Experimental demonstration of artificial dielectrics with a high index of refraction

A. Pimenov and A. Loidl
Experimentalphysik V, Center for Electronic Correlations and Magnetism, Universität Augsburg, 86135 Augsburg, Germany
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Recently, it has been suggested that metamaterials with high refractive index can be constructed using metal gratings with periodic subwavelength slits [J. T. Shen *et al.*, Phys. Rev. Lett **94**, 197401 (2005)]. We designed such metamaterials and investigate their transmittance and reflectance in the terahertz frequency range. The spectra can be directly compared to that of a conventional dielectric slab with effective refractive index of $n \simeq 5.5$. As theoretically predicted, the effective index of refraction only depends on the ratio of the width of the slits to the periodicity of the gratings. Existing small differences to the dielectric slab are discussed.

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Artificially constructed metamaterials[1] have attracted much interest recently due to the potential to create unusual electromagnetic phenomena such as subwavelength resolution[2] or the possibility to construct an invisibility device.[3] In general, the design degree of freedom, which is available in metamaterials, opens new ways to construct devices with exotic optical properties. Further examples of such properties are negative refraction,[4,5] artificial magnetism,[6] or extreme plasmonic response.[7]

One specific class of metamaterials is represented by metallic gratings with periodic arrays of holes or slits. An extraordinary property of these materials is the resonant transmittance for wavelengths much larger compared to the hole diameter.[8] Various modifications of a simple periodic grating have been investigated both theoretically and experimentally[9,10] which even led to the reconsideration of the well-known diffraction experiment by Young.[11] Basic mechanisms for the unexpectedly high transmittance of the metallic grating are excitations of surface plasmon polaritons,[12] interference of evanescent waves,[13] or waveguide resonances,[14] where the last mechanism is especially important for gratings with narrow slits. Recently, the possibility to obtain a subwavelength resolution using metallic gratings has been demonstrated.[15]

Another unusual property of an array of slits in a metal is the possibility to design artificial dielectrics with high effective refractive index.[16,17] Recently, it has been shown theoretically[17] that a metallic grating with periodic slits must behave similar to a dielectric media with controllable refractive index. In this case the effective refractive index does not depend upon the properties of the metal, but is determined solely by the geometry of the grating (Fig. 1). In a simple approximation, an effective refractive index $n=d/a$ and an effective thickness $L_{\mathrm{eff}}=L/n$ are expected. Here d, a, and L are periodicity, width of the slit, and thickness of the grating, respectively.

In this work we investigate experimentally the possibility to construct artificial dielectrics with high refractive index using metallic gratings with periodic slits. We demonstrate the close similarity of the transmittance and reflectance of metal gratings with those of a dielectric slab and discuss existing minor differences.

Metallic gratings with periodic slits have been prepared from high purity copper plates using a commercial wire-cut electrical discharge machining (EDM). Samples with $d=0.6$ mm and $a=0.1$ mm with two different thicknesses $L=2.01$ and 1.01 mm were prepared during the same run. The cross section of both samples was 15×15 mm. The sample dimensions and the geometry of the experiment are shown in Fig. 1.

The dynamic experiments for frequencies $60\ \mathrm{GHz} < \nu < 380$ GHz were carried out in a Mach-Zehnder interferometer arrangement.[18] In this experimental setup reflectance $R=|r|^2$ and complex transmittance $\sqrt{T}e^{i\varphi}$ can be measured. To obtain the effective optical parameters of the samples, Fresnel optical formulas for reflectance and transmittance[19] have been used

$$t=\frac{(1-r_0^2)t_1}{1-r_0^2t_1^2}, \tag{1}$$

$$r=\frac{(1-t_1^2)r_0}{1-r_0^2t_1^2}. \tag{2}$$

Here $r_0=(n-1)/(n+1)$ and $t_1=\exp(2\pi inL/\lambda)$. In these equations r_0 is is the reflection amplitude at the air-sample interface, t_1 is the "pure" transmission amplitude, n is the (complex) refractive index, L is the sample thickness, and λ is the radiation wavelength.

