APPLIED PHYSICS LETTERS **88**, 202905 (2006)

Omnidirectional terahertz mirrors: A key element for future terahertz communication systems

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(Received 18 January 2006; accepted 22 April 2006; published online 17 May 2006)

We present an omnidirectional mirror for the terahertz range made from polypropylene and high-resistivity silicon. The structure is characterized by time-domain terahertz spectroscopy. The experimental data are in good agreement with transfer matrix calculations. In the frequency band between 319 and 375 GHz the mirror is highly reflecting for all incidence angles and s as well as p polarization. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2205727]

Presently the potential of terahertz technology is generating considerable interest. Future terahertz applications may include imaging techniques for quality control of industrial goods and for security checks of people, mail, or luggage.[1–3] Furthermore, future short-range indoor communication systems may work at several hundred gigahertz.[4–6] For all these applications efficient, inexpensive, and compact terahertz sources and detectors need to be developed. In addition, passive elements such as terahertz mirrors, filters, and modulators are required.

Recently, the concept of polymeric dielectric mirrors for the terahertz range has been demonstrated.[7,8] Here, we present a considerably improved structure which (i) has a much higher reflectivity, (ii) a much broader reflection band, and which (iii) is omni-directional. The structure is carefully characterized in transmission and reflection under various angles. The agreement of the experimental data with model calculations is excellent.

Yet, before we present these results we will briefly outline that these mirrors could turn out to be key elements in terahertz communication systems.

Terahertz radiation is strongly absorbed by the atmosphere and free-space path losses are high. Hence, working distances will be short and individual terahertz picocells may cover only single rooms or one building at the most. To compensate for the high atmospheric and free-space losses these systems will require high directivity antennas.[5] The result will be a highly directed transmission between a transmitter and a receiver.

A practical indoor terahertz communication system, however, must be robust against shadowing, as moving people or other objects may block the direct line-of-sight beam path. Thus, for reliable operation, such a system should also make use of indirect transmission paths that involve one or a few reflections off the walls. Figure 1 shows the result of a ray-tracing simulation of a terahertz picocell in a typical office environment. We model a 30 m^2 room with furniture and randomly moving people that could block the terahertz beam. Plotted is the worst case signal level 1 m above the floor for the direct line-of-sight path (DP) and paths that involve one or two reflections off the walls. The transmitter is located in the middle of the room under the ceiling. Dark areas represent regions of insufficient signal level. As can be seen, a terahertz link cannot rely only on the DP as there is always the chance that it is blocked by somebody stepping into the beam path.

Unfortunately, reflection losses are high for common building materials at terahertz frequencies,[9] but the reflectiv-

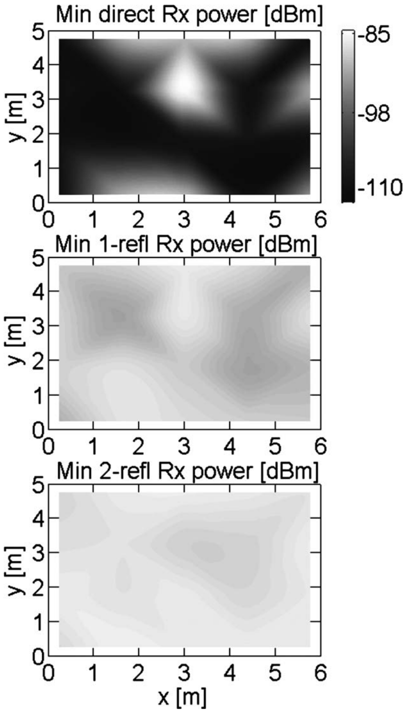

FIG. 1. Worst case signal level (in dBm) 1 m above the floor in a 5 ×6 m^2 room with typical office furniture. From top to bottom the three plots show the signal level resulting from the direct line-of-sight path, all paths that involve one reflection off the walls and all paths that involve two reflections.

