Alignment sensitivity of a WR-3.4 band quasioptical system for corneal water content sensing

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***Abstract*—A key barrier to clinical translation of THz reflection spectroscopy for corneal sensing is alignment sensitivity. Typical quasioptical systems are optimized for ideal alignment conditions and are thus not robust to errors in position between the focused wave front and corneal surface. Patient eyes are under continuous movement and, therefore, it is necessary to understand measurement fidelity degradation under cases of poor alignment. These issues are explored, via physical-optics simulations and experiments, for a two-lens quasioptical system operating in the WR-3.4 band. The misalignment tolerance is stricter on the optical axis than on the transverse plane. A 0.1 mm misalignment on the optical axis results in significant thickness and the water content measurement uncertainty and suggest an adjunct alignment verification system is necessary for clinical translation.**

I. INTRODUCTION

QUANTITATIVE measurement of corneal-tissue water content (CTWC), central cornea thickness (CCT), and tear-film thickness (TFT) via submillimeter-wave spectroscopy requires quasioptical systems for broadband, non-contact acquisition of corneal reflectivity [1, 2]. The cornea is a layered structure and this natural stratified medium sets up longitudinal resonant mode that can enhance extraction of permittivity and thickness of the cornea. Efficient coupling to longitudinal modes requires careful control of the incoming, focused THz wave front. If the incoming wave-front curvature matches the corneal anterior curvature, the observed longitudinal modes can be analyzed with plane-wave theory and Fresnel's reflection coefficients at the interfaces. Recent work with phantoms has demonstrated the efficacy of this approach in the WR-3.4 band using a pair of custom aspheric elements optimized for the wave-front matching [3].

While measurements of inert lab targets have produced promising results, the feasibility of *in vivo* measurements is unclear. Patients' bodies are under continuous, uncontrolled movement. This poses a challenge for THz spectroscopy and imaging. In this work, the alignment sensitivity of a WR-3.4 band quasioptical system for corneal-water content sensing was characterized using phantom targets. S_{11} was acquired for an ensemble of axial and transverse misalignments and the spectral effects were quantified. Experimental results were compared to physical-optics (PO) simulations.

II. RESULTS

A CAD model of the experimental system is displayed in Fig. 1 a. It consists of a corrugated horn coupled to a WR-3.4 VNA extender (VNAX), an aspheric collimating lens (L_1), an aspheric focusing lens (L_2), and a translation stage to modulate the phantom target position with respect to the beam waist. A ray-tracing diagram of lens L_2 is shown in Fig. 1 b with a surface profile that was optimized via cost functions defined on the surface of a spherical target. The VNAX was used to acquire complex S_{11} of the phantom target under the aligned case: spherical target center of curvature (CoC) positioned coincident with the focal point of L_2. This is labeled $(x, y, z) = (0, 0, 0)$. Transverse misalignment was first explored by translating the target in the x-y plane as indicated by the axes in Fig. 1 and monitoring S_{11} for every transverse displacement point $(\Delta x, \Delta y, 0)$. Axial alignment was explored by moving the target in the z-direction to axial displacement points $(0, 0, \Delta z)$. The results were compared to physical-optics simulations at WR-3.4 band (Fig. 2). E.g., misalignment from 0.30 to 0.45 mm along the x-axis results in a reduction from 2 to 5 % compared to the aligned S_{11} amplitude value.

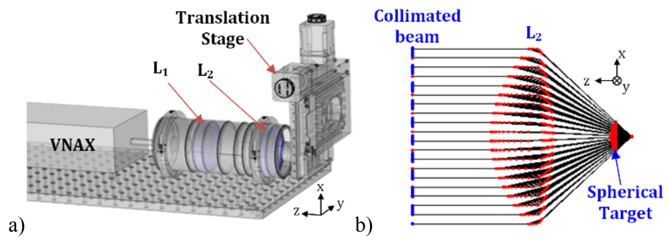

Fig. 1: a) Two-lens quasioptical system coupled to a WR-3.4 VNA extender and x-y-z translation stage. b) Ray-tracing diagram of lens L_2 with the spherical target center of curvature positioned coincident with the focal point of L_2.

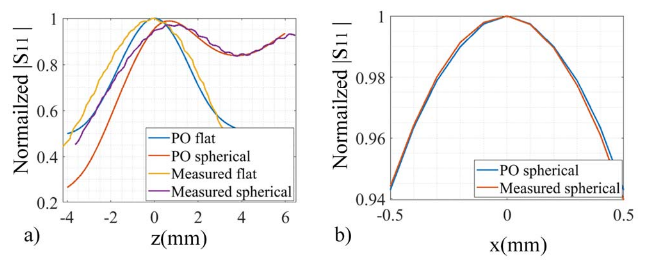

Fig. 2*:* a) PO simulation of the coupling coefficient and measured S_{11} for a spherical and a flat reflector translated along the z-axis. b) PO simulation of the coupling coefficient and measured S_{11} amplitude for a spherical reflector translated along the x-axis; all the data are normalized to the maximum value.

