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Polymeric Dielectric Mirrors for the sub-millimeter Wavelength Range

T.Dobbertin, D.Turchinovich, P.Knobloch, and M.Koch

Abstract – **We present a simple and cheap approach to fabricate large-area stopband filters and mirrors for the THz range. This approach extends the well known concept of dielectric mirrors to the far-infrared. We use alternating layers of different materials to build a flexible all-plastic mirror. The films with a typical thickness of several tens of micrometers are arranged to form pairs of quarter-wavelength-layers. The structures are characterized by THz time-domain spectroscopy. The experimental results are in good agreement with transfer matrix simulations.**

I. Introduction

THz technology is a rapidly growing field of scientific and engineering interest. The body of the work is devoted to THz spectroscopy. Besides the principles of "light"-matter interaction in the THz range, which represent problems interesting on their own right, people focus on several THz applications in the field of medical imaging and sensing in general. Another important aspect is the development of electronic devices such as Gunn, Impatt, and Schottky diodes etc [1,2,3] , which could serve as emitters and receivers in future wireless short-range communication networks. Obviously those systems will also require a variety of passive devices such as stop-band and band-pass filters, which can be used for frequency selection and impedance matching.

Several approaches to fabricate the sub-mm optical filters were reported so far including metallic meshes [4,5] and photonic band-gap (PBG) crystals [6]. Metallic meshes are periodically perforated metal films. While a wire grid represents a high-pass filter, a low-pass can be realized by an array of metal squares which are separated by sections of dielectric material. An periodic array of cross shaped metal structures on a dielectric layer represents a band-pass filter, cross shaped dielectric sections in a metal film lead to a stop-band filter. Those metallic mesh structures can be produced using photolithographic etching [4] or vacuum deposition [5]. In principle this "metal film approach" can provide filters with large lateral dimensions.

Photonic band-gap structures, on the other hand, can only act as stop-band filters. They can be manufactured using micromachining. Reported are 3-dimensional structures with a wood-pile geometry [6], i.e. they consist of layers of parallel dielectric rods which are tilted by 90 degrees from layer to layer. The overall dimensions of the structure in [6] are 2x2 cm. Such a small area will most likely be common to 3-dimensional PBG structures due to the complex fabrication process.

In this work we present an easier and cheaper method to fabricate the large area filters and mirrors. We produce dielectric mirrors for sub-mm range simply by stacking alternating $\lambda/4$ layers of polymeric materials with different refractive indices. The materials relevant for commercial dielectric mirrors should obviously satisfy the following conditions: a sufficient step in the refractive index, low absorption and dispersion, mechanical stability, processing simplicity and low cost. For a first demonstration we use commercial polymer films of polyethylene (PE), low density polyethylen (LDPE), polypropylene (PP) and Styrolux™ (SX). They satisfy the above mentioned criteria, have a thickness ranging from a few tens to more than a hundred microns and are widely available.

Material	Thickn. [μm]	Ref. ind. n	$\lambda/4$ at
PE	100	1.67	450
PE	120	1.67	375
PE	150	1.67	299
PE	100	1.73	432
PE	190	1.74	267
PP	150	1.53	326
SX	300	1.59	157
SX	100	1.8	417
SX	100	1.8	417
LDPE	60	1.7	735
LDPE	70	1.7	630
LDPE	80	1.7	551
LDPE	90	1.7	490

Table 1: Properties of the polymeric films.

II. Experimental Setup

The mirrors were characterized with a THz Time-Domain Spectrometer which contains photoconductive dipole antennas. In this experimental scheme information on the sample under investigation is obtained by comparing so called THz waveforms taken with and without a sample in the THz beam. The frequency spectra obtained via a Fourier-transformation of the waveforms extend from a few tens of gigahertz to a few terahertz. This technique gives a very high signal-to-noise ratio (not less than 1000/1). For details on such a spectrometer refer see Ref [7].

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III. Results and Discussion

To find combinations of two different films which represent a pair of $\lambda/4$ layers for a certain frequency we first estimated the refractive indices of all polymer films available. The estimation was done by measuring the time shifts introduced by the films. The refractive indices for the investigated films range form 1.5 to 1.8. They are listed in table 1.

