Optical Magnetism in Planar Metamaterial Heterostructures

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Harnessing artificial optical magnetism has required rather complex two- and three-dimensional structures, examples include split-ring and fishnet metamaterials and nanoparticles with non-trivial magnetic properties. By contrast, dielectric properties can be tailored even in planar and pattern-free, one-dimensional (1D) arrangements, for example metal/dielectric multilayer metamaterials. These systems are extensively investigated due to their hyperbolic and plasmonic response, which, however, has been previously considered to be limited to transverse magnetic (TM) polarization, based on the general consensus that they do not possess interesting magnetic properties. In this work, we tackle these two seemingly unrelated issues simultaneously, by proposing conceptually and demonstrating experimentally a mechanism for artificial magnetism in planar, 1D metamaterials. We show experimentally that the magnetic response of metal/high-index dielectric hyperbolic metamaterials can be anisotropic, leading to frequency regimes of magnetic hyperbolic dispersion. We investigate the implications of our results for transverse electric (TE) polarization and show that such systems can support TE interface-bound states, analogous to their TM counterparts, surface plasmon polaritons. Our results simplify the structural complexity for tailoring artificial magnetism in lithography-free systems and generalize the concept of plasmonic and hyperbolic properties to encompass both TE and TM polarizations at optical frequencies.

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I. INTRODUCTION

In the optical spectral range, the magnetic response of most materials, given by the magnetic permeability \( \mu \), is generally weak. This is famously expressed in the textbook by Landau and Lifshitz [1]: “there is no meaning in using the magnetic susceptibility from the optical frequencies onward, and in discussing such phenomena, we must put \( \mu = 1 \)”. The magnetic properties of natural materials arise from microscopic orbital currents and intrinsic spins and typically vanish at frequencies above the GHz range. This has motivated a search for structures and systems that may exhibit artificial optical magnetism by utilizing principles of metamaterial design. In this regime, engineered displacement and conduction currents, induced when metamaterials are illuminated with electromagnetic fields, act as sources of artificial magnetism [2].

Maxwell’s equations exhibit a duality with respect to dielectric permittivity \( \varepsilon \) and magnetic permeability \( \mu \) for the two linear polarizations of light: transverse magnetic (TM) and transverse electric (TE), respectively. Despite this symmetry, at frequencies beyond THz, far more discussion in the literature has been devoted to tailored dielectric properties of metamaterials than to artificial magnetic properties. This imbalance is understandable because, until now, the realization of magnetic metamaterials has required rather complex resonant geometries [2–4], such as arrays of paired thin metallic strips [5, 6], split ring resonators [7–9] or fishnet structures [10], which are challenging to realize experimentally at optical frequencies.

In contrast, engineered dielectric properties of metamaterials are achievable even in simple planar multilayer configurations. In fact, heterostructures of alternating metallic and dielectric layers, termed hyperbolic metamaterials (HMMs), have been explored intensively the last decade [11–13]. They are often described with an effective permittivity tensor, \( \varepsilon_{\text{eff}} = \text{diag}(\varepsilon_o, \varepsilon_o, \varepsilon_e) \), where the subscript-\( o \) (\( e \)) indicates the ordinary (extraordinary) direction. Their in-plane response is metallic \( (\varepsilon_e < 0) \) while their out-of-plane response is dielectric \( (\varepsilon_e > 0) \). HMMs support interesting electromagnetic phenomena, including negative refraction [11, 14] without the need of a negative refractive index, diverging density of optical states for Purcell-factor enhancement [13], and hyper-lensing [15]. Furthermore, the negative dielectric permittivity \( \varepsilon_o \) leads to surface-propagating plasmonic modes [16, 17], similar to surface plasmon polaritons (SPPs) supported on noble metals’ surfaces [18] or metal/dielectric arrangements and waveguides [19–22].

