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STUDY OF THE LOW-COST HIPS AND PARAFFIN-BASED TERAHERTZ OPTICAL COMPONENTS

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The ever-increasing popularity of the terahertz (THz) frequency range reveals the increasingly obvious applicability limiting factor – the price of the final setup. This study is intended to contribute to the solution by evaluating the THz frequency range suitability of the optical components, fabricated using two easily accessible materials – high impact polystyrene (HIPS) and paraffin. The primary analysis using time-domain spectroscopy (TDS) revealed promising results, as both materials had sufficient refractive indexes of $n \approx 1.55$ and a high transmittance. That allowed one to assume the feasibility of creating a low-cost THz frequency range lens. Lenses of focal lengths of $f = 20$, 30, 40 mm were fabricated using extrusion 3D printing and paraffin moulding. The produced lenses showcased the satisfactory beam focusing ability, comparable to that of already existing much less cost-efficient solutions. The THz imaging using the fabricated lenses has successfully been realized, proving the applicational possibilities of the imaging system with the proposed low-cost components employed.

Keywords: terahertz frequency range, beam shaping, paraffin lenses, THz imaging, 3D printed lenses

1. Introduction

Terahertz (THz) frequency range is currently experiencing a peak of scientific interest for both practical implementation and fundamental studies [1]. Currently, one of the major applicational interests include THz imaging [2] allowing non-invasive scanning, preferential in a wide range of applications, including security [3], pharmacy [4], and quality control [5]. In any case, a successful wide range implementation of THz frequency range solutions requires cost-effective, efficient and easily accessible imaging component solutions. Beam shaping components are considered as one of the most important imaging elements, stipulating the quality of the whole imaging system [2]. As standard glass-made optical components are absorbent for THz waves, a lot of strides in discovering innovative designs and testing various materials for lenses have been performed. Currently, typically employed optics are usually made of silicon [6], Teflon [7] or special z-cut quartz [8]; however, they require a special manufacturing equipment. Another solution for THz beam shaping is the employment of complementary meta-lenses [9], allowing conduction of exciting experiments and being comparably simple to fabricate. Still, specific machinery, which may not be easily accessible, is required. Therefore, there still is a need for beam-shaping elements made of inexpensive materials, ensuring an easy on-site customization, simple fabrication techniques and the required equipment, supplying wide possibilities not only for applications, but also for low-budget experiments.

Recently, paraffin wax attracted a lot of attention, being a cheap alternative, suitable for the manufacturing of THz beam control elements. Paraffin-based optics have already proven the operational principle [10]. However, in the mentioned work, the lens shape is solely described by the tension forces, thus it cannot be optimized to be more efficient, or for different focal lengths.

A mould-based lens [11] allows the creation of complicated lens shapes. For example, the creation of diffractive optics [12] may ensure a better beam focusing performance, compared to that of standard refractive lenses. However, as the mould is usually 3D printed, resolution limitation becomes a serious issue at higher frequencies. Furthermore, a sophisticated design leads to fabrication difficulties and increased error possibilities. As a result, the development of old-style refractive lenses is still considered reasonable. Such lenses were successfully applied along with low-cost THz detector solutions, significantly decreasing the price of the total imaging system [13]. Still, the proper optimization of materials and shapes can further substantially increase the imaging quality and efficiency.

The high impact polystyrene (HIPS) is considered another promising material for the creation of THz range-applicable beam shaping components [14]. Such components are produced employing the injection molding technique [15] or 3D printing [16, 17]. HIPS based solutions are expected to deliver the performance comparable to that of paraffin, and in the case of nonplanar convex solutions [18], they are susceptible to the same fabrication-related problems.

In this article, we present planar convex lenses for the THz frequency, made of two common household materials: high impact polystyrene (HIPS) and paraffin. Spectral properties of both proposed materials show promising results to be used for the THz spectral range. Paraffin-based lenses were produced out of a 3D printed mould, while HIPS-based lenses were directly 3D printed. Lenses of different focal lengths were manufactured, and their shaping and imaging performance was extensively analyzed and compared with that of the pre-simulated models.

