Chapter 9
Development of an Instantaneous Phase-shifting Lensless Digital Holographic Otoscope for Quantitative Imaging of the Human Eardrum *in-vivo*

Daniel Ruiz-Cadalso, Jonathan O. Luiz, Jeffrey T. Cheng, and Cosme Furlong

Abstract We report the development of a digital holographic otoscope for high-resolution, quantitative imaging, providing insights into ear dynamics for improved diagnostics and treatment of hearing-related pathologies, with improved temporal stability over previously developed holographic otoscopes. This is achieved with the use of an instantaneous polarization imaging sensor, which contains a micro-array of four-pixel units of linear polarizing filters overlayed on the detectors, enabling the instantaneous recording of four phase-shifted holograms. Preliminary results of the realized holographic otoscope in the measurement of acoustically induced vibrations are demonstrated. The system is tested with artificial samples that are 5-10 mm in diameter and acoustically sensitive to the audible frequency range of humans. Single-shot holograms of the response to tonal stimuli of up to 20 kHz are recorded and computed in real-time using lensless reconstruction techniques, and vibration amplitudes of as small as 26 nm are quantified using stroboscopic imaging. The results show a significant improvement in the measurement stability of quantitative digital holographic otoscopes, promising the ability to characterize and diagnose eardrum pathologies in living subjects.

Keywords Digital holography · Eardrum · Otoscope · Polarization imager · Single-shot phase-shifting · Lensless reconstruction

Introduction

Digital holographic interferometry is a quantitative imaging method for extracting the optical phase of light and has been widely used for non-destructive testing (NDT) [1–3], measurement of micro- to nano-scale displacements [4], and vibration analysis [5, 6], among other applications and physical phenomena. As a high-resolution metrology technique, digital holography provides detailed full-field information about dynamic mechanical behaviors with sub-wavelength accuracy. However, it is highly sensitive to external disturbances [7], which introduce noise and limit its stability. Additionally, holographic imaging often faces challenges such as low imaging contrast, signal saturation on highly reflective surfaces [8], and computationally intensive post-processing that can hinder real-time applications.

Previous studies have explored the application of instantaneous phase shifting techniques [9-12] to overcome limitations associated with traditional phase-shifting digital holography. Instantaneous polarization imagers, which enable real-time phase retrieval through the acquisition of optically phase-shifted holograms in a single exposure, have proven effective in microscopy [13], nondestructive testing in aerospace applications [14], and acoustics and sound field imaging [10]. However, most implementations rely on transmission-mode imaging or highly specular reflective surfaces, where speckle noise is not significant. When applied to holography in diffuse reflection conditions, speckle noise becomes a major limitation for parallel phase shifting (PPS) [15], requiring new strategies to ensure robust phase retrieval and imaging stability.

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This paper presents the development of a novel digital holographic otoscope utilizing an instantaneous polarization imager, designed to improve temporal stability in clinical environments. The proposed otoscope is constructed and tested on artificial samples that mimic human eardrum acoustically driven vibrations, demonstrating its capability to measure nanometer-scale displacements in real time. The results validate the effectiveness of instantaneous phase shifting methods for highly stable quantitative imaging, paving the way for future in vivo applications for diagnosing hearing-related pathologies.

Materials and Methods

Digital holography

Digital holography is an optical technique used to extract the amplitude and phase of light. In order to properly extract these parameters, digital holography uses the superposition of two unique coherent wavefronts which stem from the same light source but have each undergone diverse conditions in their respective paths. The recorded complex field, $\Gamma = Ae^{i\Phi}$, is computed using the phase-shifted holograms as, $\Gamma = (I_0 - I_\pi) + i\left(I_{3\pi/2} - I_{\pi/2}\right)$. Since Γ can be rewritten as, $A\cos\Phi + i\,A\sin\Phi$, the optical phase can be extracted by [16],