The plasmonic and hyperbolic properties of planar, multilayer heterostructures have featured prominently in photonics, however, their relevance has been limited to TM polarization, based on their effective dielectric response. TE polarization-related phenomena have re-
mained unexplored, as the effective magnetic permeability of such systems has been widely considered to be unity [11–13, 23]. By contrast, fishnet metamaterials are known to exhibit a magnetic response and, recently, a magnetic hyperbolic metamaterial was demonstrated [10]. However, the fishnet structure is by definition biaxial, thus, TE and TM polarizations cannot be independently manipulated.

Here, we focus on the magnetic properties of unpatterned, one-dimensional (1D) multilayer uniaxial systems, where TE and TM polarizations are uncoupled. Inducing an artificial magnetic response in these systems is of interest for generalizing their hyperbolic and plasmonic properties to encompass both TE and TM polarizations. For example, a metal/dielectric planar system with opposite magnetic permeabilities along different coordinate directions ($\mu_\alpha \mu_\beta < 0$) is double hyperbolic with unbound wavevectors for TE polarization (Fig. 1a and inset). Furthermore, no TE counterpart of the surface plasmon polariton, i.e., a magnetic surface plasmon (Fig. 1b), has been reported at optical frequencies, due to lack of negative magnetic response. Artificial epsilon-and-mu-near-zero (EMNZ) metamaterials at optical frequencies are interesting building blocks for electrostatic-like systems, due to near-zero phase advance in the material [24] (Fig. 1c). While it is straightforward to tailor the permittivity to cross zero in planar metamaterials [25], a simultaneously EMNZ metamaterial at optical frequencies has not yet been demonstrated.

![FIG. 1](image)

**FIG. 1.** (a) TE hyperbolic refraction in type II HMMs ($\mu_\alpha < 0$, $\mu_\beta > 0$)-inset: 3D isofrequency diagram (b) TE magnetic plasmon: TE polarized surface state at the interface between air and magnetic material ($\mu < 0$), analogous to TM polarized surface plasmon polaritons ($\epsilon < 0$). (c) $\epsilon$ and $\mu$ near zero (EMNZ) regime: phase diagram demonstrating vanishing phase advance at EMNZ wavelengths.

In this paper, we perform a comprehensive study of artificial magnetism in planar, 1D multilayer metamaterials. The practical importance of our results lies in the drastic simplification of the structural complexity of previous generation magnetic metamaterials; the realization of split-ring resonators [7–9], fishnet structures [10], and nanoparticles [26, 27] at optical frequencies requires multi-step lithographic processes and synthesis. By contrast, pattern-free multilayer metamaterials are readily realizable with lithography-free thin-film deposition. We start by introducing the physical concept for inducing an artificial magnetic response in 1D systems (Sec.II). In Sec.III A, we briefly discuss a simple approach based on which this magnetic response can be taken into account in the design of multilayer metamaterials by relaxing previously made assumptions in widely used effective medium theories [11–13, 28, 29]. In Sec. III B, we experimentally confirm our findings and demonstrate magnetic resonances at optical frequencies in multilayer HMMs. Motivated by the non-trivial effective magnetic response that we observe experimentally, in Sec. IV we theoretically investigate its implications using a simple transfer-matrix approach. Contrary to the majority of work in planar plasmonics and HMMs, we investigate TE polarization phenomena. We find that concepts previously discussed for TM polarization, based on engineering the dielectric permittivity, are generalizable for both linear polarizations. The proposed effective description of 1D systems in terms of effective dielectric and magnetic parameters provides a simple and intuitive understanding of the underlying physics.

