are well suppressed, especially so at 9.65 GHz. A relatively smooth E -field distribution is observed at 9.65 GHz, with a refraction angle estimated to be 37.6° from Fig. 8(b), close to the expected angle of around 38.5° based on Eq. (6). Comparing the results from the 4-cylinder supercell (Fig. 8) and those from the three-cylinder supercell structure (Fig. 7), increasing the supercell size decreased the achieved S parameter corresponding to the first transmission mode from 0.51 to 0.43 at the corresponding operation frequencies (although not shown in the figures, the zeroth-mode reflection coefficient rises slightly from 0.35 to 0.4). In the mean time, the beam-steering angle reduced by nearly 10° .

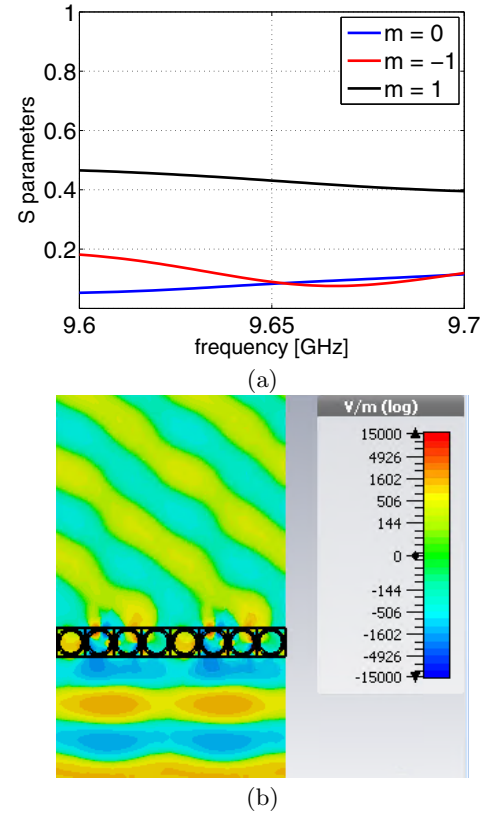


FIG. 8. Simulated transmission through a gradient structure of four coated cylinders per supercell, with $R_p = 5$ mm, $R_{out} = 6$ mm, $a_x = 12.5$ mm, $f_p = 10, 21.9, 23, 31.7$ GHz. The operational frequency is 9.65 GHz. Panel (a) shows the transmission coefficients of the zeroth mode (blue), first mode (negative is red and positive is black). Panel (b) is the E -field distribution at 9.65 GHz.

Increasing the number of plasma cylinders within the supercell further decreases the beam-steering angle. For example, five cylinders per supercell results in a refraction angle of around 25° near 10 GHz, again corresponding to the transmission mode $m = 1$. The gradual decrease in the beam steering efficiency can be explained by the imperfect local transmission exhibited by the individual plasma cylinders in the environment of nonidentical neighbors [as indicated in Fig. 6(a) which serves as a local-periodic approximation]. With more cylinders of different f_p , bearing local phases that form a discretized linear phase gradient covering 2π , it is inevitable that some of these cylinders may exhibit locally low transmission (i.e., high reflection), degrading the overall beam steering performance. To conclude at this point, the supercell design composed of three plasma cylinders, shown in Fig. 7, has resulted in the largest beam steering angle and efficiency for our selected plasma cylinder configuration, while control of the steering angle can be achieved via variation of the supercell period which is not complex to realize in practice.