It has been assumed that the magnetic permeability $\mu=1$ in the frequency range of our experiments.[20] In principle, nonmagnetic photonic crystals can have some effective mag-

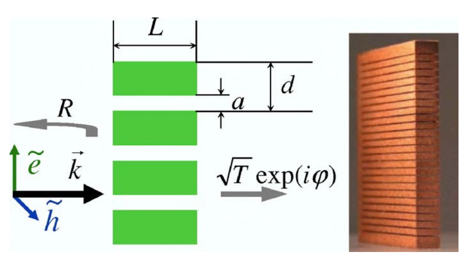

FIG. 1. (Color online) Schematic geometry of the transmittance and reflectance experiment. $\vec{k}$, $\tilde{e}$, and $\tilde{h}$ are the wave vector, electric field, and magnetic field of the electromagnetic wave, respectively. The characteristic dimensions of the metallic gratings are $d=0.6$ mm, $a=0.1$ mm, $L=2.01/1.01$ mm, and the sample cross section is 15×15 mm. The picture shows the grating with $L=2.01$ mm

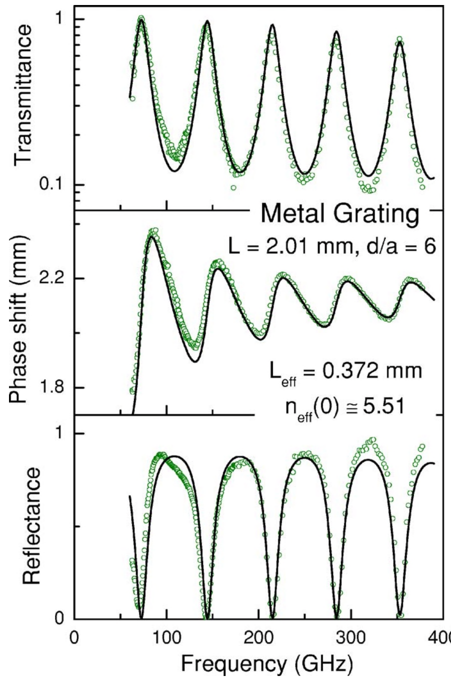

FIG. 2. (Color online) Transmittance (upper panel), phase shift (middle), and reflectance (lower) of the metallic grating shown in Fig. 1. Symbols: experiment, lines: model calculations assuming $L_{\mathrm{eff}}=0.372$ mm and $n_{\mathrm{eff}}=5.51$. See text for details.

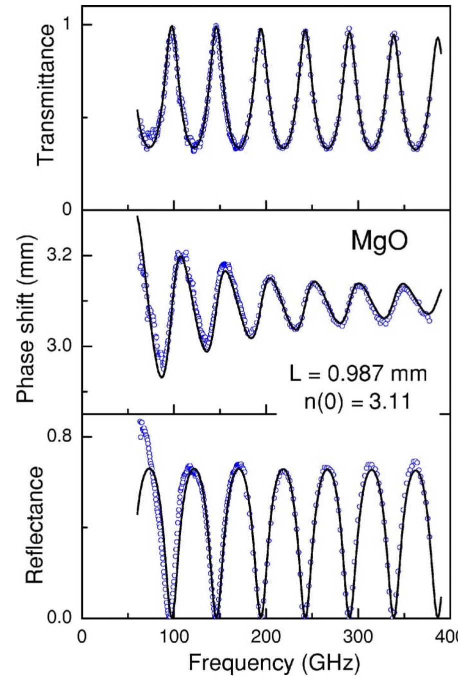

FIG. 3. (Color online) Transmittance (upper panel), phase shift (middle), and reflectance (lower) of dielectric slab with $L=0.987$ mm made from magnesium oxide. Symbols: experiment, lines: model calculations assuming $n(\nu)=3.11+(0.002+0.0002i)\nu$.

netic permeability,[6] e.g., due to the skin effect, which can lead to additional effects of magnetic origin. Good agreement of the measured data with "nonmagnetic" Eqs. (1) and (2) supports the approximation, used in the present experiment.

Figure 2 shows transmittance, reflectance and the phase shift of the metallic grating with $L=2.01$ mm in the frequency range of the experiment. The phase shift φ as obtained from the complex transmission coefficient $\sqrt{T}\exp(i\varphi)$ has been transformed to an effective optical thickness via $\varphi \rightarrow \varphi\lambda/2\pi$. Symbols in Fig. 2 represent the experimental data and solid lines are the results of simultaneous fits of the full data set of reflectance and transmittance using Eqs. (1) and (2). The following values have been obtained from the fit $L_{\mathrm{eff}}=0.372$ mm and $n(\nu)=5.51+(5.7+0.5i)\times 10^{-4}\nu$. A small term which is linear in frequency had to be added to the effective refractive index in order to account for the variation of the parameters in the frequency range investigated.

A remarkable feature of the spectra shown in Fig. 2 is the appearance of sharp Fabri-Perot resonances in transmittance and corresponding minima in reflectance. At frequencies of the resonances ν_{res}, the refractive indices fulfil a simple equation $2n_m L_{\mathrm{eff}}=mc/\nu_{\mathrm{res}}$, where m is the number of the maximum in transmittance and c is the speed of light. As is clearly seen from Fig. 2 the measured spectra can well be described by the formulas of a dielectric slab with effective thickness L_{eff} and refractive index n_{eff}. Only at the lowest frequencies deviations can be observed. We attribute these deviations to the influence of diffraction effects. Taking into account the beam aperture ($\sim$40 mm) and the focal length of the focusing system ($\sim$120 mm), the width of the focal spot can be estimated as $\sim 3\lambda$, which is close to sample dimensions for frequencies below 100 GHz. Summarizing, Fig. 2 clearly demonstrates that the metal grating indeed can be represented using an effective thickness and an effective index of refraction.

