Complete measurement of fiber modal content by wavefront analysis

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Abstract: We propose and demonstrate the use of a wavefront analyzer based on lateral shearing interferometry to characterize the modal content of multimode fibers. This wavefront measurement technique is applied to large mode area fibers, and allows us to recover both the intensity and relative phase of each guided mode. This constitutes an innovative complete characterization of the beam, and might be used as a probe in deterministic active wavefront correction techniques.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (140.3510) Lasers, fiber.

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1. Introduction

Optical fiber lasers and amplifiers are nowadays established in many applications as efficient and reliable high power sources. However, nonlinear effects still induce limitations in the achievable output power of these systems, especially in pulsed operation. Since nonlinear effects are enhanced by the strong confinement of the optical field in the guided mode of the fiber, a natural way to increase the appearance threshold of those detrimental effects is to increase the fiber core size. However, as the core diameter is increased, it becomes difficult to maintain strictly transverse single mode operation. As a consequence, most high power fiber systems are based on large mode area (LMA) fiber designs that are not strictly single mode, but are operated in a quasi single mode regime. The output modal content depends on several experimental conditions such as the geometrical arrangement of the fiber (coiling), the mode-dependent gain behavior of the fiber, and the input excitation. This content determines the spatial quality of the output beam, and the ability to use it in various applications.

It is therefore highly desirable to precisely characterize the modal content at the output of LMA optical fibers, and several methods have recently been proposed and demonstrated. The intensity profile at the output of the fiber is the easiest measurement to perform. By measuring this intensity profile in two distinct planes, it can be shown that the modal weight of the different modes composing the multimode beam can be retrieved [1]. This method is particularly interesting to access the modal content of the multimode beam but do not allow the complete reconstruction of the electric field since the phases of the modes cannot be retrieved. The S^2 imaging technique [2] consists in exciting the fiber under test with a broadband source. The output beam is then spectrally and spatially resolved to observe the spatial dependence of mode interferences. This method allows the measurement of the power contained in each mode with a very large dynamic range. A recent improvement of this technique showed that the relative phase between the modes and the spatial phase profiles of each mode can also be obtained [3]. However, it requires the use of a broadband source and cannot be used to characterize the modal content of the beam during nominal operation. It also requires the assumption that one of the mode is dominating in terms of power content. A similar interferometric method in the time domain has also been demonstrated recently and led to similar results on the determination of modes intensity profiles and relative phases [4]. Contrary to the S^2 imaging technique, there is no need for a predominant mode propagating inside the fiber as the modes are measured by comparison with a reference beam propagating in air. However, this technique still requires the use of a low-coherence illumination source.

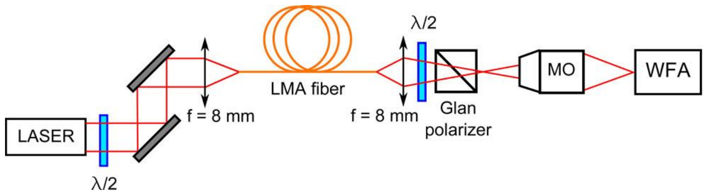
An alternative method consists in retrieving the wavefront of the beam exiting a multimode fiber by considering only the intensity profile [5]. Two measurements in two distinct planes are done and an iterative Gerchberg-Saxton algorithm is used to retrieve the wavefront. This technique gives access to both the intensity and the relative phase of each mode composing the multimode beam, but the use of an iterative algorithm is time-consuming and difficult to implement experimentally. A similar technique based only on intensity profile measurement has been recently applied at a high repetition rate to analyze the instabilities in high power fiber lasers [6]. Eventually, another technique has been proposed recently where computer generated holograms are used to retrieve the modal decomposition of a multimode beam [7]. This method has been demonstrated experimentally and showed excellent results for reconstructing complex multimode beams and obtaining their modal decomposition. Again, retrieving the intermodal phase remains difficult and relies either on the use of phase retrieval algorithms or on the addition of an interferometric information on the modal analysis element containing the hologram. This last method needs the fundamental mode to be predominant, which is not always the case for multimode beams.