D. Sensitivity

So far we have considered low-loss and normal-incidence conditions only. Here the sensitivities of the phase-gradient

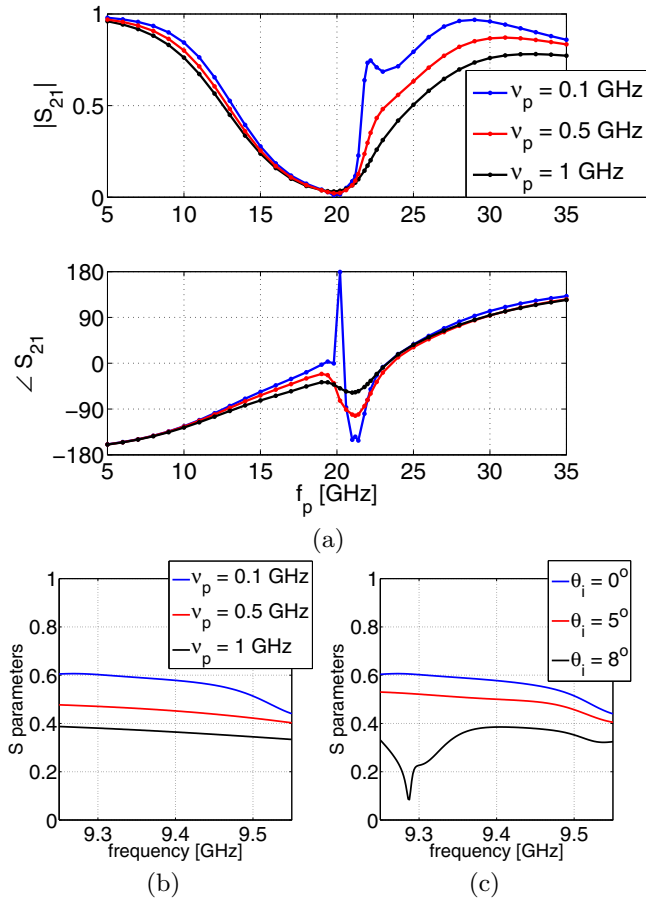


FIG. 9. Simulated transmission coefficients through arrays of coated plasma cylinder ($R_p = 5$ mm, $R_{out} = 6$ mm, $a_x = 12.5$ mm) to demonstrate the effects of the collision frequency and the angle of incidence. Three different cases (normal incidence) with collision frequency $\nu_p = 0.1$ GHz (blue), $\nu_p = 0.5$ GHz (red), $\nu_p = 1$ GHz (black) are shown in panels (a) and (b). Panel (a) is the simulated S_{21} evaluated at 9 GHz over f_p for homogeneous arrays of coated plasma cylinders, showing both the magnitude (upper) and the phase in degrees (lower). Panel (b) is the transmission in the first mode for a gradient structure with three coated cylinders per supercell. Panel (c) is with the reference collision frequency $\nu_p = 0.1$ GHz, but changing the angle of incidence θ_i , with $\theta_i = 0^\circ$ (blue), 5° (red), and 8° (black).

structure to the losses and angle of incidence are discussed. Take the gradient structure with three coated plasma cylinders per supercell as a reference case, of which the beam steering performance has been shown in Fig. 7. First, keeping the normal-incidence condition unchanged, the reconfigurability of the coated plasma cylinder is shown for homogeneous coated plasma cylinder arrays of different collision frequencies, $\nu_p = 0.1$ GHz (blue), 0.5 GHz (red), and 1 GHz (black) in Fig. 9(a). The S_{21} evaluated at 9 GHz are plotted against varying plasma frequencies f_p . Increasing ν_p increases the losses, and $|S_{21}|$ drops for higher f_p values. The influence on the phase of S_{21} is limited, except for the ranges of f_p near 20 GHz. As ν_p increases, certain ranges of $\angle S_{21}$ no longer correspond to high transmission coefficients—e.g.,