**II. PHYSICAL MECHANISM: INDUCED MAGNETIC DIPOLES IN 1D SYSTEMS**

Magnetic fields at radio frequencies are usually manipulated with induction coils that generate and induce magnetic flux. They operate based on circulating conduction currents in coil loops that can be approximated as magnetic dipoles. This concept is widespread in metamaterials design [30, 31], where the conduction current is often replaced by displacement current in artificially magnetic structures at higher frequencies. Similar to the RF regime, by properly shaping metamaterial elements to produce a circulating current flow, magnetic dipoles are induced. Dielectric nanoparticles [26, 27, 32–35] and nanorods [36, 37] have been the building blocks for three (3D)- and two (2D)-dimensional magnetic metamaterial structures, respectively (Fig. 2a, b). In both cases, the circular geometry allows for loop-like current flow, generating a magnetic moment. We note that the magnetic response of these arrangements is sometimes incorporated into an equivalent, alternative, spatially dispersive permittivity. Although this is, in principle, always possible [1, 38, 39], we stress that, similar to naturally occurring substances, described with a permittivity $\epsilon$ and a permeability $\mu$, a metamaterial description based on ($\epsilon$, $\mu$) allows for physical intuition and reduces complexity, especially when it is straightforward to relate the dielectric (magnetic) response with physical macroscopic electric (magnetic) moments. This can be particularly useful for uniaxial planar and unpatterned 1D multilayers, as, in this case, TE and TM linear polarizations are decoupled and directly associated with $\mu$ and $\epsilon$, respectively.

Here, we demonstrate, a principle for strong magnetic response in 1D layered metamaterial heterostructures. We start by considering a single subwavelength dielectric slab of refractive index $n_{\text{die}}$ and thickness $d$. When illuminated at normal incidence ($z$ direction in Fig. 2c), its displacement current $J_3 = i\omega\varepsilon_0(n_{\text{die}}^2 - 1)\vec{E}$ induces a macroscopic effective
In the long-wavelength limit, only the fundamental and the design parameters for enhanced magnetic response; the same principle applies for grazing incidence, with the displacement current inducing a magnetic response in the out-of-plane \((z)\) direction.

In order to make this magnetic response significant, we consider the case of two parallel metallic wires in air, carrying opposite currents; their magnetic moment scales with their distance, as dictated by \(\vec{M} \propto \vec{r} \times \vec{J}\). In the planar geometry considered here, an equivalent scheme is represented by two high-index layers separated by air, as shown in Fig. 2c. Indeed, as demonstrated with the black curve in Fig. 2f, the magnetic permeability \(\mu_{\text{eff}}\) of this system strongly deviates from unity. In fact, the separation layer is not required to be air; any high-low-high refractive index sequence will induce the same effect. For example, replacing the air region with a layer of metal, with \(n_{\text{metal}} \ll 1\) at optical frequencies, does not drastically change the magnetic response. This is shown for a separation layer of silver in Fig. 2f with the red curve. Therefore, at optical frequencies, where the conduction current in metallic layers is small, metals do not contribute significantly to the magnetic response, in contrast to the GHz regime, where the metallic component in resonant structures has been necessary for strong magnetic effects \([6–9]\). From the inset of Fig. 2f, one can see that the average magnetic field faces in the direction opposite to the magnetization, expressing a negative magnetic response for the dielectric/silver unit cell.

III. COMBINING HYPERBOLIC DIELECTRIC AND MAGNETIC PROPERTIES

Alternating layers of metals and dielectrics have a distinct dielectric response, which is hyperbolic for TM polarization; the metallic component allows for \(\varepsilon_o < 0\), while the dielectric layers act as barriers of conduction in the out-of-plane \((z)\) direction, leading to \(\varepsilon_e > 0\). We combine this concept with the principle for creating magnetic resonances in planar systems, discussed in Sec.II. We show that it is possible to induce an additional magnetic response in planar dielectric/metal hyperbolic metamaterials, if the dielectric layers are composed of high-index materials, capable of supporting strong displacement currents at optical frequencies. Previous considerations mostly pertained to lower-refractive index dielectric layers, for example, LiF \([41]\) or Al₂O₃ \([23, 42, 43]\) and TiO₂ \([13]\). As can be inferred from Fig. 3 in what follows, for layer thicknesses below \(~50\)nm, these lower-index dielectric/metal systems exhibit magnetic resonances in the ultraviolet (UV)-short wavelength visible regime.

The effective magnetic response of planar multilayer metamaterials is a uniaxial tensor \(\vec{\mu}_{\text{eff}} = \text{diag}\{\mu_o, \mu_e, \mu_e\}\) and, as we demonstrate below, it may also be extremely anisotropic, which has interesting implications for TE polarization (See Sec.IV). We point out, however, that the dielectric hyperbolic response \(\varepsilon_o\varepsilon_e < 0\) in planar systems is broadband. In contrast, the magnetic permeabilities
along both coordinate directions \( \mu_a \) and \( \mu_c \) deviate from unity in a resonant manner, thus, TE polarization-based phenomena are more narrow-band in nature.