In this work, we demonstrate the use of lateral shearing interferometry to characterize the output beam of LMA optical fibers. This wavefront measurement technique consists in analyzing the interference pattern generated by several replicas of the incoming wavefront that are propagating at an angle [8]. The replicas are generated by a diffractive optical element in a non chromatic way, which allows the characterization of large spectral bandwidth beams [9] and applicable to ultrashort-pulsed laser [10]. The wavefront is subsequently projected onto the fiber mode basis, allowing the retrieval of both the intensity and relative phase of each mode. We demonstrate the technique by first characterizing several isolated modes of a 30 µm core LMA fiber using selective injection. Then, we show that it is possible to measure both the power content and relative phase between modes for a complex output beam consisting of several modes. Our technique requires a single measurement and a standard phase reconstruction algorithm. In this work, a single polarization state is analyzed. To analyze completely the modal polarization state, a full vectorial analysis should be performed [11]. Since the wavefront characterization could be performed at video rate and provides the relative phase between modes, this fiber modal analysis might be used as a building block for closed loop deterministic wavefront correction techniques.

2. Experimental setup and procedures

2.1 Experimental setup

The experimental setup used to perform the modal decomposition is shown in Fig. 1. The LMA step-index fiber has a core diameter of 30 µm and a numerical aperture of 0.07, therefore supporting 6 LP modes at 1064 nm. Four of these modes (the LP_{11}, LP_{21}, LP_{31} and LP_{12} modes) are degenerated, leading to 10 distinct intensity patterns possible for all the modes. The degenerated modes are called either "even" or "odd" modes, depending on the expression of their angular component [12]. The fiber is passive, 5 m-long, and is not polarization maintaining. A linearly polarized laser source producing 800 ps pulses at 40 kHz with an average power of 250 mW is used to illuminate the fiber and excite several modes. The beam is coupled with a lens of focal length 8 mm and passes through a half-wave plate before injection. The end facet of the fiber is imaged on the wavefront sensor with an optical system composed of an 8 mm focal lens and a x10 microscope objective. A half-wave plate and a Glan polarizer are used to select only one polarization direction.



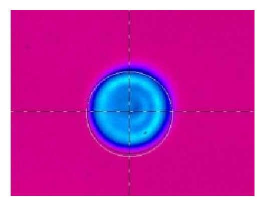


Fig. 1. (Left) Experimental setup. MO: microscope objective. WFA: wavefront analyzer. (Right) Calibration intensity profile obtained by coupling a low coherence light source to the fiber.

The wavefront analyzer we used is a SID4-HR manufactured by Phasics. This analyzer relies upon the use of lateral shearing interferometry [13]. The incident beam is split into four identical replicas which propagate with a different angle. After few millimeters of propagation, the interference pattern between these four replicas is recorded on a CCD camera and leads to the spatial phase gradient of the incident beam. The provided software integrates this gradient map and allows accessing the wavefront of the beam. The device allows a measurement of the wavefront on a 300x400 grid with a total aperture of 8.9x11.8 mm².

The fiber is placed on a 3 axis positioning stage and an additional mirror is used before injection to adjust the angle of the beam coupled to the fiber. In the geometrical approach, one can consider that each mode corresponds to a specific propagation angle. Therefore, by adjusting the position of the input mirror, it is possible to excite a limited combination and even a single mode of the fiber.

The wavefront analyzer used in this experiment allows measuring the intensity $I_{mes}(x,y)$ and the phase $\Phi_{mes}(x,y)$ of the multimode beam coming out of the fiber. The measured electric field can therefore be retrieved as:

$$E_{mes}(x,y) = \sqrt{I_{mes}(x,y)}.\exp(i\Phi_{mes}(x,y)). \quad (1)$$

This measured field is decomposed on the theoretical LP modes E_{LPjk} supported by the fiber. The calculation of these theoretical modes requires the knowledge or the measurement of the refractive index profile of the fiber under test. Since this actual profile is difficult to obtain, we considered in this proof of principle demonstration that the fiber is an ideal step-index one. The decomposition is obtained by simply projecting the measured field on the modes. The projection coefficients are given by:

$$c_{jk} = \frac{\iint E_{mes}(x,y).E_{LPjk}^{*}(x,y)\,dxdy}{\sqrt{\left(\iint \left|E_{mes}(x,y)\right|^2 dxdy\right)\left(\iint \left|E_{LPjk}(x,y)\right|^2 dxdy\right)}} \quad (2)$$