if $-90^\circ < \angle S_{21} < 0^\circ$, $|S_{21}| < 0.5$ for $\nu_p = 0.5$ GHz; and if $-90^\circ < \angle S_{21} < 40^\circ$, $|S_{21}| < 0.5$ for $\nu_p = 1$ GHz. This may have contributed to the degraded beam steering performance of the phase-gradient structure, as quantized in Fig. 9(b), where the transmission coefficients corresponding to the first mode are plotted for the three cases of increasing collision frequency. The phase-gradient structure (three coated cylinders per supercell) has been optimized and smooth refracted E -field distribution at 9.5 GHz has been numerically demonstrated [Fig. 7(b)]. Keeping f_p of the cylinders unchanged, increasing ν_p by ten times reduces the transmission coefficient of the first mode by around 30% (power is roughly reduced by half) at the optimum frequency of 9.5 GHz. As for the effects of the angle of incidence (ν_p kept as 0.1 GHz), the transmission coefficients of the first Floquet mode are shown in Fig. 9(c), where blue curve is the reference case of incidence angle $\theta_i = 0^\circ$. Again the f_p of the cylinders remained unchanged, as optimized for the $\theta_i = 0^\circ$ case. When θ_i increases, the transmission drops as expected, since the impinging TE waves experience different phase gradients across the supercell as the incident angle is varied. This may be improved if further optimization is performed for different θ_i , but is out of the scope for the current study.

V. CONCLUSION

A reconfigurable phase-gradient metasurface, based on an array of tunable plasma cylinders, has been demonstrated. Analytical calculations of the scattering properties from a single plasma cylinder show that the generalized Kerker condition can be satisfied, where the electric dipole and quadrupole moments are balanced, justifying the possibility of using a plasma cylinder for the design of a Huygens metasurface. Numerical results for cylinder arrays show that both high transmission and wide phase coverage can be achieved simultaneously. Thanks to the tunability of plasma EM properties, a phase-gradient metasurface has been designed and optimized for beam steering at the selected operational frequency, with plasma cylinders as meta-atoms.

To practically realize the phase-gradient structure, plasma discharges enclosed by quartz tubes can be used. The analysis has been therefore extended to plasma cylinders with borosilicate coatings. Similar effects of Huygens behavior have been observed, and reconfigurable gradient structures have been designed and demonstrated. We have also described both the frequency tunability and the dynamic reconfigurability of the beam steering angles through controlling the plasma frequencies of the plasma discharges, with no requirements of mechanical movements. Practical aspects, such as the sensitivities to losses as well as the angle of incidence, have been addressed. Control of the sources (e.g., the voltage source) for igniting and sustaining the plasma discharges is one approach for tuning the electron density in practice [63], and hence the plasma frequency. Such a metasurface based on plasma cylinders can be incorporated in antenna systems to tailor the emitted field in a reconfigurable way. For instance, a hybrid metal-plasma antenna array has been discussed in Ref. [54]; switchable plasma array acting as a reflecting or directing array for a horn antenna has been proposed in Ref. [64]. In

the form of a cylindrical array or a dome [18], a metasurface based on plasma can surround an antenna, such as a dipole antenna, and tailor its radiation pattern in real time.

ACKNOWLEDGMENT

This work was supported by the European Union under the call “EIC Pathfinder Open 2022” (Project PULSE, Project No. 101099313).

APPENDIX

The normalized scattered power from a single plasma cylinder, with the numerical results (circles) validating the analytical predictions (solid) [57] are shown in Fig. 10. Forward scattering (red) reached high values close to $f/f_p = 0.6$, while the back scattering (blue) is suppressed.

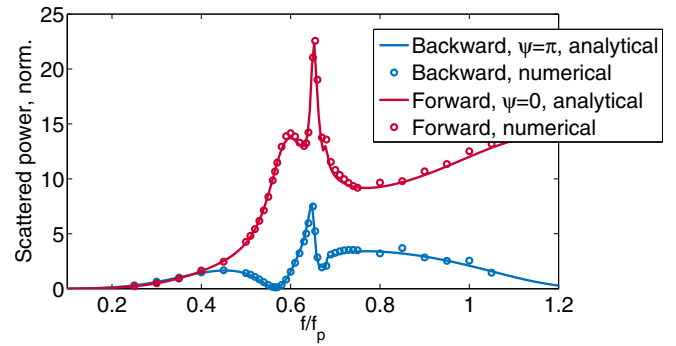


FIG. 10. Normalized scattered power from a single infinite plasma cylinder, both from analytical (solid) and numerical (circles) calculations, in the backward (blue), and forward (red) directions. The angle ψ as denoted in Ref. [57] is the in-plane angle from the forward direction.

