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**Abstract.** We present a simple and cost-effective method for the fabrication of optical elements in the terahertz regime. Caramelized sucrose is used as the refractive medium in the frequency range from 0.1 to 0.4 THz. The absorption coefficient of  $7 \text{ cm}^{-1}$  and the high index of refraction of 2.45 at 0.3 THz enables the fabrication of thin optical elements in the near-millimeter wavelength range. The THz beam profiles of the fabricated parabolic lens in focus, evaluated with terahertz pulsed imaging, show the near diffraction limit performance. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.55.9.090505](https://doi.org/10.1117/1.OE.55.9.090505)]

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Recent advances in the terahertz part of the electromagnetic spectrum (0.1 to 3 THz) have enabled the first industrial applications of nondestructive evaluation with T-rays. THz hyperspectral imaging has already been employed in food production to detect foreign bodies in chocolate, such as metal or glass particles,<sup>1</sup> as an interesting alternative to ionizing x-rays. The broadband terahertz radiation was generated predominantly using expensive femtosecond lasers interacting with nonlinear crystals or biased semiconductor antennas. With the advent of a low-cost quasitime domain spectrometer based on a simple multimode diode laser,<sup>2</sup> and with the discovery of THz wave generation from graphite,<sup>3</sup> the perspective of bringing the submillimeter waves out of the laboratory and using them on a large scale has become more real.

The first industrial applications had a significant impact on the development of cost-effective terahertz optics. A natural stone, dolomite, proved to be a reasonable replacement for the costly high-resistivity hyper-hemispherical silicon lens attached to a terahertz photoconductive antenna (PCA).<sup>4</sup> For the sake of introductory stage prototyping, lenses made of materials easier-to-process than stone have emerged. Diffractive paper,<sup>5</sup> micropowder-based,<sup>6</sup> and oil-based variable-focus lenses<sup>7</sup> are complementary to the conventionally fabricated ones with highly transparent polymers (high-density polyethylene, polytetrafluoroethylene, or cyclic olefin

copolymer), processed using additive manufacturing techniques.<sup>8</sup>

Still, the aforementioned lens-making techniques require plotters, three-dimensional (3-D) printers, curved polishing plates, and so on. In this letter, we propose to use caramelized sugar for casting terahertz optics with a high refractive index for use in dry environments. Not only is it easy to fabricate (see Fig. 1), but it also enables one to change its geometry *ad hoc*, when necessary.

The caramelization reaction of sucrose, used as a refractive medium, is a complex chemical process, wherein sugar undergoes thermal decomposition.<sup>9</sup> First it dehydrates, then condenses or polymerizes into more complex chemical molecules of higher molecular weight.<sup>10</sup> The first known studies of the caramelized sucrose indicated that the three dominant products of the thermal decomposition are the dehydration product, caramelan ( $\text{C}_{12}\text{H}_{18}\text{O}_9$ ), and two polymers: caramelen  $\text{C}_{36}\text{H}_{50}\text{O}_{25}$  and caramelin  $\text{C}_{96}\text{H}_{102}\text{O}_{51}$ .<sup>11</sup> Heavy organic molecules usually strongly absorb the terahertz radiation; therefore, we have tested the suitability of caramel as an optical medium, in the time-domain spectroscopic measurement, as shown in Fig. 2. The usable bandwidth of caramel used for the fabrication ranges between 0.15 and 0.4 THz, where the absorption does not attenuate the signal considerably (below  $10 \text{ cm}^{-1}$ ). Within this range, the performance of caramel is comparable to regular paper<sup>5</sup> at the expense of strongly dispersive behavior.

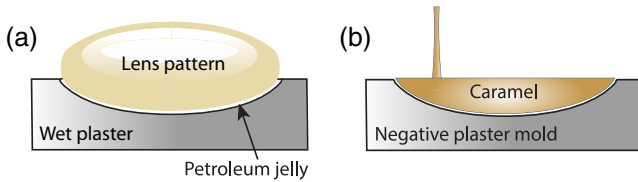
To fabricate a testing sample pellet (and a lens), the semi-dry sucrose diluted with water was heated slowly to the hard-crack stage ( $150^\circ\text{C}$ ) in a pot, wherein the temperature was monitored with a thermocouple (with an accuracy of  $\pm 2^\circ\text{C}$ ). The appearance of the hard crack stage was verified empirically by dripping the molten sugar into an ice-water bath. When this reaction point is reached, the molten droplet solidifies, forming breakable threads with a brownish sphere at the end.