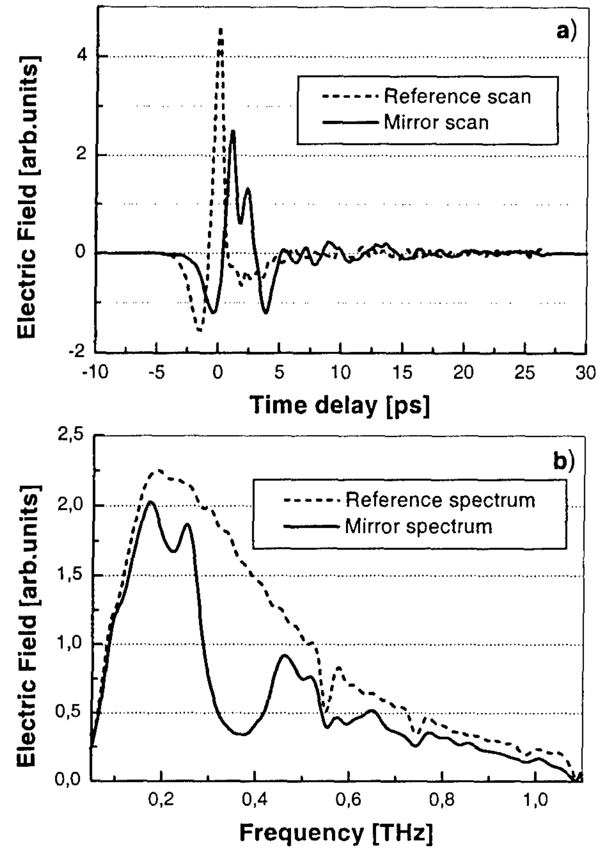

Fig. 1: a) Solid line: THz waveform after passing through an air-plastic mirror. Dashed line: free space reference scan. b) Spectra corresponding to the data in a).

Based on the results of table 1 we have fabricated several structures comprising different film combinations. To obtain a tight structure and to avoid air bubbles between the layers they were mechanically pressed together using a specially designed holder. Here we restrict ourselves to an area of 2x2 cm.

Besides all-plastic structures one can also easily assemble an air-plastic mirror. This is accomplished by using spacers with a desired thickness. In our first attempt we simply cut out some area from a plastic film to produce a spacer. The advantage of such a structure is the higher step in the refractive index between the layers.

The transmission functions of the dielectric mirrors are obtained from a comparison of a freespace reference measurement and a measurement with the sample in the beam. Fig. 1a shows the waveforms of a reference scan (dashed line) and a scan on a structure consisting of 3.5 pairs of 100 μm PE and 200 μm air (solid line). The corresponding frequency spectra are shown in Fig 1b. The sharp dips around 0.56 and 0.75 THz, which can be seen more clearly in the reference spectrum, correspond to rotational transitions of atmospheric water vapor. The transmission spectrum obtained for this structure is shown in Fig. 2 as a solid line. At the position of the stop-band which is centered around 350 GHz the transmission is suppressed by 95%.

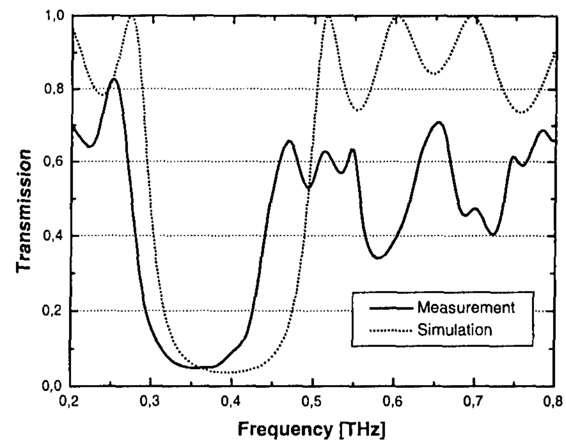

Fig. 2: Solid line: experimental transmission spectrum of a mirror consisting of 3.5 pairs of 100 μm PE films and 200 μm air films. Dashed line: simulated transmission spectrum.