- [1] S. Tretyakov, Metasurfaces for general transformations of electromagnetic fields, *Philos. Trans. R. Soc. A* **373**, 20140362 (2015).
- [2] S. B. Glybovski, S. A. Tretyakov, P. A. Belov, Y. S. Kivshar, and C. R. Simovski, Metasurfaces: From microwaves to visible, *Phys. Rep.* **634**, 1 (2016).
- [3] M. Papaioannou, E. Plum, J. Valente, E. T. Rogers, and N. I. Zheludev, Two-dimensional control of light with light on metasurfaces, *Light Sci. Appl.* **5**, e16070 (2016).
- [4] R. Alaei, M. Albooyeh, and C. Rockstuhl, Theory of metasurface based perfect absorbers, *J. Phys. D* **50**, 503002 (2017).
- [5] A. Monti, A. Alù, A. Toscano, and F. Bilotti, Narrowband transparent absorbers based on ellipsoidal nanoparticles, *Appl. Opt.* **56**, 7533 (2017).
- [6] Z. Li, E. Palacios, S. Butun, and K. Aydin, Visible-frequency metasurfaces for broadband anomalous reflection and high-efficiency spectrum splitting, *Nano Lett.* **15**, 1615 (2015).
- [7] A. Díaz-Rubio, V. S. Asadchy, A. Elsakka, and S. A. Tretyakov, From the generalized reflection law to the realization of perfect anomalous reflectors, *Sci. Adv.* **3**, e1602714 (2017).
- [8] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.-P. Tetienne, F. Capasso, and Z. Gaburro, Light propagation with phase discontinuities: Generalized laws of reflection and refraction, *Science* **334**, 333 (2011).
- [9] N. M. Estakhri and A. Alù, Recent progress in gradient metasurfaces, *JOSA B* **33**, A21 (2016).
- [10] Y. Ra'di, D. L. Sounas, and A. Alù, Metagratings: Beyond the limits of graded metasurfaces for wave front control, *Phys. Rev. Lett.* **119**, 067404 (2017).
- [11] A. V. Kildishev, A. Boltasseva, and V. M. Shalaev, Planar photonics with metasurfaces, *Science* **339**, 1232009 (2013).
- [12] C. Pfeiffer and A. Grbic, Metamaterial Huygens' surfaces: Tailoring wave fronts with reflectionless sheets, *Phys. Rev. Lett.* **110**, 197401 (2013).
- [13] M. Chen, M. Kim, A. M. Wong, and G. V. Eleftheriades, Huygens' metasurfaces from microwaves to optics: A review, *Nanophotonics* **7**, 1207 (2018).
- [14] R. Colom, E. Mikhcheeva, K. Achouri, J. Zuniga-Perez, N. Bonod, O. J. Martin, S. Burger, and P. Genevet, Crossing of the branch cut: The topological origin of a universal 2π -phase retardation in non-Hermitian metasurfaces, *Laser Photonics Rev.* **17**, 2200976 (2023).
- [15] A. Hassanfiroozi, Y.-C. Cheng, S.-H. Huang, Y.-T. Lin, P.-S. Huang, Y. Shi, and P. C. Wu, Toroidal-assisted generalized Huygens' sources for highly transmissive plasmonic metasurfaces, *Laser Photonics Rev.* **16**, 2100525 (2022).
- [16] C. Pfeiffer and A. Grbic, Cascaded metasurfaces for complete phase and polarization control, *Appl. Phys. Lett.* **102**, 231116 (2013).
- [17] M. Chen, E. Abdo-Sánchez, A. Epstein, and G. V. Eleftheriades, Theory, design, and experimental verification of a reflectionless bianisotropic Huygens' metasurface for wide-angle refraction, *Phys. Rev. B* **97**, 125433 (2018).
- [18] A. Monti, S. Vellucci, M. Barbuto, D. Ramaccia, M. Longhi, C. Massagrande, A. Toscano, and F. Bilotti, Quadratic-gradient metasurface-dome for wide-angle beam-steering phased array with reduced gain loss at broadside, *IEEE Trans. Antennas Propag.* **71**, 2022 (2023).
- [19] D. Lin, P. Fan, E. Hasman, and M. L. Brongersma, Dielectric gradient metasurface optical elements, *Science* **345**, 298 (2014).
- [20] M. Lawrence, D. R. Barton III, J. Dixon, J.-H. Song, J. van de Groep, M. L. Brongersma, and J. A. Dionne, High quality factor phase gradient metasurfaces, *Nat. Nanotechnol.* **15**, 956 (2020).
- [21] D. C. Zografopoulos and O. Tsilipakos, Recent advances in strongly resonant and gradient all-dielectric metasurfaces, *Mater. Adv.* **4**, 11 (2023).
- [22] Z. Li, M.-H. Kim, C. Wang, Z. Han, S. Shrestha, A. C. Overvig, M. Lu, A. Stein, A. M. Agarwal, M. Lončar *et al.*, Controlling propagation and coupling of waveguide modes using phase-gradient metasurfaces, *Nat. Nanotechnol.* **12**, 675 (2017).
- [23] O. Tsilipakos, A. C. Tasolamprou, T. Koschny, M. Kafesaki, E. N. Economou, and C. M. Soukoulis, Pairing toroidal and magnetic dipole resonances in elliptic dielectric rod metasurfaces for reconfigurable wavefront manipulation in reflection, *Adv. Opt. Mater.* **6**, 1800633 (2018).
- [24] R. Alaei, R. Filter, D. Lehr, F. Lederer, and C. Rockstuhl, A generalized Kerker condition for highly directive nanoantennas, *Opt. Lett.* **40**, 2645 (2015).