These coefficients are complex and can be written:

$$c_{jk} = c_{Pjk}.\exp(i\Phi_{jk}), \quad (3)$$

where c_{Pjk}^{2} is the modal weight of the LP_{jk} mode and Φ_{jk} is its phase. The initial field can be reconstructed by using the relation:

$$E_r(x,y) = \sum_{1}^{N} c_{jk}.E_{LPjk}(x,y). \quad (4)$$

In theory, the reconstructed field E_r and the measured field E_{mes} are equal. In practice, they can differ due several reasons:

- there is noise on the measured intensity and phase maps and imperfections in the experimental setup
- the theoretical modes used for the decomposition can differ from the actual modes supported by the fiber, due to uncertainties on the knowledge of the actual opto-geometric parameters of the fiber

Therefore, the comparison of the reconstructed field and the measured one gives direct information on the validity of the intensity and phase measurement. To estimate the accuracy of the reconstruction, we define the error between the measured and the reconstructed fields by:

$$\Delta = \frac{1}{N_{pixels}} \sqrt{\sum_{Npixels} \left|E_{mes} - E_r\right|^2}. \quad (5)$$

Such a definition has the advantage of being very sensitive to small reconstruction errors. It can be used directly during the calibration step to adjust the centering of the device (see section 2.2). However, the error values obtained are not bounded. Therefore it can be useful to define another bounded error coefficient, in terms of a correlation coefficient between the measured and the reconstructed field:

$$C = \max\left|\int E_{mes}(r'-r).E_r^{*}(r')dr'\right|. \quad (6)$$

Both errors will be mentioned in the experimental results presented in section 3.

2.2 Calibration procedure

The fact that the reconstructed field is obtained directly by projecting the measured field on the theoretical one makes the whole reconstruction sensitive to the centering of the measured profile with respect to the theoretical one. For example, the projection of an off-centered fundamental mode on the theoretical modes can lead to non-zero coupling coefficients on higher order modes. To avoid this, a calibration of the position and the size of the fiber must be made. This is done by coupling the light coming from a halogen lamp to the fiber. Due to the low coherence of the light source, the fiber can be considered as a light pipe and no modal structure is observed. The light fills the entire core area of the fiber and one can easily determine the position and the size of the fiber core (Fig 1. right). The precision of such a centering method can be estimated by looking directly at the reconstruction error given above. Indeed, we computed the theoretical error due to the projection of an LP_{02} mode on itself with a slight lateral misalignment. The result of this computation is shown in Fig. 2 left. The maximum possible error for this case is 0.028 and a slight misalignment of 3 µm results in an error of 0.011, which is higher than the reconstruction errors presented further.

The choice of a proper reference beam is also an important issue. Indeed, an absolute wavefront measurement on the multimode beam is difficult to perform as the optical magnification system we use suffers from aberrations with amplitudes stronger than the weak phase defects due to the multimode structure we want to measure. To overcome this, a reference beam with a plane wavefront is needed. In our case, we used the same fiber in which we excited selectively a mode close to the fundamental one with the help of the input mirror and the positioning stage (Fig. 2 right). Therefore, the accuracy of the measurement is limited in our case to our ability to selectively excite the fundamental mode. Such a method can be very difficult to implement on a highly multimode fiber. In such cases, an alternative phase calibration method could be applied for example by illuminating the whole optical system and wavefront analyzer with a beam coming out of a single-mode fiber placed on the same micro-positioning stage than the multimode fiber under analysis, prior to the multimode measurement, or to put a cleaning pinhole at the output of the multimode fiber to generate a quasi plane reference wave.