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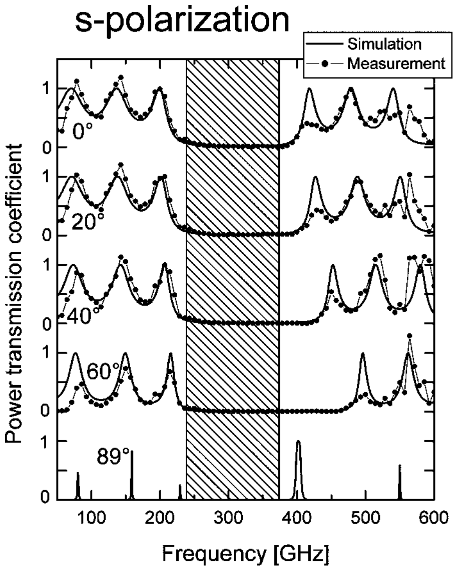

FIG. 2. Transmission spectrum through the mirror structure for various angles and *s* polarized terahertz waves. The experimental data are shown as dots, the solid lines show the result of a transfer matrix calculation.

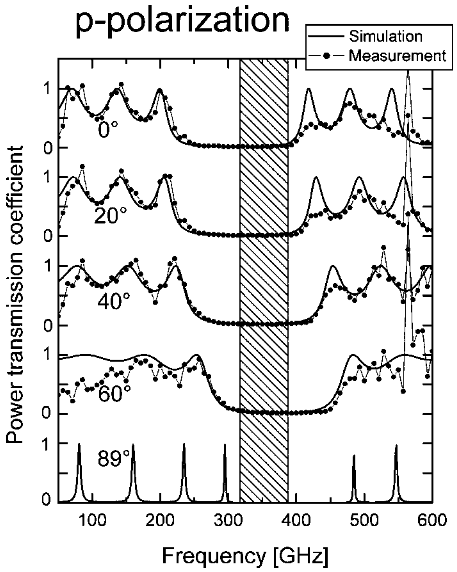

FIG. 3. Transmission spectrum through the mirror structure for various angles and *p* polarized terahertz waves.

ity of the walls could be enhanced by polymeric terahertz mirrors with reflection bands tailored to match the carrier frequency of the communication system. This would help to reduce the antenna gain which is required to establish a reliable terahertz link. Fortunately, ray-tracing simulations show that it is not necessary to cover the entire wall area in a typical room but only some "hot spots."

In order to optimize the performance, such mirrors should be highly reflective within a certain frequency band over a wide range of incidence angles. Mirrors which are highly reflective for all incidence angles are called omnidirectional mirrors and have been discussed in the literature recently. In Refs. 10–12 several criteria are given that a dielectric structure must fulfill in order to be omnidirectionally reflecting. Essentially, the step in the refractive index between the two different layers needs to be quite high. The result is a broad reflection band for normal incidence (angle 0). The position of this reflection band will blueshift and its shape might somewhat change as the incidence angle grows. If the width of the reflection band is sufficiently large (compared to the magnitude of this blueshift), then a band can be identified for which the structure is highly reflecting for all angles.

Most polymer materials have a refractive index between 1.45 and 1.8 (i.e., polyethylene 1.50–1.54, polypropylene 1.53, Teflon 1.45, polycarbonate, and polyamide up to 1.8). The refractive index step achievable with these materials is not sufficient to construct an omnidirectional mirror. Hence, one has to employ other low absorbing materials with a higher refractive index such as semiconductors.[13] Here we use polypropylene and thin slices of high-resistivity silicon to build an omnidirectional terahertz mirror.

The structure consists of five 150 μm thick layers of polypropylene with a refractive index of 1.53 and four 63 μm thick layers of high-resistivity silicon with a refractive index of 3.418. Typically, the structure of a dielectric mirror starts with the material which has the higher refractive index. However, for our mirror we used polypropylene layers as outer layers to protect the fragile, thin slices of silicon.[14] A fiber-coupled terahertz time-domain spectrometer is used to perform both transmission and reflection measurements (see, e.g., Ref. 9).