- [25] W. Liu and Y. S. Kivshar, Generalized Kerker effects in nanophotonics and meta-optics, *Opt. Express* **26**, 13085 (2018).
- [26] S. Kruk, B. Hopkins, I. I. Kravchenko, A. Miroshnichenko, D. N. Neshev, and Y. S. Kivshar, Invited article: Broadband highly efficient dielectric metadevices for polarization control, *Appl. Photonics* **1**, 030801 (2016).
- [27] W. Liu and Y. S. Kivshar, Multipolar interference effects in nanophotonics, *Philos. Trans. R. Soc. A* **375**, 20160317 (2017).
- [28] T.-J. Huang, L.-Z. Yin, J. Zhao, and P.-K. Liu, High-order multipoles in all-dielectric metagrating enabling ultralarge-angle light bending with unity efficiency, *Nanophotonics* **10**, 2859 (2021).
- [29] I. M. Hancu, A. G. Curto, M. Castro-López, M. Kuttge, and N. F. van Hulst, Multipolar interference for directed light emission, *Nano Lett.* **14**, 166 (2014).
- [30] W. Liu, J. Zhang, B. Lei, H. Ma, W. Xie, and H. Hu, Ultra-directional forward scattering by individual core-shell nanoparticles, *Opt. Express* **22**, 16178 (2014).
- [31] A. Monti, A. Alù, A. Toscano, and F. Bilotti, Design of high-Q passband filters implemented through multipolar all-dielectric metasurfaces, *IEEE Trans. Antenn. Propag.* **69**, 5142 (2020).
- [32] J. P. Turpin, J. A. Bossard, K. L. Morgan, D. H. Werner, and P. L. Werner, Reconfigurable and tunable metamaterials: A review of the theory and applications, *Int. J. Antenn. Propag.* **2014**, 1 (2014).
- [33] D. Ramaccia, A. Monti, M. Barbuto, S. Vellucci, L. Stefanini, A. Toscano, and F. Bilotti, Reconfigurability in electromagnetic metasurfaces and metamaterials for antennas systems: State-of-the-art, technical approaches, limitations, and applications, *TechRxiv* (2024).
- [34] H. Tao, A. C. Strikwerda, K. Fan, W. J. Padilla, X. Zhang, and R. D. Averitt, Mems based structurally tunable metamaterials at terahertz frequencies, *J. Infrared Milli. Terahz. Waves* **32**, 580 (2011).
- [35] T. Hand and S. Cummer, Characterization of tunable metamaterial elements using MEMs switches, *IEEE Antenn. Wireless Propag. Lett.* **6**, 401 (2007).
- [36] W. Zhu, A. Liu, T. Bourouina, D. P. Tsai, J. Teng, X. Zhang, G. Lo, D. Kwong, and N. Zheludev, Microelectromechanical maltese-cross metamaterial with tunable terahertz anisotropy, *Nat. Commun.* **3**, 1274 (2012).
- [37] D. F. Sievenpiper, J. H. Schaffner, H. J. Song, R. Y. Loo, and G. Tangonan, Two-dimensional beam steering using an electrically tunable impedance surface, *IEEE Trans. Antennas Propag.* **51**, 2713 (2003).
