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Optical path length measurement of spherical dielectric shells with axicon-generated Bessel beams; applications to corneal sensing

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***Abstract*—A custom aspheric axicon lens for corneal water content sensing, operating from 220 to 330 GHz, was evaluated with spherical, dielectric shell targets. The lens consisted of a hyperbolic back surface and conical front surface with a 25-degree axicon angle. An 8 mm radius of curvature, 1 mm thick, air backed dome was placed in the beam path and S_{11} acquired at numerous axial offsets between dome and axicon. The data was normalized by equivalent radius of curvature metallic spherical reflectors. Fits to reflectivity data ranged from $\varepsilon = 4.1$ and $t = 0.89$ mm and $\varepsilon = 4.16$ and $t = 0.885$ for lens-tip to shell-apex distances of 34 mm and 25 mm respectively. The results suggest that Bessel beam illumination may relax axial alignment constraints in THz imaging of cornea.**

I. INTRODUCTION

THz frequency measurement of corneal tissue water content (CTWC) requires careful monitoring of the relative locations between the cornea's spherical geometry and the THz transceiver aperture thus ensuring a known incident electric field distribution at the corneal surface. Poor matching between incoming wavefront and surface curvature is detrimental to model-based extraction of permittivity (water content) and thickness. Recent experimental work with Gaussian-beam illumination on corneal phantoms demonstrated the criticality of beam-cornea alignment [1]. These observations were further elucidated with theoretical simulations on the effect of transverse and axial misalignment on the estimated corneal parameters [2].

Previously we reported on the design, fabrication, and testing of a custom aspherical axicon lens consisting of a hyperbolic back surface and conical front surface with a 25-degree axicon angle [3]. The lens was manufactured from cyclic-olefin copolymer (TOPAS) designed to provide a large depth of field (DoF) in the WR-3.4 band (220 GHz – 330 GHz). Experimental results of collected backscattered intensity ($|S_{11}|$) from spherical metallic reflectors confirmed a DoF > 20 mm.

This abstract extends the previous work to see if the optical longitudinal modes of a lossless thin film (quartz spherical dome) can be accurately extracted from numerous positions along the optical axis.

II. RESULTS

A diagram of the system and experimental steps are shown in Fig 1. The hyperbolic-axicon lens was fed by a corrugated feedhorn antenna coupled to a WR-3.4 VNA extender (VNAX). The hyperbolic surface collimates the incident Gaussian beam radiation and the conical surface refraction produces an approximate Bessel beam. 91 target positions over the 9.1 mm span in the Bessel beam zone were evaluated. First, the S_{11} of a metallic spherical reference reflector with an 8 mm radius of curvature were collected from $d_1 \sim 25$ mm from the conical apex and till a second position $d_2 = 9$ mm displaced from d_1. With a spacing of 0.1 mm.

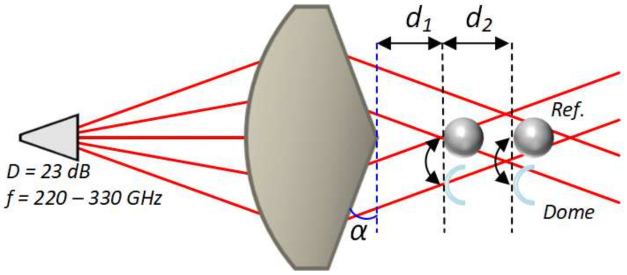

Fig. 1: Schematic of the experimental setup. A hyperbolic-axicon lens created a Bessel beam that illuminated quartz domes and reference metallic reflectors at different locations.

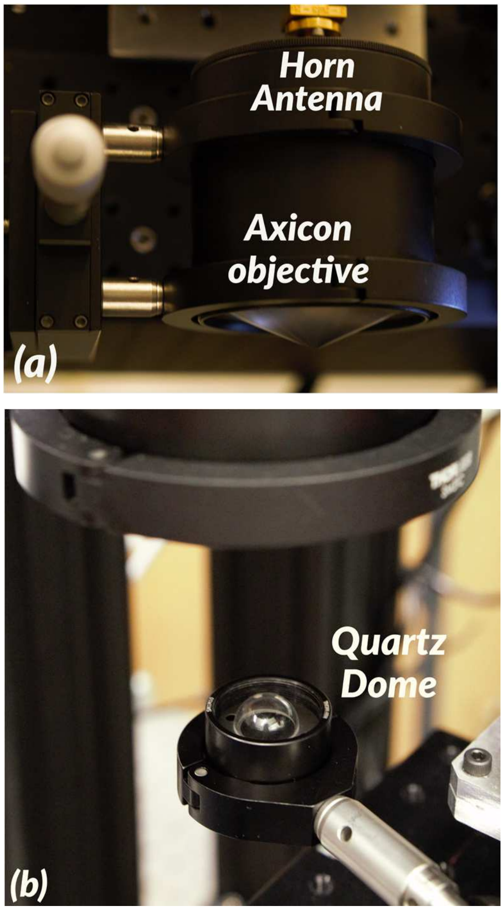

Fig. 2 Experimental setup. (a) The axicon objective. The lens is mounted on a lens tube. The antenna flange mount is partially visible at the top of the picture. (b) The quartz dome is aligned to the objective

