

# Coherent, focus-corrected imaging of optical fiber facets using a single-pixel detector

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A novel imaging technique that produces accurate amplitude and phase images of an optical fiber facet using only a phase-only *liquid-crystal on silicon (LCOS) spatial light modulator (SLM)* and a single-pixel detector is presented. The system can take images in two orthogonal polarizations and so provides a powerful tool for modal characterization of multimode fibers, which is of increasing importance due to their burgeoning use in telecommunications and medical applications. This technique first uses a simulated annealing algorithm to compute a hologram that collects light from a small region of the fiber facet. Next, the fiber facet is automatically brought into focus using adaptive aberration correction on the SLM. Finally, a common-path interferometer is created using the SLM and the phase of the optical field at each pixel is determined. Finally, high definition amplitude and phase images of a ring-core refractive index fiber are presented as a proof-of-principle demonstration of the technique.

Recently, there has been an abundance of new applications for optical fibers supporting multiple spatial modes, evidenced by the increased use of few-mode and multimode fibers for high-speed telecommunications [1] and the use of highly multimode fibers for endoscopic medical imaging [2].

This has resulted in a need to accurately characterize the modal propagation in such fibers. To do this, it is necessary to control and/or detect the spatial distribution of the power and phase of light at least one facet of the fiber. For telecommunications applications, this has been achieved in a number of ways including using digital holograms to measure the transmission matrix of the fiber based on pre-calculated mode-profiles [3] and using measured differential group delay (DGD) to determine principal mode-groups [4]. In both cases it is assumed that the underlying propagation modes of the fiber are known and that minor deviations from these will simply result in mode-coupling or slight variations in time delay. For medical imaging applications, such characterization has been achieved by scanning a diffraction-limited Gaussian spot across the input facet of a fiber and then using a reference beam, transported by a separate optical path, to produce interferometric images of the fiber facet on a charge-coupled device (CCD) [5, 6]. This is a more general approach that can determine an orthogonal set of modes for an unknown fiber so may prove useful if adapted for emerging telecommunications applications.

However, for telecommunications applications it is noted that the interferograms produced on the CCD are

not an end in themselves as they are in medical imaging. The received light must be further demodulated, typically by a much higher-speed single pixel detector (e.g. a photodiode), to extract the transmitted data. Therefore, if a CCD is used it must be on a separate optical path following a beamsplitter. The images taken from it may not then accurately reflect the potentially quite different aberrations, in particular misalignment and defocus, found on the data path.

It is also increasingly common for telecommunications systems to contain *spatial light modulators (SLMs)* on the data path to enable spatial processing and switching [7]. As a result, it is then desirable to develop an imaging technique that can coherently image a fiber facet using only an SLM and a single-pixel detector without requiring a CCD.

This letter presents a novel method for measuring amplitude and phase (i.e. coherent) images of a fiber facet in two orthogonal polarizations using a single-pixel detector and a phase-only LCOS SLM without using a separate reference beam or a CCD. The set-up used is a dual-polarization optical correlator configuration with an SLM, shown in Figure 1. Light from the fiber facet is passed through lens  $\ell_1$  so that the Fourier transform of the image on the fiber facet appears on the SLM. A *polarizing beam-splitter (PBS)* is used to split the light into two orthogonal polarizations, one of which is rotated by a half-waveplate, so that each half of the SLM can analyze one polarization. The SLM then performs phase-only processing in the Fourier domain, after which the two polarisations are recombined in their original orientations. Finally, lens  $\ell_2$  performs the inverse Fourier transform on the processed light to form the desired re-

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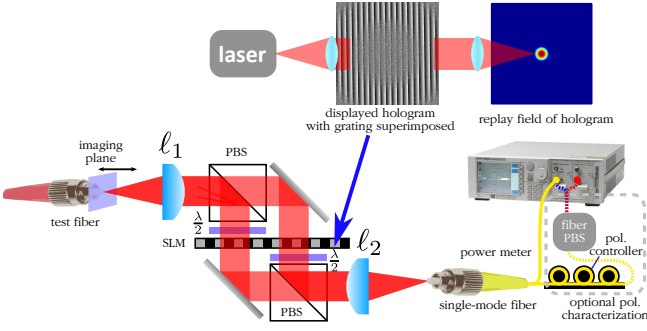


Fig. 1. Dual-polarization optical correlator set-up using an SLM to enable coherent imaging with a single-pixel detector – in this case, a single-mode fiber connected to an optical power meter. The SLM used is a phase-only LCOS  $1920 \times 1080$  Holoeye Pluto with a pixel pitch of  $8\mu\text{m}$  and 256 phase levels. The wavelength used is  $1550\text{nm}$  because of its widespread use in telecommunications systems.

play field on a *single mode fiber (SMF)* facet. In this case, the replay field is a Gaussian spot matched to the mode-field diameter of the SMF.