- [38] S. V. Hum, G. McFeetors, and M. Okoniewski, Integrated mems reflectarray elements, in *Proceedings of the 1st European Conference on Antennas and Propagation* (IEEE, Piscataway, NJ, 2006), pp. 1–6.
- [39] J. Perruisseau-Carrier, Dual-polarized and polarization-flexible reflective cells with dynamic phase control, *IEEE Trans. Antennas Propag.* **58**, 1494 (2010).
- [40] R. R. Romanofsky, J. T. Bernhard, F. W. Van Keuls, F. A. Miranda, G. Washington, and C. Canedy, K-band phased array antennas based on $\text{Ba}_{0.60}\text{Sr}_{0.40}\text{TiO}_3$ thin-film phase shifters, *IEEE Trans. Microwave Theory Tech.* **48**, 2504 (2000).
- [41] Q. Zhao, L. Kang, B. Du, B. Li, J. Zhou, H. Tang, X. Liang, and B. Zhang, Electrically tunable negative permeability metamaterials based on nematic liquid crystals, *Appl. Phys. Lett.* **90**, 011112 (2007).
- [42] M. Goldflam, T. Driscoll, B. Chapler, O. Khatib, N. Marie Jokerst, S. Palit, D. Smith, B.-J. Kim, G. Seo, H.-T. Kim *et al.*, Reconfigurable gradient index using VO_2 memory metamaterials, *Appl. Phys. Lett.* **99**, 044103 (2011).
- [43] S. Varault, B. Gabard, J. Sokoloff, and S. Bolioli, Plasma-based localized defect for switchable coupling applications, *Appl. Phys. Lett.* **98**, 134103 (2011).
- [44] B. Wang and M. Cappelli, A plasma photonic crystal bandgap device, *Appl. Phys. Lett.* **108**, 161101 (2016).
- [45] L. Fantini, S. Dennison, H. Kim, M. Sarkarat, M. Lanagan, and J. Hopwood, Plasma reconfigurable metamaterial using a 6.5 GHz dielectric resonator array, *J. Appl. Phys.* **126**, 203301 (2019).
- [46] O. Sakai, Y. Nakamura, A. Iwai, and S. Iio, Negative-permittivity plasma generation in negative-permeability space with high-energy metamaterials, *Plasma Sources Sci. Technol.* **25**, 055019 (2016).
- [47] H. Kim and J. Hopwood, Wave propagation in composites of plasma and metamaterials with negative permittivity and permeability, *Sci. Rep.* **9**, 3024 (2019).
- [48] K. Kourtzanidis, D. M. Pederson, and L. L. Raja, Electromagnetic wave energy flow control with a tunable and reconfigurable coupled plasma split-ring resonator metamaterial: A study of basic conditions and configurations, *J. Appl. Phys.* **119**, 204904 (2016).
- [49] K. Kourtzanidis and L. Raja, Analysis and characterization of microwave plasma generated with rectangular all-dielectric resonators, *Plasma Sources Sci. Technol.* **26**, 045007 (2017).
- [50] A. Monti, S. Vellucci, M. Barbuto, L. Stefanini, D. Ramaccia, A. Toscano, and F. Bilotti, Design of reconfigurable Huygens metasurfaces based on Drude-like scatterers operating in the epsilon-negative regime, *Opt. Express* **32**, 28429 (2024).