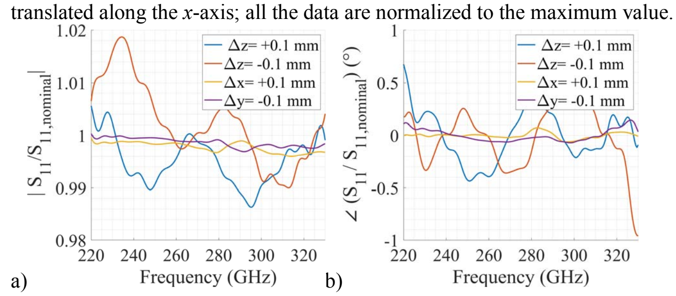

Fig. 3 Normalized a) amplitude and b) phase of the measured S_{11} with the spherical reflector at different locations.

Fig. 3 reports measured S_{11} as a function of frequency for varying the metal sphere axial positions (Δx, Δy, and Δz). It is seen that the varying position in x- and y-direction results in significantly less change in S11 than varying position in z-direction. Fig. 2 shows good agreement between the measurement results and PO, therefore it is appropriate to perform an additional sensitivity simulation based on physical

TABLE I

ESTIMATED CCT AND CTWC

ΔZ position (mm)	ΔY position (mm)	ΔX position (mm)	Estimated CCT (μm) (C)	Estimated CTWC (%) (C)	Estimated CCT (μm) (A)	Estimated CTWC (%) (A)
-0.1	0	0	587.971	82.310	408.299	82.271
0	0	0	494.400	77.996	490.830	77.997
0.1	0	0	478.086	73.844	542.867	73.995
0	0	0.1	504.835	78.012	644.922	77.946
0	0.1	0	507.221	78.002	647.441	77.942
0	0	0.5	533.175	77.200	627.268	75.268
0	0.5	0	530.240	76.880	628.678	74.920

Table I shows the estimated value for a cornea with a CCT of 500 μm and CTWC of 78% at different positions. The system of coordinates is centered at the gaussian beam waist of the aspheric lens L2. The CTWC and CCT were estimated by using only the amplitude of the signal (A) or by using both amplitude and phase (C)

optics and typical CCT and CTWC values. Cornea is known to be a mixture of collagen and water; thus its permittivity can be modeled with Bruggeman effective medium theory. The PO simulation were repeated for different frequencies and locations (misalignments) of the target in respect to the nominal position in front of the L_2 objective. The PO coupling coefficient was then compared with the reflection response of an EM stratified medium model. The model comprises 3 layers: (1) air, the path from the objective to cornea surface, (2) cornea of variable CCT and CTWC, and (3) a water half space. The water half space approximates the aqueous humor which is highly lossy and optically thick at submillimeter-wave frequencies. The CCT and CTWC are then estimated by minimizing the sum of square error between the PO coupling coefficient and the reflection response of the EM stratified medium model. Fig. 3 suggests that a 0.1 mm misalignment along the optical axis perturbs both the amplitude and the phase more than a 0.1 mm misalignment along the transversal plane. This result is in line with the cornea PO simulation results displayed in Tab I. A misalignment of 0.1 mm along the transversal plane causes a negligible error in the complex estimation of the water content, and an error of less 15 μm in thickness. Conversely, along the optical axis the water content is significantly confounded, from 78% to 82.3 or 73.8%, and the thickness has an error of more than a 100 μm. CCT is expected to be more challenging to estimate than CTWC as its estimation depends on non-trivial constructive/interference between anterior and posterior reflections. Interestingly, a positional error of 0.5 mm results in an absolute error of 1% in water content and an error of less than 40 μm in thickness. The CTWC and CCT were estimated both with amplitude only as well as with complex field. Table I suggests that amplitude information is sufficient for CTWC estimation. However, even at the nominal alignment position (0, 0, 0), it is not possible to obtain a reliable measurement of the CCT without knowledge of the complex field.

III. Summary

Alignment sensitivity of a designed Gaussian beam telescope is evaluated with simulations and measurements, which are well in line with each other's. The sensitivity to misalignment is especially pronounced in the axial direction and less significant in transversal direction. Our initial results emphasize the need for strict alignment tolerance with focused quasioptics, which may only be achieved by real-time *in vivo* measurements. Therefore, an adjunct system should be integrated to confirm optimal alignment and/or optics that tolerate misalignment should be developed.

References

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