### A. Relaxing the \( \mu_{\text{eff}} = 1 \) constraint

Prior to delving into experimental results, we briefly discuss our computational method, which allows relaxing the previously made \( \mu_{\text{eff}} = 1 \) assumption. The most extensively used approach for describing the effective response of hyperbolic multilayer metamaterials is the Maxwell Garnett effective medium approximation (EMA) [11] (and references therein), [12, 13], based on which the in-plane dielectric permittivity is given by

\[
\epsilon_{\text{MG}} = f \epsilon_m + (1 - f) \epsilon_d
\]

and the out-of-plane extraordinary permittivity is

\[
\epsilon_{\text{MG}}^{-1} = f \epsilon_m^{-1} + (1 - f) \epsilon_d^{-1},
\]

where \( f \) is the metallic filling fraction [28], while \( \mu_{\text{eff}} \) is a \textit{a priori} set to unity. Another commonly used approach is the Bloch formalism, based on which, a periodic A-B-A-B...superlattice is described with a Bloch wavenumber [44], which is directly translated to an effective dielectric permittivity [29]. These approaches are useful and simple to use, however, they are both based on the assumption of an infinite and purely periodic medium, without accounting for the finite thickness of realistic stacks.

By contrast, metamaterials other than planar ones, which are, in general, more complicated in structure, for example split-ring resonators [7–9, 45], nanoparticles [27], fishnet structures [46, 47] and many others, are modeled with exact S-parameter retrieval approaches [48, 49]. S-parameter retrievals solve the inverse problem of determining the effective dielectric permittivity and magnetic permeability, \( \epsilon_{\text{eff}} \) and \( \mu_{\text{eff}} \) respectively, of a homogeneous slab with the same scattering properties, namely transmission \( T \) and reflection \( R \) coefficients, as the arbitrary inhomogeneous, composite metamaterial system of finite thickness \( d \).

By lifting the assumption of an infinite medium, one is able to compute both transmission \( T \) and reflection \( R \) coefficients, and utilize them in S-parameter approaches. This allows to obtain an effective wavenumber \( k_{\text{eff}} \) together with an effective impedance \( Z_{\text{eff}} \) for the system under study [48, 49]. These parameters are then used to decouple the effective permittivity from the permeability through

\[
k_{\text{eff}} = \sqrt{k_{\text{eff}} \epsilon_{\text{eff}} \mu_{\text{eff}}},
\]

and

\[
Z_{\text{eff}} = \frac{\mu_{\text{eff}}}{\epsilon_{\text{eff}}}. \tag{4.1}
\]

By contrast, Bloch-based approaches [29, 44] only consider a Bloch wavenumber \( K_{\text{Bloch}} \) (based on periodicity), with no other information available for allowing decoupling \( \mu_{\text{eff}} \) from \( \epsilon_{\text{eff}} \). Both the Maxwell Garnett result [28] and its Bloch-based generalizations (for example [29]) are based on the assumption that \( \mu_{\text{eff}} = 1 \). For a schematic comparison of the two approaches, see Figs. 3a, b.

Contrary to the extensive use of EMAs, we utilize the S-parameter approach to describe dielectric/metal multilayer metamaterials of finite thickness. By letting the magnetic permeability \( \mu_{\text{eff}} \) be a free parameter, instead of \textit{a priori} setting \( \mu_{\text{eff}} = 1 \), we obtain magnetic resonances at wavelengths where magnetic dipole moments occur, as demonstrated in Figs. 2c, f. This confirms the physicality of the non-unity \( \mu \); based on the arguments discussed in Sec.II, magnetic resonances arise at wavelengths at which systems support circular or loop-like current distributions.