The experimental data are compared to a numerical simulation based on the transfer matrix method (TMM) [8]. In TMM a characteristic transfer matrix is assigned to each layer. The overall optical properties of the whole structure are then described by a matrix obtained by multiplying the individual matrices. The result of this simulation using the experimentally determined film thickness and refractive index is shown in Fig. 2 as a dashed line. We obtain a reasonable agreement between measured and simulated data. Yet, the experimental stop-band is slightly red-shifted with respect to the theoretically predicted one. This red-shift is observed for all mirror structures we have fabricated. It may result form small random tilts of the interfaces inside the mirror structure or from slight uncertainties in values of the refractive index.

Similar results are obtained on an all-plastic mirror. The results shown in Fig. 3 are obtained for a structure that consists of 8.5 pairs of 190 μm thick PE and 300 μm thick Styrolux^{TM} films. In the experimental spectrum (solid line) the fundamental stop-band is observed around 175 GHz together with the second order stop-band at 350 GHz. In addition, there are indications for higher order stop-bands. The latter conclusion can be drawn from a comparison of the experimental curve with the

TMM simulation (dashed line) which shows all stop-bands equally pronounced.

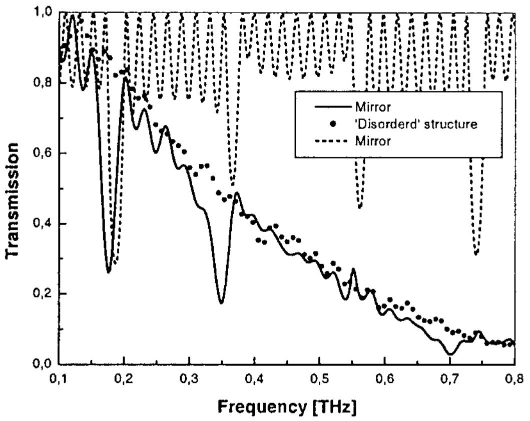

Fig. 3: Experimental transmission spectra of an all-plastic mirror (solid line) and 'disordered' structure (dots). Simulated transmission spectrum of the mirror (dashed line). The mirror consisted of 8.5 pairs of 190 μm PE and 300 μm Styrolux^{TM} films.

Again, good agreement between both curves is found regarding the width and positions of the stop-bands. There is however a striking difference in the overall transmission. Experimentally the transmission is strongly suppressed at higher frequencies; an effect which can also be observed in the data of Fig. 2. To investigate the nature of this effect we performed measurements on a "disordered" structure which contains the same layers but without the periodic arrangement. The transmission function of the disordered structure is plotted as dots in Fig. 3. It shows the same drastic decrease with increasing frequency, yet, without the stop-bands which are typical for the mirror arrangement. Since the THz absorption of polymeric materials is quite low (typically less than a few inverse centimeters) and, in addition, does not strongly depend on the frequency, we can exclude absorption as the loss mechanism at higher frequencies. We therefore conclude, that the losses are due to scattering arising from film imperfections. In fact a profile scan of a Styrolux^{TM} film (not shown here) reveals a micro-roughness with a typical length scale in the order of 400-500 μm. Although more profile scans and further analysis are needed, it is obvious that thickness fluctuations on this length scale should lead to strong scattering for frequencies above a few hundred GHz.

IV. Conclusion

In conclusion, we have presented a cheap and easy approach to build large area dielectric mirrors and filters for the sub-mm wavelength range. Even with no special but commercially available plastic films, we were able to demonstrate the main effects and to observe pronounced stop-bands. The produced structures show, however, frequency depending losses due to film roughness. Future efforts will focus on the fabrication of high quality mirrors using smoother polymer layers. In addition, we will build a reflection setup to detect the THz radiation reflected from our structures.

The structures presented here may act as wallpaper to shield and isolate single buildings or rooms in future wireless pico-cellular networks [9].

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