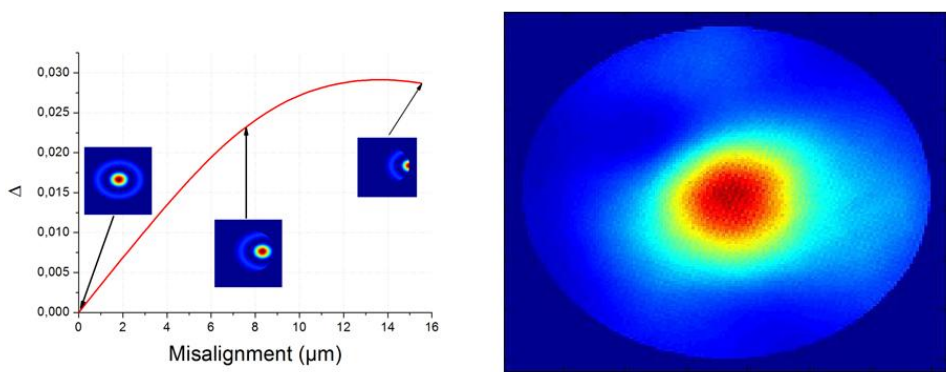


Fig. 2. Left : theoretical reconstruction error induced by a misalignment of a LP_{02} beam. Right : intensity profile of the experimental reference beam.

2.3 Influence of the reference beam

As stated in the previous paragraph, the accuracy of the measurement depends on the reference wave chosen. Since it is difficult to selectively excite the fundamental mode of the fiber, it is interesting to study the impact of a non perfect reference mode on the modal reconstruction. We simulated a beam reconstruction where the reference field is composed of 90% LP_{01} mode and 10% LP_{11} mode with a random relative phase between the modes (Fig. 3). A 5 µm waist off-centered Gaussian beam is first projected on the theoretical modes supported by the 30 µm diameter LMA fiber. After propagation, we obtain an output beam to be characterized by the measurement setup (Fig. 4 top). This beam will be called the "actual" beam. The phase of the non-perfect reference beam presented in Fig. 3 is subtracted from the phase of the actual field and the amplitude remains unchanged. This simulates what we would measure in practice with the wavefront analyzer and will be called the "measured" beam (Fig.

4 middle). This simulated "measured" beam is finally decomposed on the theoretical modes supported by the fiber and creates the "reconstructed" beam (Fig. 4 bottom). Several conclusions can be drawn from these results:

- the intensity of the reference beam given in Fig. 3 appears to be clearly off-centered with respect to the core of the fiber. This centering defect can be detected and corrected with our centering method described above.
- no significant change is observed in the intensity and phase profile in the core region, i. e. in the region where the phase is actually measured by the wavefront analyzer. To quantify this, the reconstruction error as defined in equation (5) is $8.6.10^{-4}$, which is well below the experimental values presented further.
- the most important issue is the error with respect to the actual multimode field coming out of the fiber, before subtraction of the reference field phase. This error is not measurable by experimental means and therefore represents the absolute limitation of our measurement. In this simulation, the value of the error between the reconstructed field and the actual field, due to the non perfect reference beam, is $1.4.10^{-3}$, which is still below the typical experimental reconstruction errors presented further, and still allows good modal content analysis.

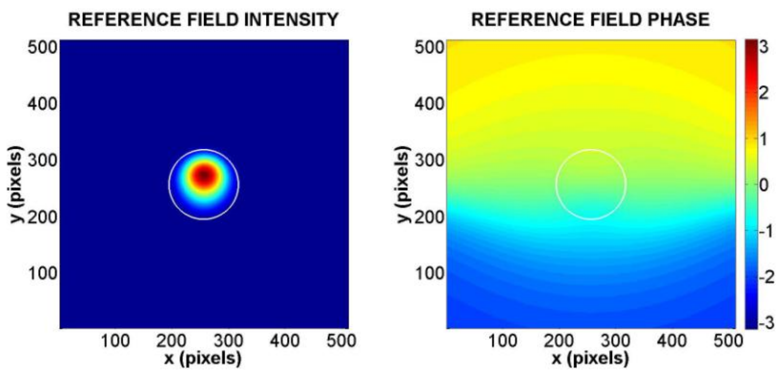


Fig. 3. Simulated reference field composed of 90 % LP01 and 10 % LP11 with a random phase. The white circle indicates the dimensions of the fiber core.