By accounting for the uniaxial anisotropy in planar heterostructures, we obtain both the ordinary and the extraordinary permeabilities \( \mu_o \) and \( \mu_e \), together with their dielectric permeivity counterparts, \( \epsilon_o \) and \( \epsilon_e \). As a sanity check, we first consider homogeneous metallic and dielectric slabs with known dielectric permeability \( \epsilon_o = \epsilon_e \) and \( \mu_o = \mu_e = 1 \), which we recover upon application of our retrieval [50].

Another way to establish the validity of the the effective parameters is to perform an impedance-matching sanity check. Based on electromagnetic theory, the impedance of a structure at normal-incidence, \( Z_{\text{eff}} = \frac{\mu_{\text{eff}}}{\epsilon_{\text{eff}}} \), must be unity at transmittance \( |T|^2 \) maxima. As seen in Fig. 3c, the retrieved parameters \( \epsilon_o \) and \( \mu_o \) accurately describe the scattering properties of planar dielectric/metal arrangements of finite thickness. On the contrary, not accounting for a magnetic permeability leads to inaccurate prediction of transmittance maxima. This is seen both by utilizing our S-retrieval-based approach while setting \textit{a priori} the magnetic permeability to unity (\( Z_{\mu=1} \) in Fig. 3c), and with the traditional

![FIG. 3. Comparison between (a) traditional EMA and Bloch approaches and (b) the general concept of S-parameter retrievals. (c) Impedance-matching sanity check at normal incidence for a 25 layers dielectric/metal stack with \( n_{\text{dual}} = 4 \). The transmittance \( |T|^2 \) calculation was performed with the transfer-matrix formalism [44] for the physical multilayer system in the lossless limit. The dielectric and magnetic effective model \( (\epsilon_o, \mu_o) \) accurately captures the structures resonances unlike the non-magnetic approach \( (\epsilon_o, \mu_o = 1) \) and the Maxwell Garnett EMA.](image-url)
EMM; both approaches fail to predict the structure’s resonances.

By sweeping the angle of incidence from 0 to 90 degrees, in other words, by varying the in-plane wavenumbers \(k_{1//}\), we obtain angle-independent [50], local material parameters for the systems we consider. This makes ellipsometry a suitable method to experimentally characterize our metamaterials in terms of local material tensorial parameters \(\tilde{\mu}_{\text{eff}}\) and \(\tilde{\epsilon}_{\text{eff}}\), as shown in the next section. For larger \(k_{1//} \gg \frac{\omega}{c}\), due to the plasmonic nature of the metallic layers, metal/dielectric arrangements exhibit some degree of spatial dispersion [51]. This effect is distinct from the magnetic resonances we investigate, which are the result of induced magnetic dipole moments (Sec.II), consistent with the consensus in the field of artificial magnetism [2]. Spatial dispersion is fully taken into account in what follows. This is done by extending our previous approach [50] to consider as a free parameter not only the magnetic permeability, but also spatial dispersion in the form of wavenumber \((k_{1//})\) dependence (See discussion in Sec.IV for Figs.5b, c) [51]. Furthermore, as seen by the experimentally confirmed effective parameters discussed in Fig. 4, all constituent permittivity and permeability components \((\epsilon_o, \epsilon_e, \mu_o, \mu_e)\) are passive, causal, with positive imaginary parts and no antiresonance artifacts. Such artifacts are often observed with weak form of spatial dispersion (see [52] and discussion [53, 54] among others).

Other approaches are also able to capture this artificial magnetic response by accounting for an effective permeability in 1D metamaterials [55].

B. Experimental Results

We fabricated multilayer structures by electron-beam evaporation and first measured the optical constants of the individual constituent layers with spectroscopic ellipsometry. We also determined their thicknesses with transmission electron microscopy (TEM). Thus, we were able to homogenize the layered metamaterials by assigning them effective parameters \(\tilde{\epsilon}_{\text{eff}}\) and \(\tilde{\mu}_{\text{eff}}\) using parameter retrieval methods [50], while taking into account fabrication imperfections. We then performed ellipsometric measurements of the full metamaterials and fit the experimental data with the effective parameters \(\epsilon_o, \epsilon_e, \mu_o\) and \(\mu_e\) in a uniaxial and Kramers-Kronig consistent model, while fixing the total metamaterial thickness to the value determined through TEM imaging. The fitting was over-determined as the number of incident angles exceeded the total number of fitting parameters.