2. Methods

Lens manufacturing parameters relied on dash is missing 3D-FDTD (finite-difference time-domain) parametrization. The lens type was chosen to be plano-convex in order to ensure an easier manufacturing process. To ensure a convenient usability, a circular base with a diameter of 60 mm and a height of 5 mm was chosen. Optical components were constructed by obtaining a spherical segment with the height equal to $1/R$, where R is the radius of the sphere. The desired radii for different focal lengths of the lens were obtained by 3D FDTD parametrization by running a parameter sweep. The value of the refraction index that was used in simulations was obtained by terahertz time-domain spectroscopy (cf. Fig. 1(a)), since the refraction indexes differ only slightly, and the refraction index of $n = 1.55$ was used for the simulation of both materials. One should note a high transmission in the sub-THz frequency range, making these materials

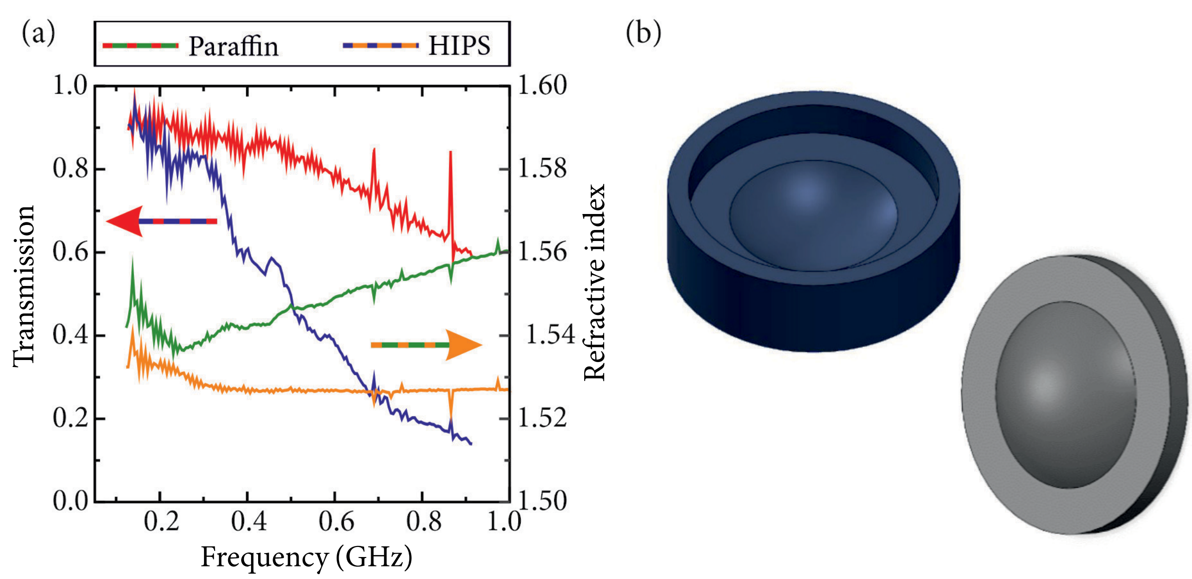

Fig. 1. (a) Transmission spectra and refractive indexes of paraffin and HIPS measured using a *TERAVIL*, 'T-SPEC Real-Time Terahertz' TDS spectrometer. (b) 3D models used for manufacturing of $f = 30$ mm paraffin lens moulds (blue) and 3D printed HIPS lenses. More details on fabrication in the text.

suitable for the proposed beam shaping element creation. The high transmission in paraffin pertains up to the THz frequency range while in the case of HIPS one may note a significant decrease, making this material ineffective for higher than sub-THz frequency range applications. One should also note an almost constant refractive index within the analyzed frequency range. The parametrization results pointed to radii of 20, 27 and 33 mm for focal distances of $f = 20$, 30 and 40 mm, respectively.

The manufacturing process was followed by creating 3D models of lens moulds for paraffin lenses and HIPS lenses themselves (Fig. 1(b)). An 'Ultimaker 2' printer was used with a nozzle size of 0.4 mm and the lowest layer height of 0.06 mm. The moulds were printed using a PLA (polylactic acid) filament with the infill patterns of lines with a density of 30% and a layer height of 0.15 mm. HIPS lenses were printed using a filament of this material with a concentric infill pattern with a density of 100% and the lowest possible layer height of 0.06 mm. The HIPS lenses required no additional efforts for manufacturing, while for the paraffin lens fabrication moulds had to be filled with melted paraffin and extracted after solidification.

