Towards Synthetic Wavelength Imaging through Multi-mode Fibers

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Abstract: This work exploits synthetic wavelength imaging to circumvent scattering artifacts and measure phase fronts emerging from multi-mode fibers. These fibers behave as single-mode fibers at synthetic wavelengths, enabling the possibility to acquire unspeckled wavefronts and range information.

Keywords: Fiber optics, holography, interferometry, synthetic wavelength imaging, computational 3D imaging.

1. Introduction

The use of multi-mode fibers (MMFs) for guiding images has received significant interest in recent years. The small cross section of MMFs, relative to multi-core fibers, makes them an attractive candidate for medical imaging applications like key-hole access with endoscopy, e.g., in neurology. In procedures such as brain surgery, the small cross section helps minimize the risk of tissue agitation near the imaging region [1].

MMFs are promising candidates for imaging, as they carry information from a scene in the form of multiple transverse modes. However, these modes become encoded during transmission resulting in a scrambling of transmitted information. Under coherent illumination, the interference of these different modes results in the formation of a speckle field. State-of-the-art techniques exploit various mechanisms such as phase conjugation [2] or estimation of the transmission matrix [3] to minimize the scrambling effects and transmit information.

In this work, we examine the possibility of recovering 3D range information from light guided through MMFs, which has the potential to unlock several novel applications in biomedical imaging, such as mapping of 3D tissue structures. To this end, we utilize the computational imaging technique, called *synthetic wavelength imaging* (SWI) [4-6]. We have used SWI in [4] to extract information from light fields with scrambled wavefronts introduced by scattering and to recover holographic field information. The approach leverages the slight phase differences between acquired speckle fields measured at two closely spaced optical wavelengths. The resulting *synthetic field* is selectively sensitive to large scale fluctuations introduced by the 3D object and is robust to the influence of scattering. The subsequent sections describe our approach and experimental results of acquiring an unspeckled, *synthetic* wavefront through MMFs.

2. Method and Results

SWI [4-6] uses pixel-by-pixel measurements of a scene captured at two optical fields, $E(\lambda_1)$ and $E(\lambda_2)$. These measurements are computationally combined to create a field $E(\Lambda)$ at a *synthetic wavelength* Λ which can be picked significantly larger than either of the two measured optical wavelengths λ_1 and λ_2:

$$\Lambda = \frac{\lambda_1 \cdot \lambda_2}{|\lambda_1 - \lambda_2|} \tag{1}$$

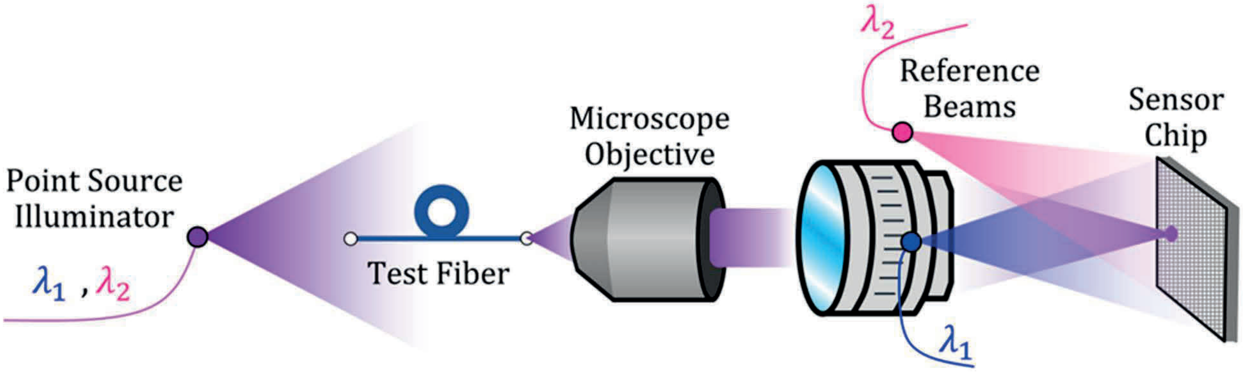

Fig.1. Schematic setup for the single-shot synthetic field capture through a multi-mode fiber.