To use this set-up for imaging, a simulated-annealing algorithm is first used to compute a hologram which, when illuminated by a Gaussian beam of known size, will produce a small Gaussian spot in the far-field. The hologram is then used in reverse to measure light from a small spot on the fiber facet, without needing to change or move lenses. As a result, the optical path does not need to be modified for characterization purposes and so the system alignment can remain the same for subsequent transmission experiments. Next, a blazed grating is used to scan this spot across the fiber facet, measuring the power at each point. A parabolic grating, representing a second-order Zernike defocus correction polynomial, is then applied to shift the focal plane of the spot and images are taken for different defocus offsets. Using the Brenner technique from microscopy [8], the 2-D derivative is used to determine when the focal plane coincides with the fiber facet, i.e. when it is in focus. Following this, a common-path interferometer is created using the SLM in order to measure the phase of each point in the image. To do this two holograms are displayed simultaneously on the SLM, each sampling light from spots at different locations. By varying the absolute phase of one of the holograms and measuring the resultant interference at the detector, the relative phase of the field at the two points is determined. This process is repeated across the fiber facet, using the most powerful spot as a reference each time. This method of phase-measurement has the advantage that it avoids the need for a separate optical reference, which is often not practical in long telecommunications links.

Finally, experimental measurements of a ring-core fiber are presented that demonstrate the measurement of the amplitude and phase of modal profiles on the fiber facet. To the authors' knowledge, this is the first

demonstration of an autofocussing holographic single-pixel imaging system used for modal imaging of fibers.

In order to image the amplitude profile of a fiber facet using the set-up shown in Figure 1, it is first necessary to determine a hologram for display on the phase-only SLM that is able to sample light from a small spot on the fiber facet. Because the system is optically reciprocal, this is equivalent to determining a hologram that will convert a Gaussian beam incident on the SLM into a small spot in the replay field, as illustrated in Figure 2.

If the focal lengths of the two lenses and pixel pitch of the SLM are known, it is possible to compute the replay field of any hologram displayed at a given wavelength. Determining the hologram that produces a desired replay field, in this case a small spot, is then an optimization problem with two metrics: the quality of the hologram and the efficiency of the hologram. The quality is measured using a cross-correlation error function that quantifies deviation from the target replay field. The efficiency measures the amount of power that must be scattered in order to produce the desired replay field using a phase-only SLM. There is in general a trade-off between the two quantities.

Here, a simulated annealing algorithm is used to find the optimal hologram [9]. The resultant replay field is a Gaussian spot with a FWHM of  $5.2\mu\text{m}$  and a conversion efficiency of 8%, as shown in Figure 2. The size of this spot can be further reduced by using a shorter focal length lens for  $\ell_1$  of Figure 1 or an SLM with a smaller pixel pitch.

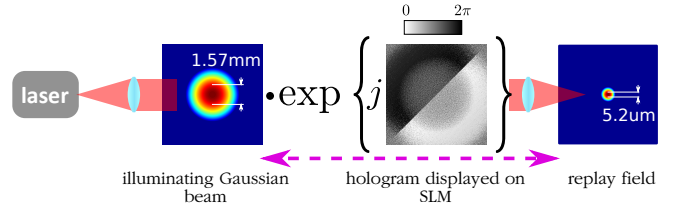


Fig. 2. Illustration of a hologram displayed on the SLM converting an incident Gaussian beam to a small spot in the far field, and similarly in reverse.

By superimposing a blazed grating on this hologram, it is possible to translate the replay field (i.e. the spot) across the fiber facet. A blazed grating in the Fourier plane corresponds purely to translation in the image plane and so the size of the translated spot remains the same. The result is spatial cross-correlation function between the image plane and the replay field. If the image has features that are relatively large compared to the spot size of  $5.2\mu\text{m}$ , then the resultant measurement is a good approximate amplitude image of the fiber facet, akin to correlation with a delta function. If not, then the cross-correlation will have the effect of applying a low-pass Gaussian filter to the image.

The light used here is produced by an *amplified spontaneous emission (ASE)* noise source at  $1550\text{nm}$  followed by a  $2\text{nm}$  bandpass filter. If broader bandwidth light

were used then the quality of the replay of the field would deteriorate thereby reducing image quality. However, this could be avoided by introducing a narrowband optical filter at the receiver, effectively taking an image at a particular wavelength.

