Wire-Cloth-Mesh Metamaterials for GHz and THz Frequency Regime

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Abstract

Wire-cloth-mesh structures are introduced as metamaterials. They are experimentally investigated in terms of their metamaterial properties. It is shown that they exhibit pronounced pass-band characteristics in GHz and THz bands. Transmission minima are explained in terms of Rayleigh-Wood anomaly. While slow-light propagation occurs in pass-band region, fast-light outside the mentioned region. This allows us to investigate abnormal propagation effects in these materials. These meshes are commercially available as precisely fabricated chemical particle filters and come in many sizes which facilitate their application as metamaterials in optical devices, antennas, multilayer structures, and so on.

1. Introduction

Recently, there has been growing interest in metamaterials (MTMs) because of their unique physical features not readily found in nature. Especially MTMs with negative refractive index and their possible applications in imaging systems, antennas, absorbers, and etc. have intrigued the scientific community. Another subgroup, low-index (LI) MTMs with a positive index less than unity have recently found considerable attention as well. Simple versions of such materials are perforated metal sheets with specially tailored arrays of holes. They exhibit pass-band characteristics which is useful for filter applications. They come in many forms, such as circular, square, or elliptical holes, all displaying interesting pass-band characteristics and – not so well-studied – a sub-unity refractive index in certain frequency ranges [1-8]. Wire-cloth-mesh structures have already found some interest with regard to their properties as possible frequency filters for radiation in the far-infrared spectral region [9]. We extend such studies and explore wire-cloth-meshes as MTMs for the sub-1-THz spectral region, applying time-domain THz reflection and transmission measurements. These allow us not only to measure power-transmission and -reflection spectra, but also to determine the complex dielectric function and to explore wave-propagation aspects such as the occurrence of negative group delay.

In this study, we experimentally investigate wire-cloth-mesh MTMs which are commercially available in many hole/wire sizes as inserts of chemical particle filters. These meshes are typically made from round wires via one of several weaving techniques. They are precisely fabricated, with low tolerances over fairly large areas. Unlike many thin-film MTMs, the structures are mechanically self-supporting and do not require a substrate, thus opening important degrees of freedom to the design of multi-layer stacked MTMs, waveguides, antennas, and so on.

2. Experiment and Analysis

The experiments were performed with a standard THz time-domain measurement system, employing a 82-MHz Ti:sapphire laser, a semi-large-aperture GaAs THz emitter and electro-optical detection. Figure 1 shows the experimented single-layer wire-cloth-mesh MTM.

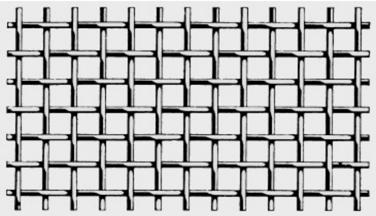

Figure 1: Single-layer wire-cloth-mesh MTM.

It has been shown that periodic metallic wire structures, when its dimensions are small compared with the wavelength, acts as a homogenous medium with a low plasma frequency [10, 11]. This means that these mesh MTMs have a plasma

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type frequency-dependent relative effective permittivity in which its plasma frequency can be given as [10, 11]:

$$f_p^2 = \frac{c_o^2}{2\pi a^2 ln(a/r)} \tag{1}$$

where c_o is the speed of the light in free space, a is the lattice constant, and r is the wire radius. If the operation frequency is slightly above the plasma frequency, the transmission characteristic of the mesh MTMs will show pass-band behavior in the frequency region of interest. Note that, the plasma frequency can be controlled by the geometrical parameters of the proposed mesh MTM. Another important term is the first Rayleigh minimum, $f_R^{1st} = c/a$, which is associated with light diffracted parallel to the grating surface for the periodic metallic structures [12–14]. As it will be seen from the measured data, the calculated first Rayleigh minimum is suited well with the measured transmission.

The experimented sample has the following geometrical dimensions: the lattice constant a is 0.65 mm and the wire radius r is 0.125 mm. For this wire-cloth-mesh MTM, the plasma frequency is at 0.143 THz and the first Rayleigh minimum is at 0.462 THz. The reflection and transmission data for the mentioned MTM is shown in Figure 2.

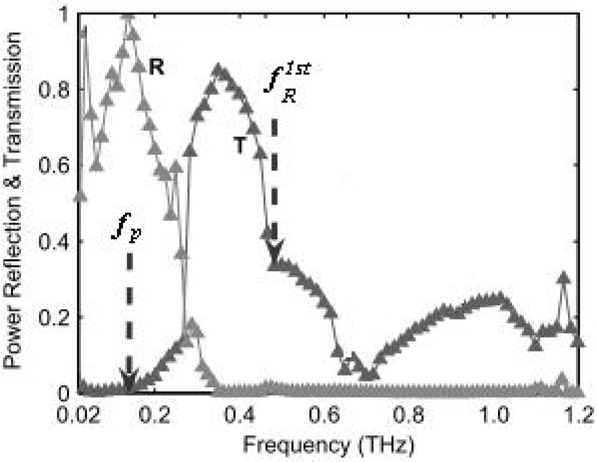

Figure 2: Power reflection and transmission spectra of the investigated wire-cloth-mesh MTM sample. The vertical arrows mark the spectral positions of the plasma frequency and the first Rayleigh minimum.