$$\Phi = \arctan\frac{I_{3\pi/2} - I_{\pi/2}}{I_0 - I_\pi} \quad . \tag{1}$$

The optical phase calculated from a single reconstructed field would yield static information, and thus, changes to the optical phase are measured interferometrically via a double exposure (DE) method. In this method, a hologram of an "undeformed" reference state is recorded and subsequently subtracted from "deformed" states of the object. The phase difference values are wrapped within $[-\pi,\ \pi]$ (mod2π). The phase can be unwrapped, and directly converted to displacements, d, by [16],

$$d = \frac{\lambda}{2\pi\left[1 + \cos\theta\,\right]}\mathrm{unwrap}\left[\Delta\Phi\right] \qquad , \tag{2}$$

where d is the out-of-plane displacement, λ is the wavelength of the light source, θ is the angle between illumination and observation axes, and $\mathrm{unwrap}\left[\Delta\Phi\right]$ is the unwrapped optical phase.

Parallel phase shifting

Conventional methods require multiple phase-shifted holograms recorded over time, making them prone to external disturbances, whereas this paper employs parallel phase shifting (PPS) using linear polarizing filters on an imaging sensor to achieve instantaneous 4-step phase shifts, enhancing temporal stability by eliminating the need for multiple exposures. Figure 1 depicts the process of acquiring the four phase shifts using a polarized sensor [14]. After combining in a beam combiner, the reference and object beams are orthogonally polarized and then pass through a quarter wave plate (QWP) oriented at 45°, converting them into right-hand and left-hand circularly polarized light. The phase shifting for each beam at the polarized sensor can be described mathematically using Jones calculus. The recorded intensity becomes, $I = A + B\cos\left(\phi + 2\theta\right)$, where θ is the polarization filter angle.

Design of opto-electronic holographic otoscope

The design of the opto-electronic holographic otoscope is displayed in Figure 2. A continuous-wave single-longitudinal mode laser (Oxxius, Inc. L1C$^+$-AOM-532) generates a 200 mW beam with a center wavelength of 532 nm and an acousto-optic modulator (AOM) for stroboscopic capabilities. The beam is split into two and subsequently coupled into polarization-maintaining optical fibers. At the holographic otoscope head, the object beam is used to illuminate the sample, and the scattering field combines with the reference beam through a polarizing beam combiner. The polarization aspect of the optical combiner helps in ensuring orthogonality between each beam's polarization state and improving signal-to-noise ratios (SNR). Then, as described in Section 2.2, a rotatable QWP is placed.

Realized Holographic Otoscope

To achieve a compact and clinically viable digital holographic otoscope, the system design uses a Heine Beta 200 otoscope head, integrating key optical components while maintaining the ergonomic requirements for medical use. The setup, shown