Using this technique, amplitude images of the fiber facet can be produced. However, images produced using only this technique may include significant optical aberrations, the most notable of which is typically defocus. In order to observe a true image of the facet, these aberrations must first be corrected.

In order to produce sharp images of the fiber facet, it should ideally be placed at the focal point of the lens. The fiber mount can be aligned approximately by first inserting a single-mode fiber and ensuring the resultant beam after the lens is collimated. However, when the single-mode fiber is replaced with the target fiber, the new facet is not always exactly at the focal point due to slight variations in connectors and in the fiber. Furthermore, quadratic phase aberrations are introduced by the fact that the SLM is not placed exactly at the focal point of either lens due to space constraints [10]. Fortunately, it is possible to correct for this defocus aberration by superimposing a quadratic Zernike polynomial phase mask on the hologram, in addition to the blazed grating [11]. The composite phase-mask,  $A$ , displayed on the SLM is then:

$$A = \arg \left\{ e^{iP} e^{i(a_x Z_1^{-1} + a_y Z_1^1)} e^{ia_z Z_2^0} \right\} \quad (1)$$

where  $P$  is the hologram for display,  $a_x$ ,  $a_y$  and  $a_z$  are coefficients representing shifting of the replay field in the  $x$ ,  $y$  and  $z$  axes respectively, and  $Z_m^n$  is the order  $m$  Zernike polynomial defined from the centre of  $P$ . By scanning in the  $x$ ,  $y$  and  $z$  axes, it is possible to take images at different levels of defocus, as shown in Figure 3 for a ring-core fiber. This is equivalent to taking images from different planes in the  $z$ -axis.

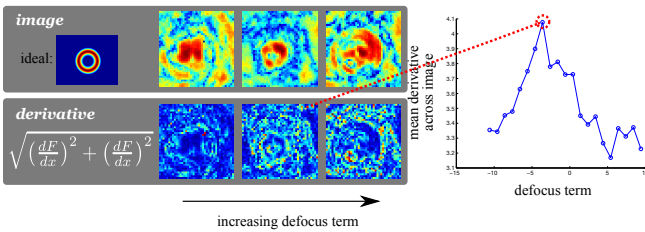


Fig. 3. Illustration of the automatic focus detection using the Brenner algorithm [8]. A ring-core fiber is used so that a defined ring shape can be observed when the correct focal plane is found [12].

Although the correct focal point may be visually clear if the target image is known, it is preferable to have an automatic detection algorithm to cover a broader range of scenarios. Given this, a modified version of the Brenner algorithm, which makes use of 2-D derivatives, is

used to calculate a metric of the quality of focus correction [8]:

$$M = \sum_{u,v} \sqrt{\left( \frac{\partial F(u,v,a_z)}{\partial u} \right)^2 + \left( \frac{\partial F(u,v,a_z)}{\partial v} \right)^2} \quad (2)$$

where  $M$  is the metric representing the quality of the defocus correction term  $a_z$  and  $F(u,v,a_z)$  is the image taken at defocus level  $a_z$  in terms of pixel coordinates  $u$  and  $v$ . It can be seen from Figure 3 that there is a clear peak, corresponding to the appropriate defocus correction that brings the fiber facet into focus.

Once the defocus has been corrected, a common-path interferometer is created using the SLM to enable measurement of the relative phase of each pixel in the image [13]. In order to achieve this, two holograms that measure the power from single spots are superimposed, each with a different blazed grating – that is, each measuring light from a different spatial point on the fiber facet. The absolute phase of each hologram can then be adjusted, to give a total phase mask of:

$$A_{\text{comp}} = \arg \left\{ e^{iP} e^{i(a_x Z_1^{-1} + a_y Z_1^1)} e^{ia_z Z_2^0} + e^{i\phi} e^{iP} e^{i(b_x Z_1^{-1} + b_y Z_1^1)} e^{ia_z Z_2^0} \right\} \quad (3)$$

where  $P$  is the hologram for the spot,  $a_x$  and  $a_y$  determine the  $x$  and  $y$  positions of the reference spot,  $b_x$  and  $b_y$  determine the  $x$  and  $y$  positions of the spot for which the phase is to be measured, and  $\phi$  is the relative phase between the spots. By adjusting  $\phi$ , it is possible to interfere the light from the two spots on the single pixel detector, as shown in Figure 4. Here,  $\phi$  is set to 16 equally-spaced values from 0 to  $2\pi$ . A sine curve is then fitted to the resulting interferometric power measurements to estimate the relative phase relationship between the two spots. In each case, the reference pixel used is the most powerful pixel as measured during the amplitude-only scan discussed previously. Variations of this technique have been used previously to measure the relative phase of different propagation modes in a fiber [3] and to phase-match modal excitations for fiber characterization [5].