The power transmission spectra exhibit pass-band characteristics which are very similar to those published in the literature for custom-made hole arrays in metal films. As in those structures, we observe a pass-band response dominated by a high-transmission low-frequency band and less-pronounced higher-frequency bands. It is noteworthy that the main pass-band exhibits a peak power transmission of more than 80% for the investigated sample – a high value comparing well with literature data for other metallic grid structures [1-8]. The left-most arrow marks the calculated plasma frequency, f_p = 0.143 THz. The plasma frequency identifies the onset of the experimentally observed low-frequency cut-off of our two-dimensional material quite well, although the value of f_p has been calculated with the formula derived for three-dimensional meshes, as stated above. The transmission of radiation is evanescent as it is expected for a plasmonic cut-off. Furthermore, beside the main peak, the transmission spectra have several side peaks and sharp dips which can be explained by the surface plasmon polaritons theory and Rayleigh-Wood anomaly. We can say that the surface plasmon polaritons excited by the THz wave extend over both the front- and the back-side of the wire-cloth-mesh, which helps to understand the side peaks and the high transmission value observed at the lowest-order transmission maximum. The abrupt changes (sharp dips) in the transmission spectra of the MTM sample are due to excitation of Rayleigh-Wood anomaly. These kinds of anomalies were firstly discovered by Wood and explained under the name passing-off orders by Rayleigh. We identify them as Rayleigh minima which reflect the grating effect resulting from the periodicity of the hole array.

For the extraordinary (or perfect) transmission (EOT) with a transmission coefficient of (or close to) one, the following conditions have to be fulfilled [15]:

(i) The main transmission peak must lie below the frequency of the first Rayleigh minimum
(ii) The coverage of the holes should be larger than 19 %

(iii) The real part of effective permittivity should be -2 for perfect impedance matching (the effective impedance of the structure has to be matched to vacuum for EOT which can be calculated as follows [15]):

$$\left|Z_{eff}\right| = Z_0 \sqrt{\frac{1}{1+\Re(\varepsilon_{eff})}} \ . \tag{2}$$

For our sample, the coverage is 38 % which is larger than 19% and the first Rayleigh minimum is at 0.4615 THz. The main transmission peak is at around 0.35 THz and it is smaller than the first Rayleigh minima. Then, the first TWO conditions for a high transmission are satisfied. The main transmission peak is located at 0.35 THz with the amplitude peak of 0.92. Furthermore, the effective permittivity is around 0.18 at 0.35 THz and it is not negative. The effective permittivity is calculated from standard retrieval method using measured reflection and transmission data. According to our expectations, the effective permittivity is negative below the plasma frequency and it is lower than unity after the plasma frequency for such wire mesh metamaterials. The calculated data for the effective permittivity satisfies our expectations in which the studied structure has a refractive index less than unity. According to Equation 2, absolute value of the effective impedance is $0.9206Z_0$. This explains why the transmission is not unity although the coverage is larger than 19 %. This result matches perfectly with the measured amplitude peak value of 0.92. Hence, while impedance matching to vacuum is not satisfied perfectly, we still have pronounced transmission. Consequently, the third condition is also satisfied with a justification. Note that a custom wire-cloth-structure for EOT can be designed by arranging the geometrical parameters of the structure (lattice constant and wire radius).

Finally, we investigate the speed of wave propagation in different spectral regions. We focus on the group velocity which we explore in terms of the differential group delay experienced by a wave packet induced by the presence of the wire-cloth-mesh MTM. A positive value of the differential group delay implies subluminal propagation speed, a negative value abnormal propagation with two possible cases of (a) superluminal propagation and positive group velocity or (b) negative group velocity. Figure 3 shows the frequency response of the differential group delay. Positive the differential group delay is observed over most of the pass-band regions. Negative the differential group delay with an absolute value as large as 4 ps occurs in narrow frequency regions between pass-bands, where the transmission is reduced – a situation typical for evanescent fields.

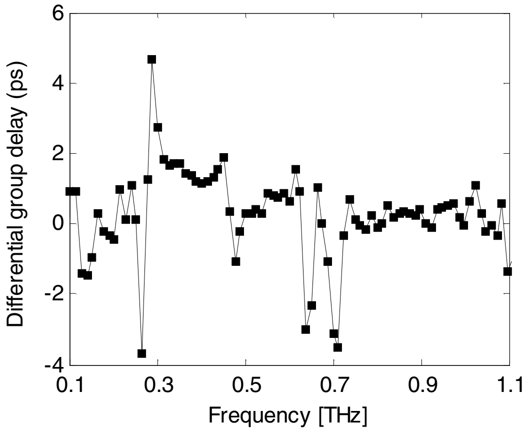

Figure 3: Differential group delay versus frequency.

3. Conclusion

Free-standing wire-cloth-mesh structures are proposed as metamaterials for GHz and THz applications. Such mesh structures are commercially available in many forms and sizes. Possibly applications include resonators, AR-coatings, filters, antennas, chemical sensors, and etc. The measured transmission pass-band and dip characteristics are consistent with the picture of excitations of surface plasmon polaritons theory Rayleigh-Wood anomaly. The width of the zeroth-order transmission pass-band is accordingly wide. In addition, investigating the speed of wave propagation in the structures, we identify spectral regions with negative differential group delay, which is evidence for abnormal group velocities (superluminal propagation or negative group velocity).

4. References

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