These results show that the sensitivity of the reconstruction procedure with regard to the reference beam seems to be low when the degradation of the reference beam is limited. When several modes in a high proportion compared to the fundamental one are composing the reference beam, the reconstruction loses its validity; but such cases can be easily detected by looking directly at the intensity profile of the reference beam.

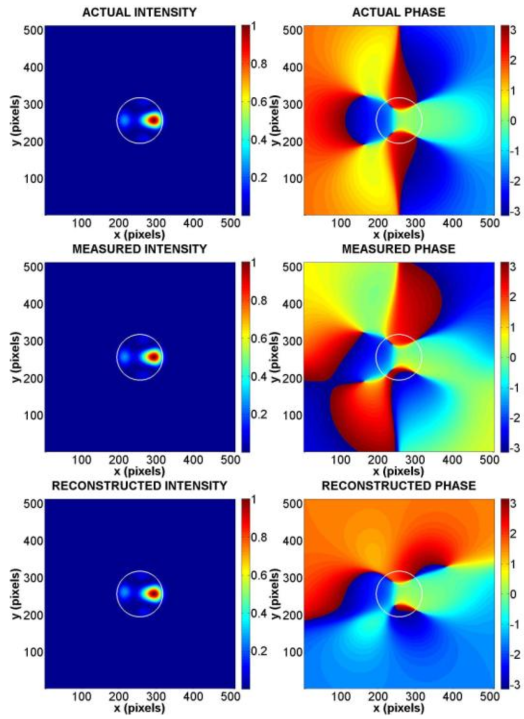


Fig. 4. Simulated reconstruction of the multimode beam with subtraction of the reference field phase. Top: simulated actual beam (no reference phase subtraction) at the output of the fiber. Middle: simulated measured beam (reference phase subtracted). Bottom: projection of the measured beam on the theoretical modes supported by the fiber.

3. Results and discussion

The experimental setup described above is used to retrieve the modal decomposition of slightly multimode beams. In the experimental results presented below, the intensity profile is slightly cropped to avoid low intensity zones on the surrounding of the measurement pupil. In these regions, the spatial phase is not well defined and it can lead to incorrect wavefront measurement.

In a first experiment, we excite a mode superposition as close as possible to the LP_{02} mode. As described previously, we use the injection mirrors to couple the beam into the fiber with a slight angle in order to excite only one mode. The resulting intensity and phase profiles measured with the wavefront analyzer are given in Fig. 5(a). The measured intensity profile is composed of a central lobe surrounded by an outer ring. This profile is very close to the theoretical one. The phase profile also shows a step close to $\pi/2$ between the central lobe and the surrounding ring. This difference with the expected π step for the LP_{02} mode comes from the fact that the excitation is not pure: a small amounts of other modes are excited, whose relative phases lead to such a phase step value. One can also note a narrow region between the central part and the ring where the phase drops down to $-\pi$. This abnormal behaviour corresponds to the region where there is no intensity. This region is therefore very sensitive to noise and the phase is not well defined. The measured electric field can be obtained from these measured intensity and phase profiles and is projected on the theoretical modes of the fiber (Fig. 5(b) and (c)). As expected, the multimode beam is mainly composed of the LP_{02} mode by more than 80 %. The field can be reconstructed from this decomposition and the corresponding intensity and phase profiles are given in Fig. 5(a) bottom. These profiles are very close to the measured one.