A lower precision was maintained for the paraffin moulds since the infill is used primarily to maintain the mould shape, and, additionally, at the desired 0.1 THz the surface roughness of 0.15 mm makes only 1/20λ, which is negligible for refraction effects. The quality and reproducibility of the produced elements, obtained by evaluation using a KH-7700 digital microscope, are depicted in Fig. 2(b). The HIPS lenses demanded a higher precision since they had to be constructed as homogenous as possible in order to minimize the possibility of air gap formation inside the lens structure.

The characterization of experimental lens beam focusing (right) and the imaging (left) setup are presented in Fig. 2(a). The setup consists of an InP Gunn diode oscillator emitting 93.8 GHz radiation, a parabolic mirror (PM) and a microbolometer THz detector [19], placed on a 2D linear stage system. As the parabolic mirror collimates and redirects the beam, the lens under the test focuses the beam onto the detector. The focusing properties are revealed by *xy* and *xz* scanning. To perform THz imaging, the setup is transformed by inserting two additional lenses. These lenses are inserted to collimate the beam after the target and then focus it onto the detector. In the imaging setup, the detector is being fixed and the sample is being moved by the stage system. Two samples were observed during imaging – a 1952 USAF steel foil target with

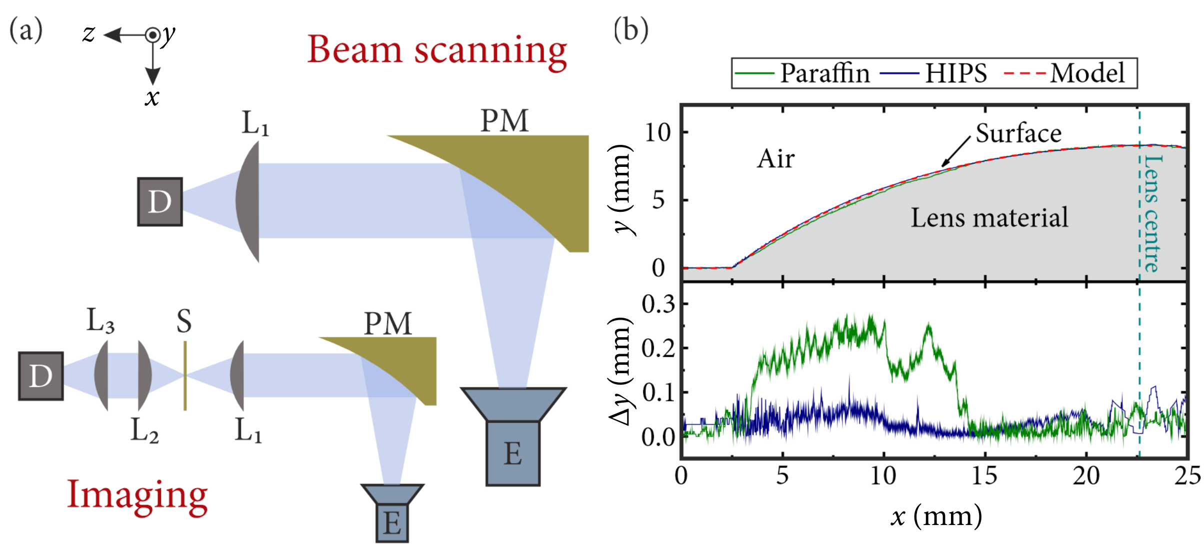

Fig. 2. Experimental setups. (a) Right: focusing performance analysis – beam scanning. THz source is an InP Gunn diode oscillator (E), a parabolic mirror (PM), HIPS or a paraffin wax lens that is being tested (L_1) and a microbolometer detector (D). Left: imaging setup – two lenses (L_2, L_3) are additionally inserted for beam formation on the detector (D) after it passes through the sample (S). (b) Comparison of the produced THz lens profiles for the case of paraffin and HIPS materials. The results depict a good lens quality and reproducibility.

dimensions, modified for the THz frequency range: different rectangular holes spanning from 0.3 to 3 mm in width. The second target was a credit card that was placed in an envelope.