The fabricated metamaterials were composed of SiO\(_2\)/Ag, TiO\(_2\)/Ag and Ge/Ag alternating layers (See TEM images and schematics in insets of Figs. 4e, f and g respectively). The indices of the selected dielectric materials at optical frequencies are \(n_{\text{SiO}_2} \approx 1.5\), \(n_{\text{TiO}_2} \approx 2\) and \(n_{\text{Ge}} \approx 4.5\). As shown in Fig. 4a, increasing the dielectric index redshifts the magnetic resonance in the ordinary direction \(\mu_e\); the SiO\(_2\)/Ag metamaterial supports a magnetic resonance in the long-wavelength UV regime (~300nm), whereas the TiO\(_2\)/Ag and Ge/Ag metamaterials exhibit resonances in the blue (450nm) and red (800nm) part of the spectrum, respectively. The enhanced absorption in Ge at optical frequencies leads to considerable broadening of the Ge/Ag metamaterial magnetic resonance, yielding a broadband negative magnetic permeability for wavelengths above 800nm.

The presence of Ag induces a negative ordinary permittivity \(\epsilon_o\) (Fig. 4b) which, for the Ge/Ag metamaterial, becomes positive above 800nm due to the high-index of Ge. Notably, \(\epsilon_o\) crosses zero at 800nm, similar to \(\mu_e\), as emphasized with the asterisks in Figs. 4a, b. Thus, the Ge/Ag metamaterial exhibits an EMNZ response at optical frequencies. The EMNZ condition is confirmed by transfer-matrix analytical calculations of the physical multilayer structure. As shown in the inset of Fig. 4a), at the EMNZ wavelength, the phase of the transmission coefficient vanishes, showing that electromagnetic

![FIG. 4. Experimentally determined (a) \(\mu_{\text{eff}}\), (b) \(\epsilon_{\text{eff}}\), (c) \(\mu_{\text{eff}}\), (d) \(\epsilon_{\text{eff}}\) for SiO\(_2\)/Ag-green, TiO\(_2\)/Ag-blue, Ge/Ag-red metamaterial. Solid lines-real parts, dashed lines-imaginary parts. Asterisks in (a) and (b): EMNZ wavelength for the Ge/Ag metamaterial, inset in (a)-phase of transmission coefficient at the EMNZ wavelength. (e1)-(e3) \(\Psi\), (f1)-(f3) \(\Delta\), solid lines-experiment, points-model for: (e1), (f1): SiO\(_2\)/Ag metamaterial, inset TEM scale bar: 100nm, (e2), (f2): TiO\(_2\)/Ag metamaterial, inset TEM scale bar: 50nm, (e3), (f3): Ge/Ag metamaterial, inset TEM scale bar: 100nm.](image)
fields propagate inside the metamaterial without phase advance [24].

By comparing Fig. 4a to Fig. 4c one can infer that increasing the dielectric index leads to enhanced magnetic anisotropy. The parameter $\mu_m$ only slightly deviates from $\mu_o$ for the SiO$_2$/Ag metamaterial, while the deviation is larger for the TiO$_2$/Ag one. For the Ge/Ag metamaterial, $\mu_m$ remains positive beyond 800nm, while $\mu_m < 0$, indicating magnetic hyperbolic response for TE polarization. Furthermore, all three heterostructures exhibit hyperbolic response for TM polarization, with $\epsilon_o < 0$ and $\epsilon_e > 0$ (Figs.4b, d). This makes the Ge/Ag metamaterial one with double hyperbolic dispersion.