Transverse scans were also performed at numerous locations along the axis to ensure co-location of lens and reflector optical axes. Then, an 8 mm radius of curvature, 1 mm thick

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quartz dome was placed in the same locations and their corresponding S_{11} acquired. The dome S_{11} was normalized by the metallic reflector S_{11} to obtain a calibrated target reflectivity. The experimental setup is shown in Fig. 2.

The calibrated reflectivity was fit to a stratified medium model and particle swarm optimization was used to estimate thickness and permittivity from the data. Reflectivity data and stratified media model fits are represented by the dashed and solid lines respectively in Fig. 3(a)

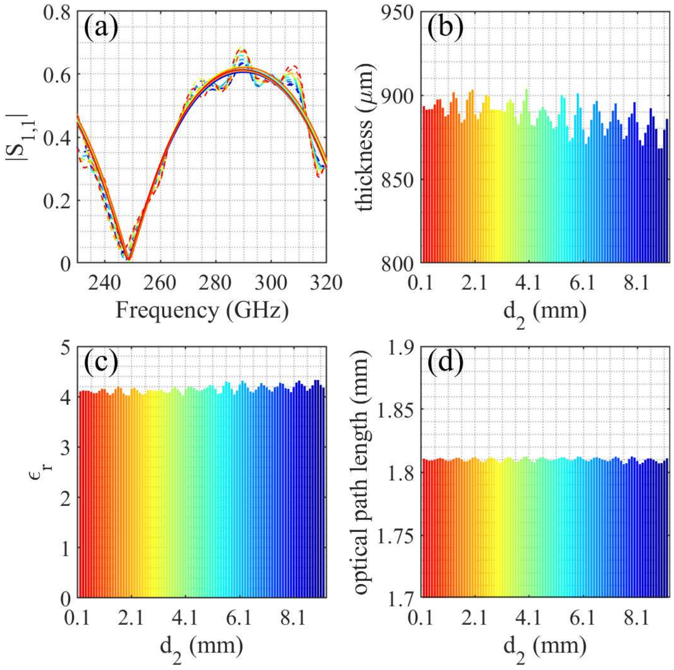

Fig. 3 (a) The reflectivity amplitude of the measured (dashed line) and its fits (solid data). Only data from nine positions are displayed. The jet colorbar is used as an indication of positions and matches the other subplots' convention (b) The extracted thickness as a function of dome position. (c) The extracted relative permittivity as a function of dome position (d) The optical path length as a function of position.

The fits yielded $\varepsilon = 4.1 \pm 0.1$ and $t = 0.89$ mm ± 0.005 mm in the $d_1 + d_2$ position and $\varepsilon = 4.16 \pm 0.1$ and $t = 0.885 \pm 0.01$ mm in the d_1 position as seen in Fig. 3(b) and (c). . Reference [4] reports fused silica permittivity values that span from 3.88 up to 3.99, which is somewhat lower than the extracted values of 4.1 - 4.16. Fused silica THz permittivity may vary depending on the fabrication process and these details may contribute to the differences of our extracted values and literature values.

The extracted optical path, computed as the product of the physical thickness and refractive index is reported in Fig. 3(c). The extracted optical path depends heavily on the estimated resonance frequency. In other words, the reflectivity minimum at ~245-250 GHz sets the optical path length. The optical length stays invariant for all the measurements, meanwhile variations in the amplitude maximum affect the permittivity, therefore the estimated thickness and the refractive index are inversely proportional. The possible error seems to be systematic as the measurements are approximately invariant to position. A possible source of error might be the radius of curvature mismatch between the calibration target and the quartz dome.

III. CONCLUSION

The axicon generated Bessel beam enabled amplitude reflectivity estimates of spherical dielectric quartz dome permittivity and thickness across a large optical axis range. We anticipate optics with relaxed positional constraints will aid in the clinical translation of THz corneal sensing by enabling detection of corneal edema and assessment of corneal hydration status in the presence of uncontrolled patient movement.

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