3. Results

Focusing lens from HIPS and paraffin with different focal lengths (f = 20, 30, 40 mm) were manufactured. Their beam focusing performance was theoretically and experimentally investigated. The top inset of Fig. 3 represents the simulation results of the normalized THz beam intensity along the optical axis, corresponding to the shape of the manufactured lenses of different focal lengths. The middle inset depicts the experimental results, obtained for the HIPS lenses, using the previously described beam scanning setup (Fig. 2(a)). The results for the case of paraffin wax lenses are located in the bottom inset. It is seen that the experimental intensity maximums are shifted to longer distances, compared to the simulated ones, which are most noticeable for the lenses of 20 mm focal length. That might be caused by fabrication imperfections and nonparaxial effects occurring in small focal length optical devices [9]. One may note the increase of the intensity with the increase of focal distance for the case of simulated lenses. However, during the experimental characterization, the increase of the focal length leads to the decrease in intensity, which is opposite to the theoretical results (Fig. 3). This mismatch is caused by the size of the THz beam emitted from the source, which in comparison to the beam used in the theoretical simulations is smaller than the effective lens area. According to the lens design, with the increase of focal length, the effective (curved) lens area also increases and becomes not fully covered by the beam from an InP emitter, while this is not the case in the numerical simulations.

To properly evaluate the possibility to employ the proposed lenses for imaging, the abovementioned modified 1951 USAF target was employed. Based on this data, a modulation transfer function (MTF) was calculated to quantitatively assess the image sharpness [20]. The ImageJ ASI_MTF plugin was used to carry out the analysis. The first step was to choose the most visible half-moon target. For each pixel line in the area, a derivative was calculated from the spatial frequency response (SFR), which resulted in the line spread function (LSF). After fitting a Gaussian curve, the fast Fourier transform was performed. The final MTF values were then normalized. The frequency at which the MTF reaches 50% contrast was determined. The results of the MTF calculation for our system yielded an MTF@50 value of 0.15 cycles/pixel. The frequency can be converted from cycles per

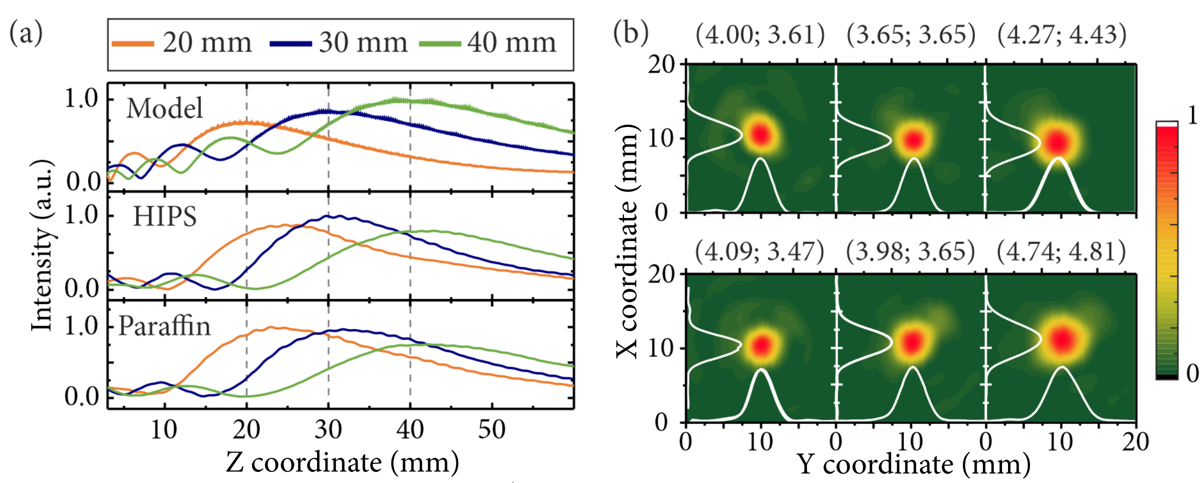

Fig. 3. (a) Simulated (top) and experimental (middle is HIPS, bottom is paraffin) beam XZ profile of the manufactured lenses. One should note the intensity mismatch between the simulated and experimental profile intensity for different focal lengths. This effect is visible as the collimated area is smaller, compared to the effective area of the large focal distance lenses. (b) Experimental XY profiles (top is HIPS, bottom is paraffin) of the lenses with different focal length. One should note the comparable FWHM (vertical and horizontal FWHM in mm are given above each graph) for both materials.