The shape of the parabolic aspheric lens was obtained with the ray-tracing analysis based on the ABCD matrices. We used the matrix of refraction at a parabolic interface separating the two media with different refractive indices.<sup>12</sup> Since the parabola with a vertex at (0,0) can be approximated by  $(x = y^2/2R)$ , we can use the simplified lens maker's equation  $[f = R/(n - 1)]$ ,<sup>13</sup> substituting  $R = p$ . Initially, we designed a high-density polyethylene planoconvex lens (refractive index  $n = 1.54$ ) given as

$$x^2 = 2 \cdot 23.525 \cdot y = 2py. \quad (1)$$

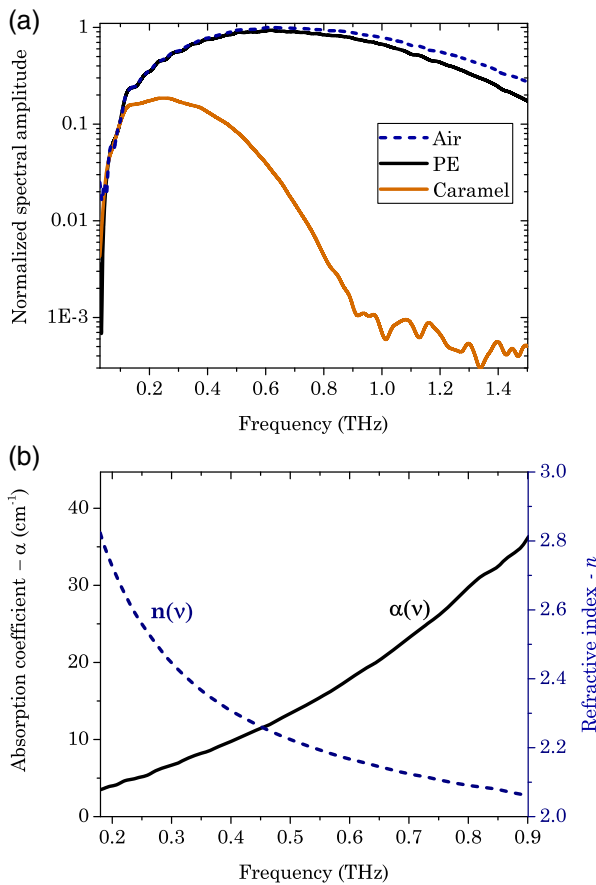
Its diameter was 30 mm, the effective focal length was 43.6 mm, and the back focal length was 42.4 mm. Having had our high-density polyethylene (HDPE) lens machined using a computer numerical control milling machine, we impressed it in wet plaster, thereby forming a mold, wherein we casted the liquid caramel prepared in the same manner as the pellet. To prevent the medium from sticking, we greased the mold with a thin layer of petroleum jelly. After extracting the lens from the mold, we semidry polished the surface to remove its slight imperfections. Due to the high refractive index of caramel (mean value of 2.47 between 0.2 and 0.4 THz), the theoretical focal length of the lens has shortened to 16.0 mm, i.e., almost three times compared to the polyethylene-based lens.

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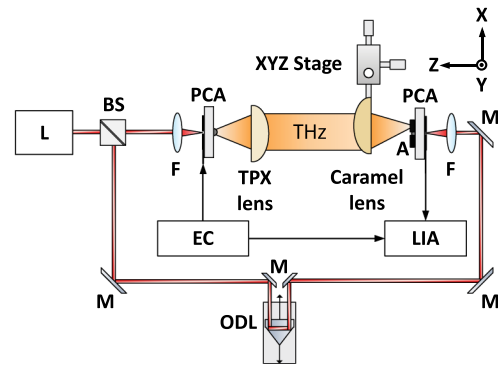


**Fig. 1** Two-step fabrication process of the caramel terahertz lens: (a) pattern is impressed in wet plaster and (b) caramel is poured into a mold covered with petroleum jelly. In further processing, we removed it and semidry polished the surface to remove minor imperfections.