- [51] O. Sakai, T. Naito, and K. Tachibana, Experimental and numerical verification of microplasma assembly for novel electromagnetic media, *Phys. Plasmas* **17**, 057102 (2010).
- [52] O. Sakai and K. Tachibana, Plasmas as metamaterials: A review, *Plasma Sources Sci. Technol.* **21**, 013001 (2012).
- [53] S. Nijdam, K. V. Desai, S.-J. Park, P. P. Sun, O. Sakai, G. Lister, and J. G. Eden, Foundations of plasma photonics: Lamps, lasers, and electromagnetic devices, *Plasma Sources Sci. Technol.* **31**, 123001 (2022).
- [54] G. Mansutti, P. De Carlo, M. Magarotto, M. A. Hannan, P. Rocca, A.-D. Capobianco, D. Pavarin, and A. Tuozi, Design of a hybrid metal-plasma transmit-array with beam-scanning capabilities, *IEEE Trans. Plasma Sci.* **50**, 662 (2022).
- [55] J. T. Gudmundsson and A. Hecimovic, Foundations of DC plasma sources, *Plasma Sources Sci. Technol.* **26**, 123001 (2017).
- [56] R. J. Vidmar, On the use of atmospheric pressure plasmas as electromagnetic reflectors and absorbers, *IEEE Trans. Plasma Sci.* **18**, 733 (1990).
- [57] C. P. Mavidis, A. C. Tasolamprou, E. N. Economou, C. M. Soukoulis, and M. Kafesaki, Polaritonic cylinders as multifunctional metamaterials: Single scattering and effective medium description, *Phys. Rev. B* **102**, 155310 (2020).
- [58] M. Decker, I. Staude, M. Falkner, J. Dominguez, D. N. Neshev, I. Brener, T. Pertsch, and Y. S. Kivshar, High-efficiency dielectric Huygens' surfaces, *Adv. Opt. Mater.* **3**, 813 (2015).
- [59] M. I. Abdelrahman, H. Saleh, I. Fernandez-Corbaton, B. Gralak, J.-M. Geffrin, and C. Rockstuhl, Experimental

- demonstration of spectrally broadband Huygens sources using low-index spheres, [APL Photonics](#) **4**, 020802 (2019).
- [60] R. Pestourie, C. Pérez-Arancibia, Z. Lin, W. Shin, F. Capasso, and S. G. Johnson, Inverse design of large-area metasurfaces, [Opt. Express](#) **26**, 33732 (2018).
- [61] S. Larouche and D. R. Smith, Reconciliation of generalized refraction with diffraction theory, [Opt. Lett.](#) **37**, 2391 (2012).
- [62] H. Conrads and M. Schmidt, Plasma generation and plasma sources, [Plasma Sources Sci. Technol.](#) **9**, 441 (2000).
- [63] B. Wang and M. Cappelli, A tunable microwave plasma photonic crystal filter, [Appl. Phys. Lett.](#) **107**, 171107 (2015).
- [64] H. A. E.-A. Malhat, M. M. Badawy, S. H. Zainud-Deen, and K. H. Awadalla, Dual-mode plasma reflectarray/transmitarray antennas, [IEEE Trans. Plasma Sci.](#) **43**, 3582 (2015).