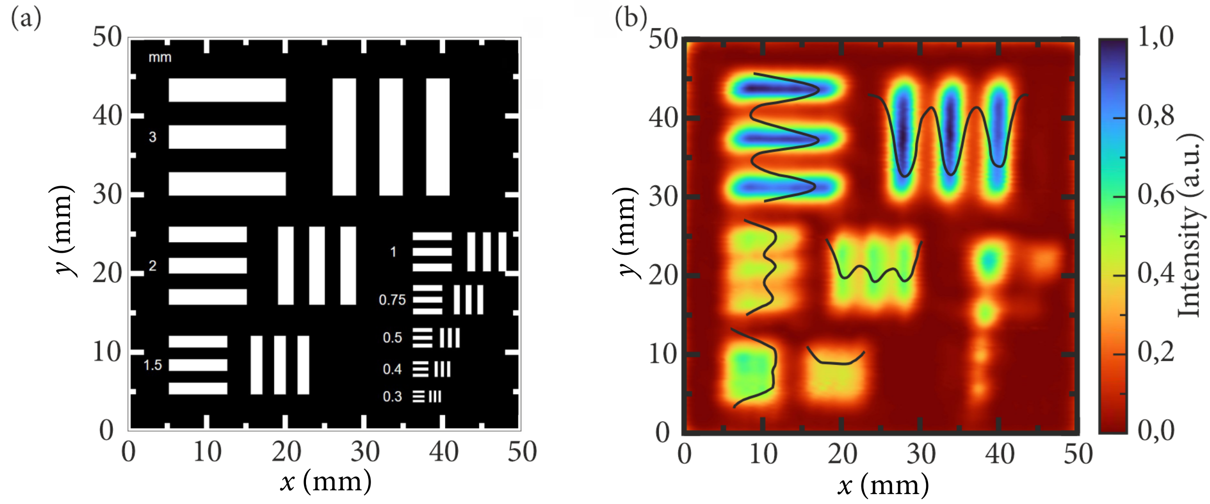

Fig. 4. (a) USAF1951 target modified for the THz frequency range. (b) Imaging of the USAF1951 target modified for the THz frequency range. In the current setup, the HIPS lens with a focal distance of $f = 20$ mm is placed before the target (L1). Imaging of such structure allows one to characterize the setup imaging possibilities by evaluating the resolution and MTF. Pixel size 0.3 mm.

pixel to cycles per millimetre by dividing by pixel size, and this results in 0.5 cycles/mm. The results from the MTF graph also indicate that with this optical system at ~1.3 cycles/mm there is loss of information, and the line pairs cannot be distinguished.

The fabricated HIPS and paraffin lenses with focal lengths of 30 mm and the HIPS lens of $f = 20$ mm were used in imaging of the plastic bank card, hidden in an envelope. The sample was placed between two 30 mm lenses made from different materials at their focal points, as seen in the imaging setup (Fig. 2(a)), and scanned under the 94 GHz illumination. The captured image is presented in Fig. 5. Because radiation does not penetrate the metal, several card components are clearly visible. We can distinguish metal contacts, a sticker, a card chip and the edge of the credit card. This result proves that the abovementioned imaging setup with the proposed low-cost lenses is suitable for the detection of concealed or THz-frequency range opaque objects.