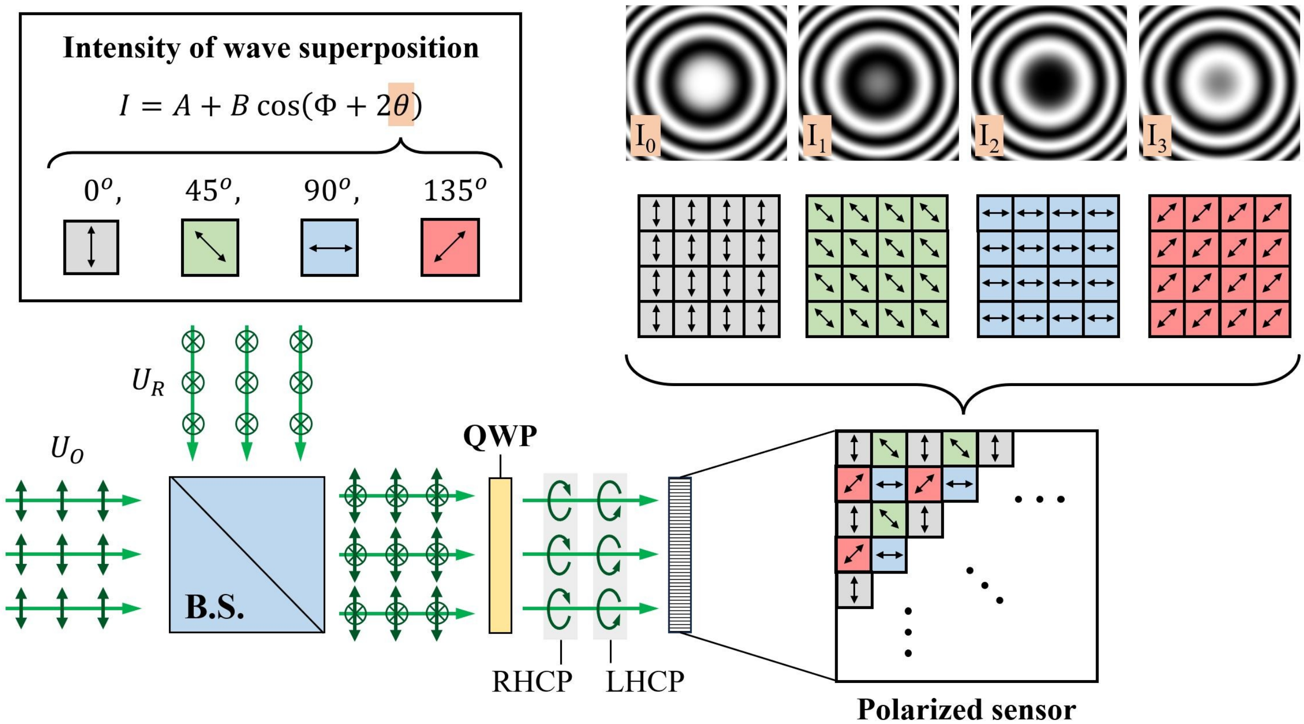

Fig. 1 Instantaneous phase shifting process by use of a polarized imaging sensor. The incoming reference and object beams are orthogonally polarized with respect to each other. With the use of a quarter waveplate (QWP), both beams are circularly polarized, one right-hand (RHCP) and the other left-hand (LHCP), which is needed for $\pi/2$-phase steps. Each step is acquired instantaneously by binning the recorded image. BS is beam splitter/combiner.

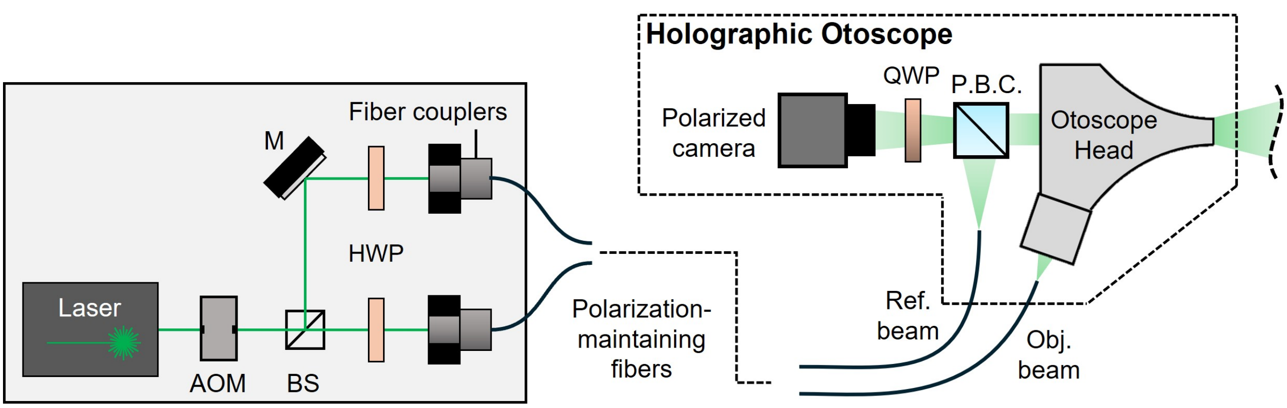

Fig. 2 Design of the opto-electronic holographic otoscope. Both interferometric beams are coupled into polarization-maintaining fibers. At the optical head, a polarizing beam combiner (PBC) is used to ensure the orthogonal polarization states. The QWP is placed between the camera and the PBC. M is mirror; HWP is half waveplate.