Figures 2 and Fig. 3 show the terahertz transmission spectra through the structure for *s* and *p* polarizations, respectively. Figures 4 and 5 show the corresponding reflection spectra. The dots represent the experimental data while the solid lines are the result of a transfer matrix simulation. The simulation is performed with the parameters given above. In the simulation, a thin layer of air is included between each layer of material. Because of the geometry of the sample holder reliable data for an incidence angle larger than 60° is not available as part of the beam is clipped.[15] In this case, theoretical curves show the transmission spectrum expected for grazing incidence. For normal incidence a broad reflection band is observed which ranges from 0.247 to 0.388 THz. Inside this band at least 95% of the incidence power is reflected. As the incidence angle increases this reflection band blueshifts for both *s* and *p* polarizations. For both polarizations a frequency band can be found for which the mirror is highly reflecting for all angles (indicated by the gray area in the graphs). The omnidirectional reflection band is broader for s-polarized waves.

Admittedly, the use of thin slices of crystalline silicon reduces the mechanical flexibility of the structure, which is one of the great advantages of polymeric mirror structures. Yet, it may be possible to replace these silicon layers by polymer layers the refractive index of which has been considerably enhanced by the addition of high-index microparticles in a compounding process. For example, a fine high-resistivity silicon powder could be mixed with polypropylene to obtain a flexible high-index dielectric. In this case the structures could be produced by coextrusion which would also avoid the air layers between the layers of the dielectric structure and hence improve the quality and uniformity of the mirror.

In summary we have demonstrated an omnidirectional mirror for the terahertz range made from polypropylene and high-resistivity silicon. For frequencies between 319 and

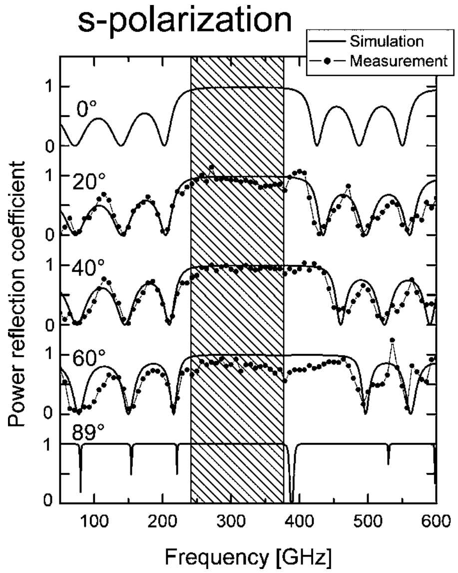

FIG. 4. Reflection spectrum of the mirror structure for various angles and *s*-polarized terahertz waves.

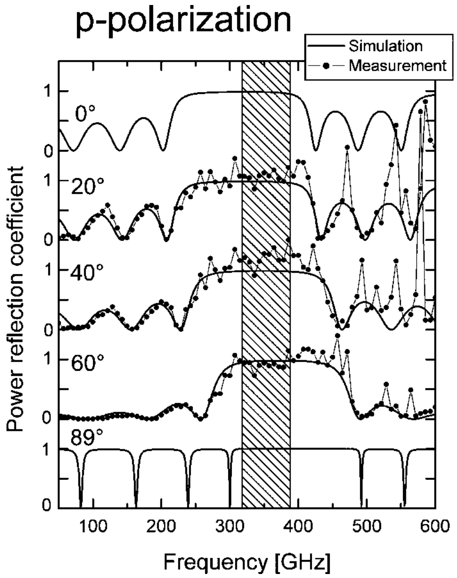

FIG. 5. Reflection spectrum of the mirror structure for various angles and *p*-polarized terahertz waves.

375 GHz the structure is highly reflecting for all incidence angles and *s* as well as *p* polarization. Future mirrors could be made from pairs of polymer films where the refractive index of one material has been enhanced by mixing it with a high-index filler. These mirrors would be mechanically flexible and could serve as wall paper to enhance the reflectivity of in-door terahertz picocells.

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[14] We note that this somewhat reduces the overall reflectivity of the mirror.
[15] Note that the experimental reflectivity in Fig. 5 for 60° and *s* polarization in the reflection band signal is already somewhat smaller than the (real) theoretical value.