The agreement between fitting and experimental data is very good, as seen in Figs. 4e1-c3, f1-f3. In Figs. 4e, f1, we also provide a Maxwell Garnett EMA-based fit for the SiO$_2$/Ag metamaterial. The EMA fails to reproduce the experimentally measured features, in both $\Psi$ and $\Delta$, that correspond to magnetic permeability resonances (See grey-shaded region in Figs. 4e1, f1). Similar EMA-based fits for the TiO$_2$/Ag and Ge/Ag metamaterials lead to large disagreement with the experimental data across the whole visible-near IR spectrum and are, thus, omitted. This disagreement is expected, as the EMA approach is based on the assumption that the electric field exhibits negligible or no variation within the lattice period [28], which does not apply to high-index dielectric layers.

IV. BEYOND $\mu_{eff} \neq 1$: FUNCTIONALIZING TE POLARIZATION IN PLANAR PHOTONICS

In the previous sections we established, theoretically and experimentally, that dielectric/metal layered systems may be described with an effective magnetic permeability that deviates from unity. The purpose of introducing this parameter is to build a simple and intuitive approach for understanding and predicting new phenomena, for example, TE polarization response in planar systems. The non-unity and, in particular, the negative and anisotropic magnetic response that we demonstrated in Fig. 4 motivates us to investigate TE characteristics of propagating modes (Figs.5) and surface states (Fig. 6). We utilize an example system of dielectric/silver alternating layers, similar to the one we investigated experimentally. We let the refractive index of the dielectric material $n_{diel}$ vary to emphasize that enhanced magnetic response at optical frequencies requires high-index dielectrics.

The calculations and full-wave simulations presented here are performed in the actual, physical, multiayer geometry (Figs.5a, d, e and Fig.6) and compared with the homogeneous effective slab picture ($\overline{\epsilon_{eff}}$, $\overline{\mu_{eff}}$ - Figs.5b, c). This helps assessing the validity of our model and emphasizing the physicality of the magnetic resonances.

First, we perform transfer-matrix calculations for the example multilayer metamaterial and we show in Fig. 5a the angle dependence for TE and TM reflectance. The strong angle dependence of TM reflectance is well under-
frequency diagrams are circular, in other words, isotropic. This agrees well with our experimental results; as shown in Figs. 4a, c, for the SiO$_2$/Ag metamaterial, ordinary and extraordinary permeabilities do not drastically deviate from each other. Increasing the dielectric index opens the isofrequency contours, due to enhanced magnetic response in the ordinary direction ($\mu_o$), which leads to magnetic anisotropy. We note that the displayed wavelengths are selected at resonances of $\mu_o$. Open TE polarization isofrequency contours for $n_{\text{diel}} \geq 2$ are consistent with both the experimental results (Fig. 4) for TiO$_2$ and Ge-based metamaterials and with the response of the physical multilayer structures, as shown in Fig. 5a; the TE reflectance indeed exhibits extreme angle dependence for increasing dielectric index. Strikingly, we observe a Brewster angle effect for TE polarization, which is unattainable in natural materials due to unity magnetic permeability at optical frequencies [56].

An open isofrequency surface allows for coupling of large wavenumbers into a structure and enhancement in the density of optical states. This translates physically to strong interaction between incident light and a hyperbolic structure, and increased absorption, when it is possible to couple to large wavenumbers from the surrounding medium. So far, only TM polarization has been considered to experience this exotic hyperbolic response in planar dielectric/metal metamaterials, due to $\epsilon_o \epsilon_e < 0$ [12, 13, 23]. Based on the open isofrequency surfaces for both TE and TM polarizations in Figs. 5b, c, a high-index dielectric/metal multilayer metamaterial may exhibit distinct frequency regimes of double, simultaneously TE and TM polarization, hyperbolic-like response. We perform finite element simulations of a $n_{\text{diel}} = 4$/silver multilayer metamaterial for both linear polarizations and set the index of the surrounding medium to $n_{\text{sur}} = 1.55$ to allow coupling to larger wavenumbers. The well-known TM hyperbolic response is evident since the electric field is strongly localized within the multilayer in Fig. 5d. Switching the polarization to TE (Fig. 5e), we observe similar behavior, which, however, cannot be attributed to dielectric anisotropic response as the electric field only experiences the in-plane dielectric permittivity ($\epsilon_o$). The TE enhanced absorption is associated with the $\mu_o \mu_e < 0$ condition [57]; the number of TE modes supported by this metamaterial in this frequency regime is drastically increased (See Supplementary Information).