in Figure 3, features a 5 MP, 3.45 μm pixel, FLIR Blackfly USB polarized camera [17], with modified housing in order to fit within the confined spatial constraints of the setup. Illumination in the system is provided through the Heine otoscope's built-in optical fiber bundle, as shown in Figure 3a, which distributes light through an array of fiber cores, delivering diffuse illumination. The system's spatial resolution is validated using a high-resolution test target, shown in Figure 3b. The validated spatial resolution is approximately 18 lp/mm.

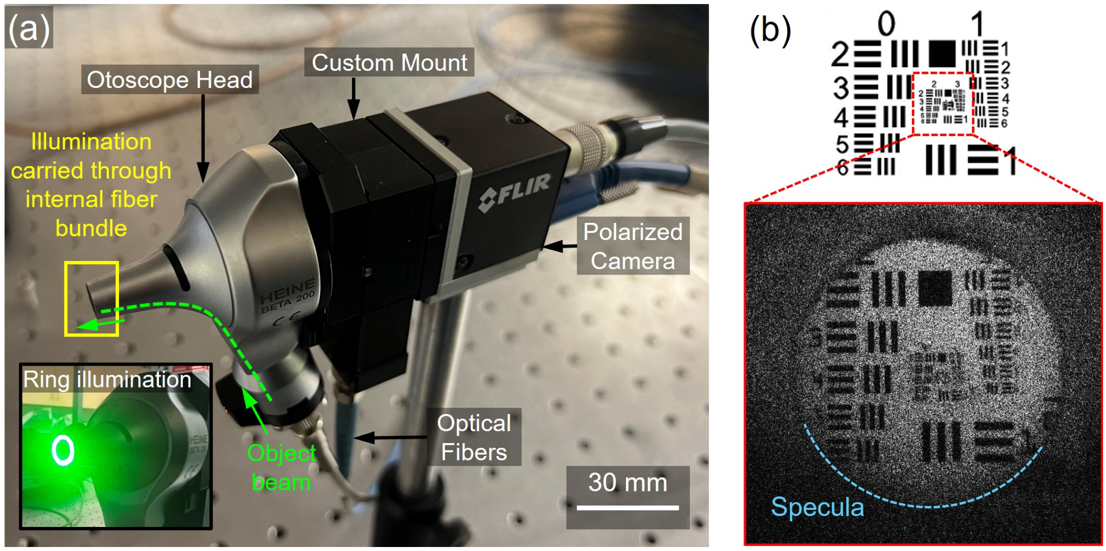

Fig. 3 Realized holographic otoscope, featuring a miniaturized design in order to achieve a clinically viable instrument: (a) realized system, which uses a Heine Beta 200, integrating key optical components while maintaining ergonomic requirements for medical use; and (b) quantitative imaging of a USAF 1951 resolution test target.

Representative Results

Acoustically induced vibrations on an artificial diaphragm

The performance of the holographic otoscope was evaluated by measuring acoustically induced vibrations of an artificial eardrum-like sample. The setup is shown in Figure 4, where the sample, which is 6 mm in diameter, is exposed to tonal stimuli within the audible frequency range of humans. Figure 4a presents the setup with the reconstructed amplitude image numerically focused on the sample. The wrapped optical phase maps describing the vibrational amplitudes were obtained for two frequencies, 3.2 kHz and 8.5 kHz, are shown in Figures 4b and 4c, respectively. The phase maps are unwrapped and converted to displacements, as described in Eq. 2, demonstrating the system's capability of capturing high-resolution acoustically induced deformations, down to 26 nm.