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As Λ is mostly dependent on the difference between λ_1 and λ_2 it can be freely chosen, and the same Λ can be realized for different carrier wavelength pairs λ_1 and λ_2 across the spectrum. Since $\Lambda \gg \lambda_1, \lambda_1$, the influence of scattering disruptive at optical wavelengths, is significantly reduced. The concept is adapted here to measure synthetic phase $\phi(\Lambda)$ information through MMFs.

To explore the proposed SW imaging through a fiber system in a first experiment, we capture the fields at the two optical wavelengths simultaneously using the single-shot synthetic wavelength imaging approach introduced in [6]. The schematic of our setup is shown in Fig.1. We are approximating a self-illuminating point source by the tip of a fiber that guides the light from two tunable lasers operating at distinct carrier wavelengths λ_1 and λ_2. One end of our MMF (core diameter: $62.5\mu m$, length:$51.0cm$) is placed after the point source. The exiting light from the MMF is collimated by an infinity-corrected microscope objective. The collimated light is imaged onto the sensor using an imaging lens. Reference beams, located in the imaging lens plane, are mounted perpendicular to one another with respect to the optical axis. Thus, interferograms are created on the surface of the sensor between each reference beam and their respective carrier wavelength from the image of the exiting fiber tip. The respective optical fields $\mathrm{E}(\lambda_1)$ and $\mathrm{E}(\lambda_2)$ are demodulated in the Fourier domain (see [6] for more details) and the synthetic field is calculated via

$$E(\Lambda) = E(\lambda_1) \cdot E^*(\lambda_2) \tag{2}$$

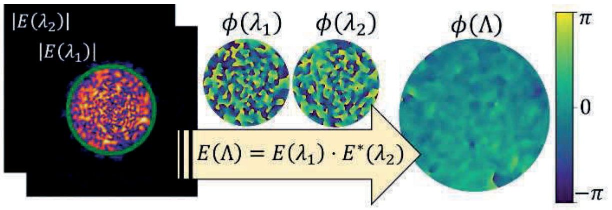

Fig.2. Mixing the captured optical fields at λ_1 and λ_2 creates our synthetic field $\mathrm{E}(\Lambda)$.

The result is shown in Fig. 2. It can be seen that the phase front of the *synthetic field* appears planar when exiting the fiber, while the two *optical phase fronts* show extensive speckle artifacts. Additionally, a phase offset correction was applied to mitigate residual low-frequency phase offset.

As the depth resolution of a potential ranging application through MMFs is directly proportional to Λ, we tested the robustness of the approach at different synthetic wavelengths. From prior experiments [4-6], it is known that longer synthetic wavelengths are more robust to phase changes from optical scattering. However, this comes at the expense of the ability to resolve fine structures. The synthetic wavelengths tested ranged from $0.4mm$ up to $62.3mm$. A selection of captured synthetic phase maps is shown in Fig. 3. For synthetic wavelengths less than $\sim 1mm$, we observe *synthetic speckle* [4,5] in the synthetic phase front, indicating that the MMF-induced optical path length difference became too large to be corrected.

3. Discussion and Conclusion

This work presents a computational approach to obtain unspeckled phase information for light guided through a multi-mode fiber – albeit at the lower resolution of a larger, synthetic wavelength. The smooth phase front captured in the synthetic field indicates that the MMF behaves as a single-mode fiber at the synthetic wavelength. Moreover, the synthetic field is robust to changes in the fiber transmission function from movements or changes in the fiber light path. We believe that our first results pave the way for a novel approach for absolute distance measurements through MMFs.

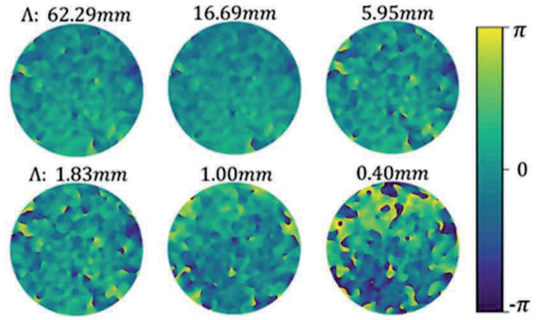

Fig.3. Captured synthetic phase maps $\phi(\Lambda)$ for different synthetic wavelengths.

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