Finally, we investigate surface wave propagation in our example system of a layered dielectric ($n_{\text{diel}}$)/silver metamaterial. We do so by utilizing the transfer matrix mode condition $m_1 = 0$ [44], which we implement numerically using the reflection pole method [58]. In order to ensure interface-localized propagation with fields decaying in air and in the metamaterial, we impose an additional constraint for the states to be located in the optical band gaps of both bounding media.

For TM polarization, the identified surface states, with dispersion displayed in Fig. 6a, bear similarity to typical SPPs on metallic interfaces [18, 19] and to plasmonic waves in metal/dielectric waveguides and systems [21]. Their plasmonic nature is evident from their dispersion, which asymptotically approaches the surface plasma frequency, similar to SPPs. We show in Fig. 6c their field distribution (dashed lines), and compare to SPPs on an equivalent silver slab (black dotted lines). Such TM surface waves on metamaterial interfaces are often associated with an effective negative dielectric response [16, 17, 22]. This is consistent with our effective dielectric and magnetic model; as we explicitly showed experimentally in Fig. 4b, the ordinary permittivity is negative $\epsilon_o < 0$, which results in TM plasmonic-like surface waves.

Performing the same analysis for TE polarized waves, we find that TE surface-bound modes also exist (Fig. 6b). Their dispersion is parabolic, resembling that of Tamm states in photonic crystals [22, 59]. However, here, we show that they also exist in the subwavelength metamaterial limit and can coexist with typical TM plasmonic surface waves. TE polarized Tamm states have been previously theoretically associated only qualitatively with an arbitrary negative magnetic response [22]. By contrast, here, we explicitly connect their dispersion to values of magnetic permeabilities that were experimentally measured (Fig. 4). We identify their physical origin, which is the strong displacement current supported in high-index dielectric layers with a loop-like distribution on resonance, as discussed in detail in Sec.II. Specifically, from Fig. 6b, those TE surface waves emerge in the visible regime for dielectric layers with refractive index $n_{\text{diel}} \geq 2$ at frequencies where the metamaterial exhibits a negative effective magnetic response, which is also con-

![FIG. 6. (a) TM and (b) TE surface wave dispersion for a 5 layers dielectric ($n_{\text{diel}}$): 55nm/Ag: 25nm metamaterial. (c) Field profiles (incidence from the left) and comparison to SPP mode on an equivalent Ag slab (black dotted line): $n_{\text{diel}} = 2.5$, wavelength=620nm, $n_{\text{diel}} = 3.5$, wavelength=880nm, $n_{\text{diel}} = 4.5$, wavelength=1100nm.](image-url)
sistent with the empirical Eq.(1). For this reason, these states may be seen as “magnetic plasmons”.

The frequency regimes in which double surface waves are supported demonstrate the possibility of exciting TM polarized plasmonic modes simultaneously with their TE counterparts in dielectric/metal pattern-free multilayers.

V. CONCLUSIONS

In conclusion, we have shown that non-unity effective magnetic permeability at optical frequencies can be obtained in one-dimensional layered systems, arising from displacement currents in dielectric layers. This makes it possible to tailor the magnetic response of planar HMMs, which have been previously only explored for their dielectric permittivity features. We experimentally demonstrated negative in-plane magnetic permeability in planar materials. By studying bulk and surface wave propagation, we have identified frequency regimes of a rather polarization-insensitive response. We reported the existence of TE polarized “magnetic surface plasmons”, attributed to the negative effective magnetic permeability, which are complementary to typical TM polarized surface plasmonic modes at the interface of negative permittivity materials. The results reported here could open new directions for tailoring wave propagation in artificial magnetic media in significantly simplified layered systems. We anticipate that these findings will enable the generalization of the unique properties of plasmonics and hyperbolic metamaterials, previously only explored for TM polarized waves and negative permittivity media, for unpolarized light at optical frequencies.

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