In the calculations of Ref. 17 the effective refractive index and the effective thickness of our structure is expected to be $n=d/a=6$ and $L_{\mathrm{eff}}=L/n=0.335$ mm, respectively, which is close to the values observed experimentally. Similar results have been observed for the sample with $L=1.01$ mm. In this case the refractive index and the thickness have been obtained as $n(\nu)=5.81+(3.3+1.2i)\times 10^{-4}\nu$ and $L_{\mathrm{eff}}=0.187$ mm. These values are again close to theoretical expectations of $n=d/a=6$ and $L_{\mathrm{eff}}=L/n=0.168$. The experimentally obtained values of the product $L_{\mathrm{eff}}n_{\mathrm{eff}}$ are in both cases by few percent higher than the expected $L_{\mathrm{eff}}n_{\mathrm{eff}}=L$. As discussed in Ref. 17, these deviations between the exact solution of the Maxwell equation and the Fresnel formula gives an estimate for errors in the approximation used.

To demonstrate the qualitative similarity of metallic metamaterial and a dielectric slab, Fig. 3 shows the spectra of transmittance, reflectance, and phase shift of a plane-parallel dielectric slab made of MgO and with the thickness $L_{\mathrm{MgO}}=0.987$ mm. In this case the coincidence between experiment and Eq. (1) is of the same quality as for the metallic grating shown in Fig. 2. We note that weak deviations at low frequencies are observed in this case, too. In the fits in Fig. 3 the refractive index $n(\nu)=3.11+(7+0.7i)\times 10^{-5}\nu$ has been used. In this case the absorption and frequency dependence of refractive index are due to the influence of a strong phonon mode close to 12 THz.

From our results there still remains a difference between metamaterial and real dielectric slab, which is related to the experimental determination of the phase shift. The experimental transmittance and reflectance spectra in Figs. 2 and 3 contain all information to determine the refractive index and the effective thickness. In fact, the positions of the transmittance maxima give both, the product $(n_{\mathrm{eff}} L_{\mathrm{eff}})$ and the modulation of the interferences independently determines the refractive index n_{eff}. On the contrary, the phase-shift is measured by an interferometer and, therefore, the path difference between reference beam and sample beam is obtained. This means that actually not the phase shift directly, but the *phase difference* $\varphi_{\mathrm{exp}}=\varphi_{\mathrm{real}}-2\pi L/\lambda$ can be measured. The second term in this equation is simply the phase shift of the air slab with the same thickness. To obtain the real phase shift, the thickness-dependent correction $\varphi_{\mathrm{corr}}=2\pi L/\lambda$ has to be added to the experimental phase difference. An important statement which follows from the present experiment is that in the case of the metal grating the necessary phase correction must be $\varphi_{\mathrm{corr}}=2\pi L/\lambda$ and not $\varphi_{\mathrm{corr}}=2\pi L_{\mathrm{eff}}/\lambda$ as would be expected if dielectric slab and metal grating were fully equivalent. We need to know both values of thickness, the real thickness L to perform the phase measurement and the effective thickness L_{eff} to carry out the calculations of the refractive index. In other words, the equivalence between dielectric slab and metallic grating is exact for the amplitudes but needs additional correction $2\pi(L-L_{\mathrm{eff}})/\lambda$ for the phase shift.

In addition to artificial high refractive index, metallic metamaterials can be used to obtain such unusual electrodynamic properties like negative refraction. In this case both dielectric permittivity and magnetic permeability must be negative simultaneously. Negative permittivity can be obtained using two-dimensional array of metallic rods,[7,20] and negative permittivity via extending metallic metamaterials to three dimensions.[6] A combination of both properties allows the realization of negative refraction,[4] which has recently been demonstrated for visible frequencies.[21]

In conclusion, using Terahertz transmittance and reflectance spectroscopy we were able to demonstrate experimentally the possibility to construct artificial dielectrics with high refractive index, in agreement with theoretical predictions. In the present case the effective refractive index close to 5.5 has been obtained in metallic metamaterial with periodic slits. Close similarity of metamaterial and dielectric slab spectra is demonstrated. The equivalence to the real dielectric slab is not exact concerning the phase shift: in this case an additional correction $\varphi_{\mathrm{corr}}=2\pi(L-L_{\mathrm{eff}})/\lambda$ must be added to the experimentally obtained phase.

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