We analyzed the caramel lens in a terahertz pulsed imaging (TPI) setup shown in Fig. 3, using a 780-nm femtosecond laser source (Menlo Systems, 82 fs, 100 MHz) in a pump-probe detection scheme. A parabolic lens ( $f = 54$  mm, Menlo) collimates a terahertz beam emerging from the terahertz PCA (100- $\mu\text{m}$  dipole with the emission peak at 0.2 THz, and the maximum frequency of 1.5 THz), biased and chopped by an electronic circuit.<sup>14</sup> To characterize the quality of the collimated beam, we blocked the THz beam after the TPX lens at different positions in two axes as in the widely used knife-edge method. The beam waist ( $2W_0$ ) measured in the X direction was 13.1 mm after the collimating lens, 14.2 mm between the two lenses spaced by 10 cm, and 12.3 mm at the caramel lens entrance. In



**Fig. 2** (a) Spectral characteristics of caramelized sucrose pellet (3.6-mm thick). Measurements for an HDPE pellet (PE) and nitrogen atmosphere (air) are shown for comparison. (b) Refractive index and absorption coefficient as a function of frequency.

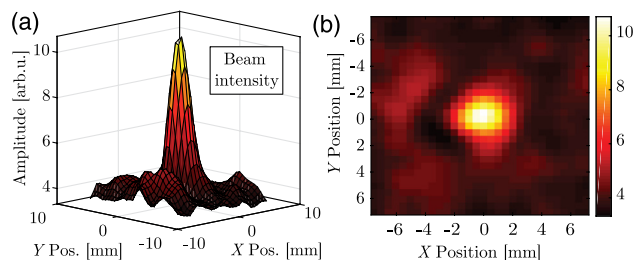


**Fig. 3** TPI setup with the XYZ stage employed to obtain the hyper-spectral image of the caramel lens. L, laser; BS, beam splitter; F, focusing lens; PCA, photoconductive antenna; M, mirror; EC, electronic chopper; LIA, lock-in amplifier; A, aperture; ODL, optical delay line.

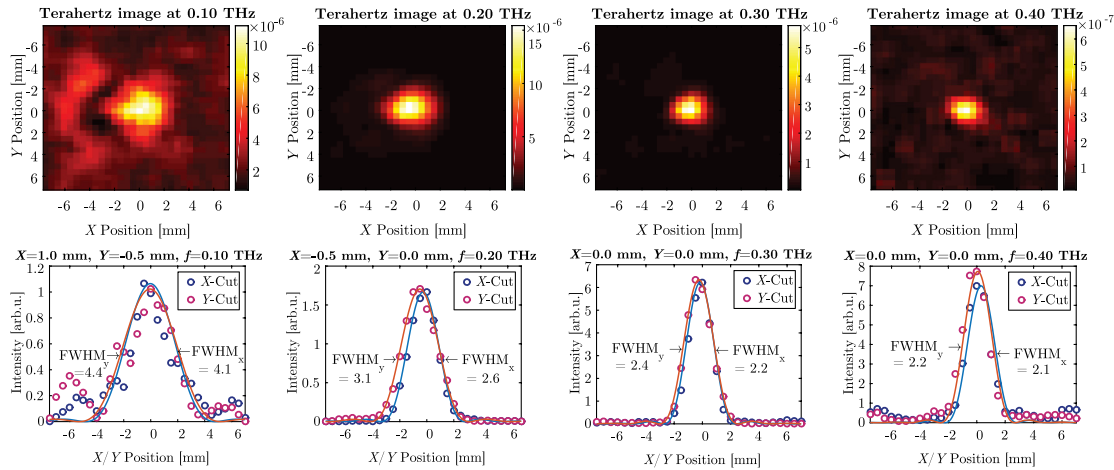
the Y-axis scan, the obtained values were 14.5, 13.3, and 13.8 mm, respectively. Notably, because of the significant diffraction, this method provides only a rough estimate of the terahertz beam parameters.

We used a PC-controlled XYZ stage to change the lens position in 0.5 mm steps. In the raster scan of the 20 ps, time-domain pulses the probing beam was time-delayed by a high precision linear stage (Newport) with a retroreflector attached. The THz waveforms were acquired with a lock-in amplifier (Stanford Research Systems) at a 1-ms time constant. To make the PCA act as a point-type detector, we placed a small iris close to the hyperhemispherical lens tip.<sup>15</sup> We set the aperture to 1.5 mm, as a trade-off between the spatial resolution and the sufficient signal-to-noise ratio,<sup>16</sup> which in our analysis was  $\geq 10$  in a single-scan time-domain signal.