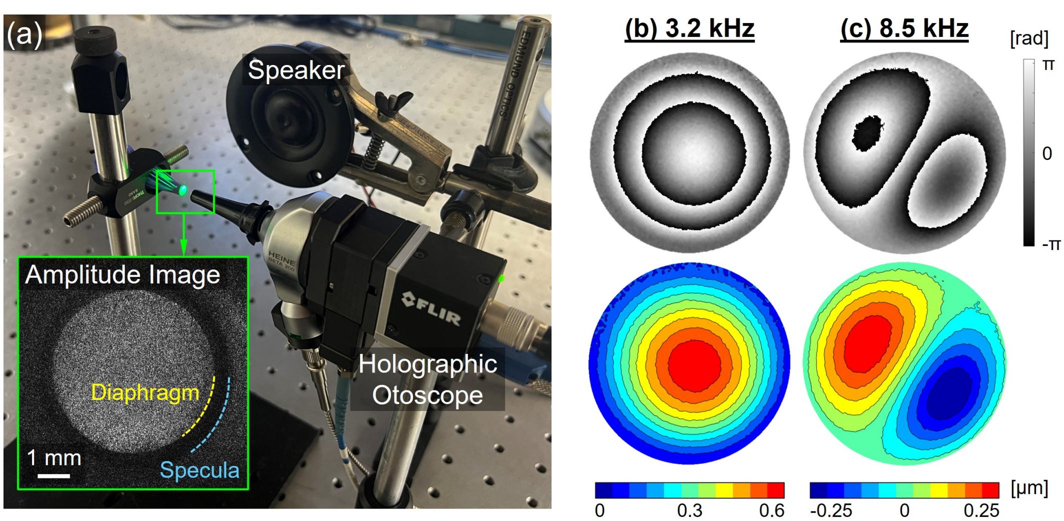

Fig. 4 Performance of the lensless digital holographic otoscope in the measurement of acoustically induced deformations: (a) setup with an artificial sample, 6 mm in diameter, a loading speaker, and the reconstructed amplitude image; (b) wrapped optical phase and amplitude displacement for 3.2 kHz; and (c) the same for 8.5 kHz.

Conclusions and Future Work

This work presents the development of a digital holographic otoscope utilizing an instantaneous polarization imager to improve measurement stability in acoustically induced eardrum vibrations. By integrating parallel phase shifting through a pixelated polarization sensor, the system effectively eliminates the need for multiple sequential exposures, significantly enhancing temporal stability and reducing motion-induced phase errors. The experimental validation on artificial eardrum-mimicking samples demonstrated the system's ability to capture real-time, single-shot holograms of high-frequency acoustic vibrations, with vibration amplitudes as small as 26 nm quantified. These findings suggest that the proposed otoscope is well-suited for noninvasive diagnostic applications in clinical environments.

Despite the promising results, several challenges remain. One major issue unique to digital holography and other laser-based optical techniques is the presence of speckle noise, which affects the accuracy of instantaneous phase shifting. While speckle size was controlled and larger than a polarization unit on the sensor, further optimization is needed to minimize degradation of phase shifting. Additionally, the miniaturization of the optical system remains a critical challenge for practical clinical deployment, as compact and ergonomic designs are necessary for routine in vivo examinations.

Future work will focus on testing the system on human subjects to assess its clinical viability for diagnosing hearing disorders and middle ear pathologies. Another key area of development will be improving the phase-shifting accuracy in the presence of speckle noise, possibly through adaptive filtering techniques or alternative polarization encoding strategies. Ultimately, the integration of this technology into clinical workflows could offer a powerful tool for quantitative, non-invasive evaluation of eardrum function, improving early diagnosis and treatment outcomes for patients with hearing impairments.

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