The error between the measured and the reconstructed fields as defined in the previous section is Δ = 0.0065 (C = 0.80). For comparison, we projected the measured field on the theoretical LP_{02} mode only. The reconstruction error is 0.011 in this case. This shows that even if the amount of modes excited apart from the LP_{02} is small, these modes play an important role on the reconstruction and do not result from measurement or reconstruction errors. In conclusion, the reconstructed field is in very good agreement with the measured one, which indicates the validity of the measurement.

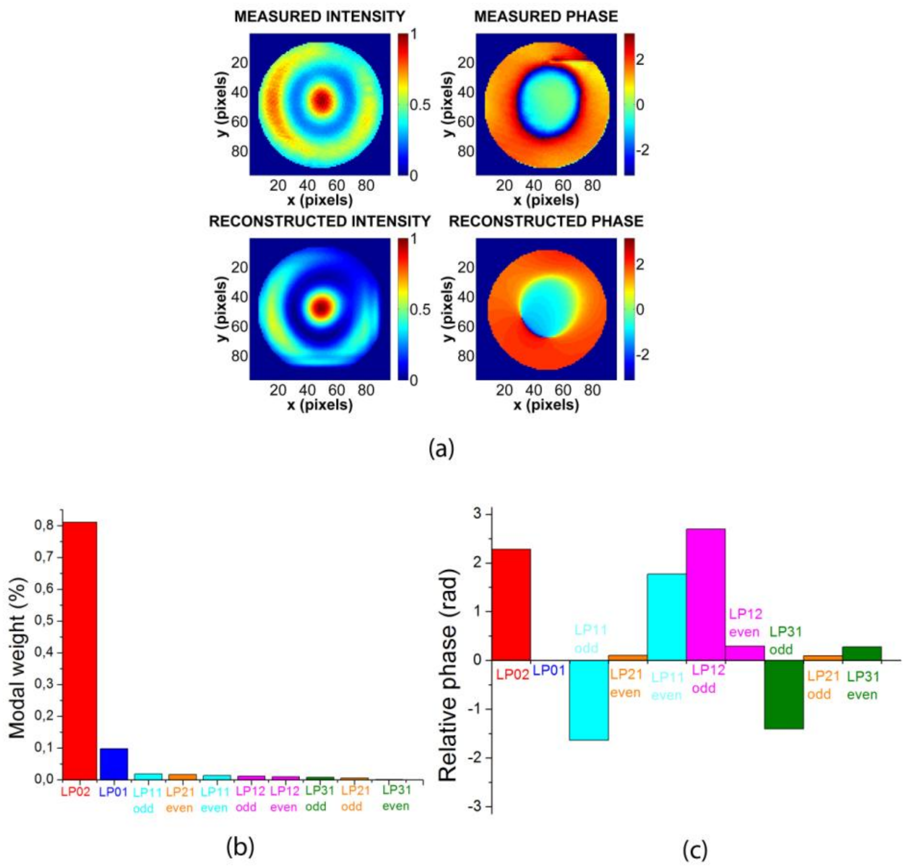


Fig. 5. (a). Top: Measured intensity and phase profiles at the output of the multimode fiber with the wavefront analyzer. The intensity is normalized and the colour scale for the phase is [-π, π]. Bottom: reconstructed intensity and phase profiles after projection on the theoretical modes. (b). Modal weights and (c) relative phase coefficients after projection on the theoretical modes. The phase coefficients given are the relative phase with respect to the one of the fundamental mode.

A second experiment is carried out and the results are presented in Fig. 6. The measured intensity profile is characterized by four distinct lobes, which is close to the theoretical LP_{21} mode. In theory, the adjacent lobes should be out of phase. In practice, the measured phase profile shows distinct phase steps between the lobes and opposed lobes are in phase (the color change from blue to red for the horizontal lobes is due to the fact that the phase is wrapped). However, one can see that the absolute value of the phase step is lower than π. This indicates that other modes are excited. Indeed, the decomposition of these measured profiles shown in Fig. 6(b) and (c) shows that the beam is composed of 48 % of the fundamental mode, 9 % of the LP_{02} mode nearly out of phase with the fundamental one and 33 % of the LP_{21} mode (split in 15 % on the even part and 18 % on the odd part). Once again the field can be reconstructed and the error is $\Delta = 0.0034$ (C = 0.90).