4. Conclusions

It was shown that the THz lenses, made of HIPS and paraffin wax materials, can reach the performance comparable to that of its high-priced industrially fabricated counterparts, achieving a close to wavelength beam size and reasonable imaging parameters. A high functionality allows these optical components to be treated as great dependable alternatives,

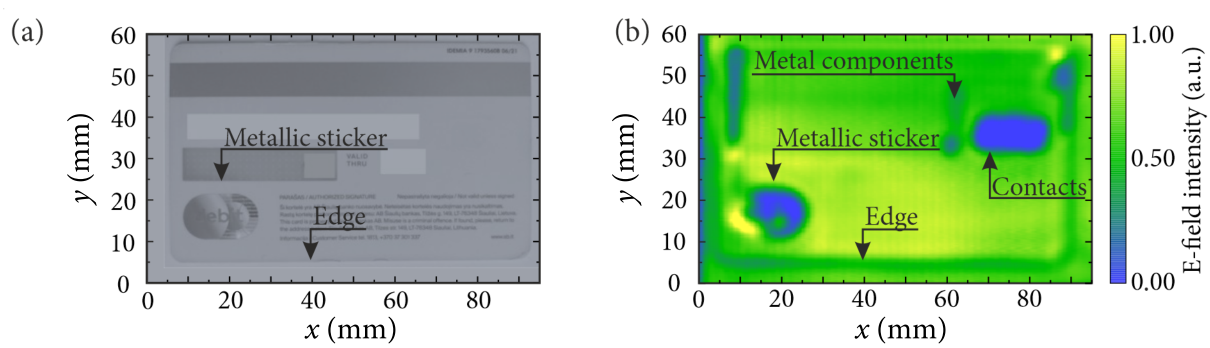

Fig. 5. (a) Credit card imaging sample. (b) Terahertz imaging results obtained by 2D sweeping of a credit card sample hidden in an envelope at frequency of 94 GHz. HIPS lenses of a focal distance of $f = 20$ mm placed before the target (L1) was used within this setup. One may note clearly distinguishable metal card components and card contours. Pixel size 0.3 mm.

as such lenses can easily be shaped to the desired structure, enabling on-site fabrication and optimization possibilities. Still, the TDS measurements of the locally acquired paraffin wax showed a larger suitability of paraffin compared to that of HIPS, for the application in a higher than sub-THz frequency range. The verification of the proposed low-cost materials and shape lenses for higher frequencies is expected in the future research. Another benefit of these materials is the recyclability of the high impact polystyrene [21]. Paraffin, on the other hand, being not recyclable, can be remoulded almost an unlimited number of times, allowing a low material consumption for a large variety of designs. The introduction of low-cost THz-frequency range innovations is expected to significantly boost up applicational and scientific involvement.

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ŽEMOS KAINOS TERAHERCINĖS OPTIKOS KOMPONENTAI IŠ POLISTIRENO IR PARAFINO

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Santrauka

Terahercinė (THz) spinduliuotė yra perspektyvi ir nuolat besiplečianti optoelektronikos sritis. Šis elektromagnetinių bangų ruožas naudojamas daugybėje įvairių taikymo sričių, įskaitant objektų vaizdų registravimą ir analizę. Plačiai pritaikyti šį dažnių ruožą trukdo aukšta įrangos kaina bei sudėtinga komponentų gamyba. Būtent šią problemą siekiama išspręsti, gaminant optinius komponentus iš pigių ir lengvai prieinamų medžiagų – parafino ir smūgiams atsparaus polistireno (HIPS). Šių medžiagų analizė laikinės skyros spektroskopijos metodu (angl. *time-domain spectroscopy*), atskleidė, kad abi šios medžiagos yra tinkamos sub-THz spinduliuotei dėl sąlyginai aukšto lūžio rodiklio $n \approx 1,55$ ir gero pralaidumo tame ruože. Šie parametrai atvėrė galimybę pagaminti lęšius terahercinam bangų ruožui – naudojantis 3D spausdinimo technologija, pagaminta po tris parafino bei polistireno lęšius, kurių židinio nuotoliai f = 20, 30, 40 mm. Pagaminti optiniai komponentai pasižymi gera spinduliuotės fokusavimo kokybe, palyginti su daug brangesniais ir sudėtingiau gaminamais lęšiais. Vaizdinimo sistema charakterizuota panaudojus MTF (*modulation transfer function*) vaizdinant modifikuotą USAF1951 taikinį. Komponentai sėkmingai pritaikyti terahercinėje vaizdinimo sistemoje, vaizdinant kredito kortelę popieriniame voke. Parodyta, kad norint sėkmingai panaudoti THz spinduliuotės ruožą, brangūs ir sunkiai prieinami komponentai yra nebūtini.