In order to demonstrate this technique, amplitude and phase images of the facet of a 2m patchcord with a ring-core refractive index profile were taken [12]. A second holographic mode launcher, identical to the set-up in Figure 1 except in reverse, is used to excite particular modes of the fiber. In this case, the LP41a mode and its associated vortex or *orbital angular momentum (OAM)* mode (i.e. LP41a +  $i$ LP41b) are launched as test cases. Figure 5 shows the measured amplitude and phase images at the output facet of the fiber. It can be seen for the amplitude images that there is a good match to what is theoretically expected with 8 individual spots observed for the LP41a launch and an annulus observed

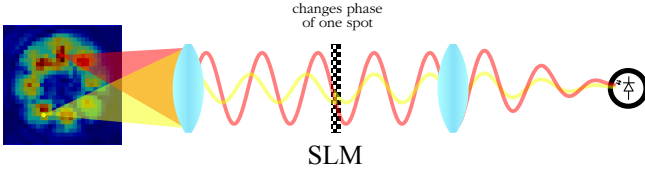


Fig. 4. Illustration of the technique used to measure the optical phase at each point on the fiber facet by creating a common-path interferometer with the SLM. It should be noted that the path-length difference between the two spots introduces negligible phase shift because the image is very small (1 pixel  $\approx 1.5\mu\text{m}$ ) compared with the distance from the lens to the SLM ( $\sim 700\text{mm}$ ).

for the vortex launch. The phase images also match well with what is theoretically expected with the vortex launch producing a linearly varying phase with a period of  $\frac{\pi}{2}$ , while the LP41a launch produces a phase profile alternating between  $-\frac{\pi}{2}$  and  $\frac{\pi}{2}$ . It is thus demonstrated that this technique is able to successfully produce phase and amplitude images of a fiber facet.

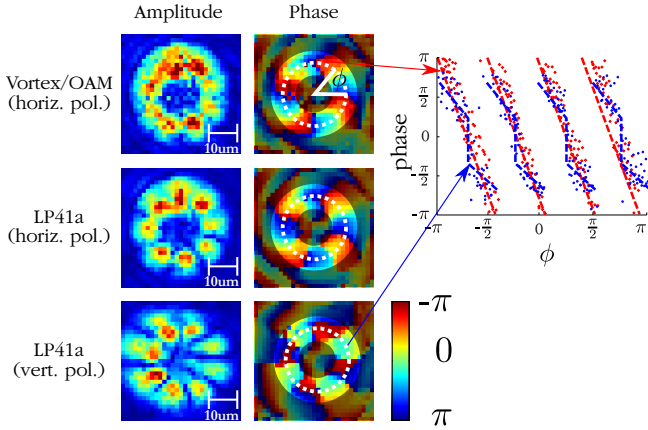


Fig. 5. Measured results showing amplitude and phase images taken from the facet of a ring-core refractive index fiber in two polarizations.

It should be noted that by introducing a polarization controller and fiber PBS, shown as optional additions in Figure 1, it is possible to create an interferometer between the two polarizations and hence measure the full polarization state [3]. However, any small differences between the optical paths for each polarization will affect the measured polarization state, as will polarization mode dispersion in the output SMF. This still allow a relative measure of polarization state and could be eliminated by precise pre-calibration of the system or use of very high precision (sub micron) components.

The main drawback of this technique is speed, which in this case is limited by the speed at which data can be read from the power-meter – about 10 readings per second, meaning that each  $29 \times 29$  phase image takes about 20 minutes to capture. However, high-speed photodiodes are readily available that could significantly re-

duce this time so that the switching speed of the liquid crystal in the nematic SLM would become the limiting factor. In that case, a single image would take less than 4 minutes. This is slower than an interferometric CCD measurement, but has the advantage of not requiring a separate optical path. By using a ferroelectric SLM or a digital micromirror device the capture time could be further reduced to the order of seconds due to faster switching speeds.

A novel dual-polarization coherent imaging technique that uses only an SLM and a single pixel detector is detailed and then shown to produce accurate images of both the amplitude and phase of the optical field on a fiber facet of a ring-core fiber. The technique makes use of a simulated annealing algorithm to generate appropriate holograms for imaging, then uses the Brenner algorithm to determine the correct focus. Finally, a common-path interferometer is constructed using only the SLM in order to accurately determine the optical phase for each measured pixel.

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