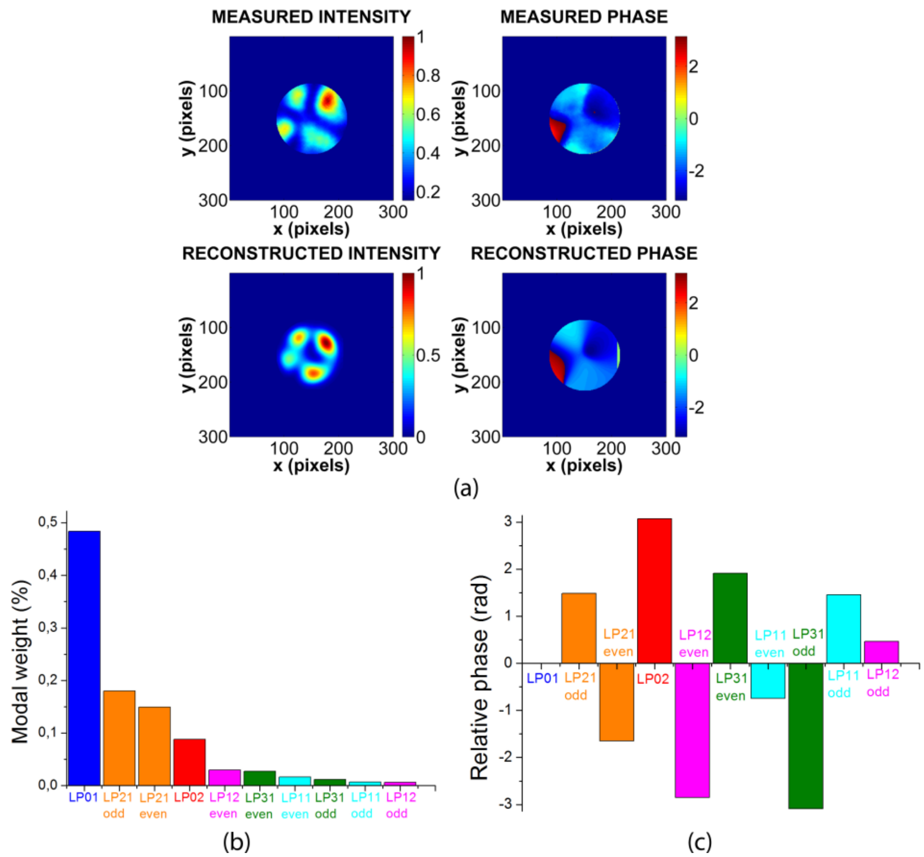


Fig. 6. (a). Measured and reconstructed phase and intensity profile in the case of an excitation close to the LP_{21} mode. The intensity profile is normalized and the phase is given between [$-\pi$, π]. (b) and (c): Corresponding modal decomposition.

Eventually, a third case is studied and presented in Fig. 7. The mode superposition excited in this case has an intensity profile composed of two separate lobes, which is close to the theoretical profile of the LP_{11} mode. However, thanks to the measurement of the phase map, it can be noticed that the two lobes are roughly in phase, which is not the case for the LP_{11} mode where there is a phase step of π. Indeed, one can see on the modal decomposition presented on Fig. 7(b) that the excitation of the LP_{11} is very low and almost negligible compared to other modes. On the contrary, the fundamental mode is mainly excited, with a modal weight of 77 %. The particular intensity profile obtained here is due to the presence of the LP_{02} and LP_{21} modes by an amount of 8 % and 9 % respectively. The reconstructed intensity and phase profiles show a reconstruction error of $\Delta = 0.0025$ (C = 0.96).

This last experiment demonstrates the importance of the wavefront information in the analysis of multimode beam and shows that the presence of higher-order modes, even in a slight amount compared to the fundamental one, leads to a strong degradation of the intensity profile, which can mislead on the modal content when considered alone.