We measured the focal length of the lens by changing its distance from the aperture along the Z-axis looking for the strongest terahertz time-domain signal,<sup>7</sup> found at  $z = 18 \pm 0.5$  mm from the detector. The discrepancy between the theoretical value of 16.0 mm and the measured value was  $2 \pm 0.5$  mm, i.e., within the experimental error ( $< 16\%$ ). After the focal length evaluation, we performed the  $30 \times 30$  pixels raster scan of the image with an interval of 0.5 mm, corresponding to the scanning area of  $2.25 \text{ cm}^2$ . Such a scanning range was chosen to ensure that the collimated terahertz beam will always be within the lens aperture  $D$ . The intensity of the terahertz signal ( $I = \int |a|^2 dt$ ) scanned along the focal plane, measured within the acquisition time slot (20 ps) is shown in Fig. 4.



**Fig. 4** Broadband intensity image of the terahertz pulses (integrated squared amplitude). (a) 3-D plot and (b) two-dimensional intensity map. Most of the energy lies in the low-frequency region, therefore the full width at half maximum (FWHM) of the beam is relatively large.



**Fig. 5** Intensity profiles of the THz radiation in the focal point of the caramel lens. Cross-sections of the hyperspectral image on the imaging plane are denoted by “X-cut” and “Y-cut” for a cross-section along the X and Y axes, respectively. Solid lines represent the Bessel fits.

The large spot size of the focused beam obtained using the time signal integration is caused by the broadband nature of terahertz pulses and may seem impractical for imaging applications. A multicolor terahertz pulse passing through the lens is focused to different spot sizes because of the diffraction limit dependence on the wavelength. Since the shorter waves can be focused to a tighter spot, we applied the Fourier transform to the time-domain terahertz pulse at each position of the lens with respect to the detector in order to characterize the performance of the lens at different frequencies. We calculated the frequency cross-sections of the hyperspectral image and averaged only the neighboring pixels for data consistency. Plots are depicted in Fig. 5 with the numerical Bessel fits to the intensity data in the focal point along the X and Y axes marked as solid lines. At 0.5 THz and above, the terahertz beam signal was buried in noise.

The theoretical full width at half maximum of the focused terahertz beam intensity at a given wavelength  $\lambda$  can be expressed as

$$\text{FWHM}(\lambda) = \frac{3.22f}{2\pi W_0} \lambda \approx 1.02 \frac{f}{2W_0} \lambda, \quad (2)$$

where  $2W_0$  denotes the diameter of the collimated beam, and  $f$  is the focal length of the lens. This equation is valid if the Fraunhofer diffraction pattern is assumed.<sup>4</sup> Alternatively, one can consider a problem of a collimated Gaussian beam with a waist  $W_0$  focused by a lens with a focal length  $f$  within the

**Table 1** FWHM in focus as a function of frequency, values are for cuts in X direction, mean  $2W_{0X} = 13.2$  mm.

FWHM frequency (THz)	Theory (2) (mm)	Theory (3) (mm)	Experiment (mm)
0.1	4.2	4.4	4.4
0.2	3.1	3.3	3.1
0.3	2.5	2.7	2.4
0.4	2.1	2.2	2.2

aperture  $D \geq 2W_0$ . Under such assumptions, the full width at half maximum of the beam intensity is given as

$$\text{FWHM}(\lambda) = \frac{4}{\pi\sqrt{2 \ln(2)}} \cdot \frac{f}{2W_0} \cdot \lambda \approx 1.08 \frac{f}{2W_0} \lambda. \quad (3)$$

Further, using Eqs. (2) and (3), we calculated the theoretical line widths of the focused beams at different frequencies. We averaged the values of the measured beam waist at three different positions and took into account the dispersive dependences of the focal length  $f$ . Results summarized in Table 1 show a good agreement with the theoretical predictions. Slight discrepancies may be caused by the frequency-dependent characteristics of the ultrafast, multicolor terahertz beam, and the radiation pattern from the PCA. Additionally, the accuracy of the knife-edge method of  $2W_0$  measurements might not be sufficient because of the considerable diffraction.

In conclusion, we have demonstrated experimentally a simple-to-prototype edible terahertz lens made of glass sucrose, caramel. We reached a near-diffraction limited performance in the near-millimeter wavelength range. The lens can be further improved by the substitution of the attenuating caramelized sugar with other confectionery substrates, e.g., sugar alcohol, isomalt.

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