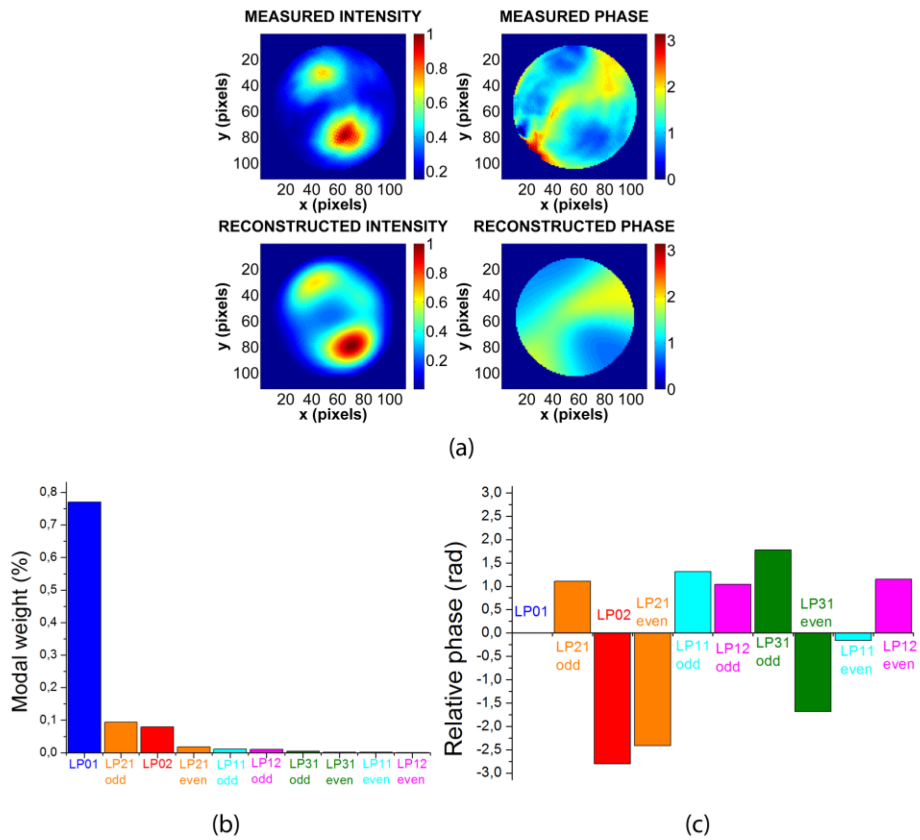


Fig. 7. (a). Measured and reconstructed phase and intensity profile in the case of an arbitrary mode excitation. The intensity profile is normalized and the phase is given between [0, π]. (b) and (c): Corresponding modal decomposition.

4. Conclusion

We have reported the complete analysis of the modal content of a 30 µm LMA multimode fiber supporting 6 modes. This decomposition is obtained by directly measuring the wavefront at the output of the fiber with a lateral shearing interferometer. The modal decomposition itself is very easy to obtain by projecting the measured electric field on the theoretical modes supported by the fiber without any further numerical calculations. Therefore, the measurement and reconstruction process can be performed at high repetition rate, which opens the path for using this method in a closed wavefront correction loop. This measurement technique also presents the advantages of accessing the relative phase between the modes and working even in the absence of a strong fundamental mode. As a result, this technique can be also used as a characterization technique for multimode beams, in addition to the traditional M^2 parameter.

The technique reported here is also applicable in the case of less conventional fibers such as rod type or photonic crystal fibers, provided their mode structure is known. Multicore fibers are also of great interest since their effective area can be increased by simply increasing the number of cores and this technique can also be used to determine the phase difference between the cores. However, the wavefront analyzer cannot be directly used for this, and the distance between the diffraction grating and the camera has to be changed in order to observe an interference pattern between adjacent cores [14].

Acknowledgements

This work was supported by the ANR MultiFemto project of the French Agence Nationale de la Recherche. Mathieu Paurisse acknowledges the funding of his Ph. D. by the Délégation Générale de l’Armement.