Annual Meeting
DGaO 2009
P79

Complete modal decomposition of optical fields in step-index fibers

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This poster presents the experimental procedure for decomposing optical fields into their eigenmodes using computer-generated holograms (CGH). With this method arbitrary beam-profiles emerging from step-index fibers, can be characterized in real-time.

Introduction

The call of industry and research for guiding high power optical fields by means of step-index fibers makes it necessary to enlarge the core size of waveguiding structures. This veering away from single mode condition causes a certain beam quality loss, due to the appearence of higher order mode content [1]. A simple experimental procedure using a CGH enables to measure both modal weights and intermodale phases of investigated beams in real-time. Since the full information about the optical field becomes available, not only beam-quality characterization is possible but also the investigation of the modal behaviour of disturbed fibers.

Modes of step-index fibers

Starting from *Helmholtz*' equation, describing the spatial structure of monochromatic light and under the assumption of a weakly-guiding step-index fiber one obtains the linear polarized (LP) modes as solutions of the eigenvalue problem. These modes build a finite, orthogonal and complete set of eigenfunctions $\{\psi_n\}$, so that an arbitrary scalar field $U(\mathbf{r})$ can be decomposed:

$$U(\mathbf{r}) = \sum_{n=1}^{n'} c_n \psi_n(\mathbf{r}), \qquad (1)$$

with the complex-valued mode coefficients $c_n=\rho_n \exp(i\varphi_n)$ [2]:

$$c_n = \iint_{R^2} d^2\mathbf{r}\, \psi_n^* U. \qquad (2)$$

Since the possible LP-modes for a given fiber (***Fig. 1***) can be easily calculated [3], only the coefficients c_n have to be determined to achieve full field information.

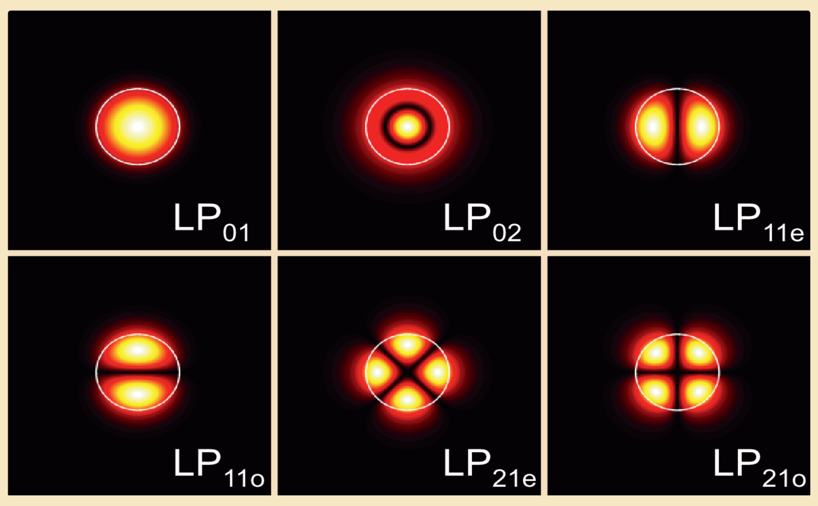

Fig. 1: Intensity distribution of the six lowest order LP-modes

MODAN and experimental setup

In the case under consideration, we need information about modal strengths ρ_n^2 as well as about intermodal phases φ_n. A suitable corresponding transmission function T has been found and implemented in the CGH (called "MODAN", mode analyzer) as a binary amplitude mask, encoded by *Lee*-method. The system under test is a commercial LMA fiber with V≈5. As a consequence, in one polarization state a maximum of six modes can be excited and correspondingly as many "channels" are included. For each intermodal phase measurement two more channels are added into T [4]. In the *Fourier*-plane behind the illuminated MODAN (***Fig. 3***, CCD_2) one obtains a correlation pattern, containing the field information (***Fig. 2***). The required buildup is shown in ***Fig. 3***. It basically consists of a simple 2f-setup - the mayor advantage of our method.

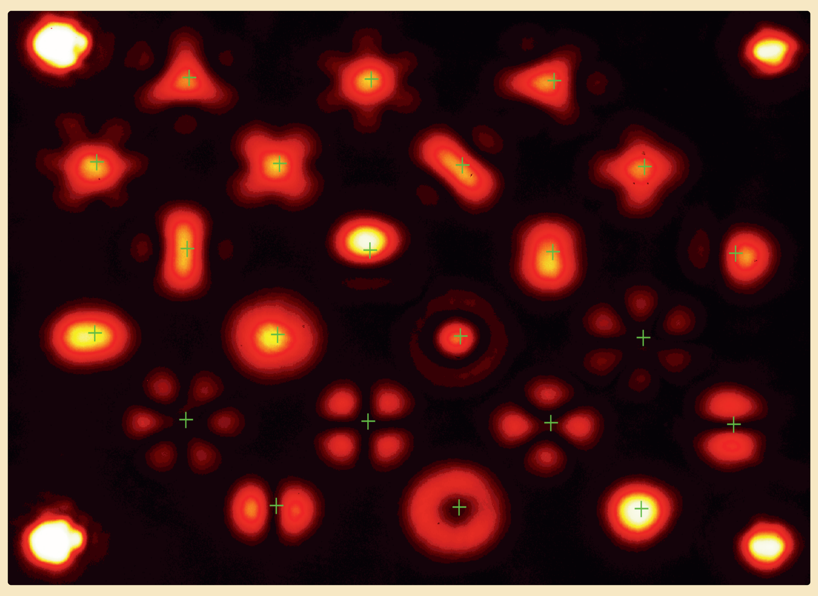

Fig. 2: Correlation pattern

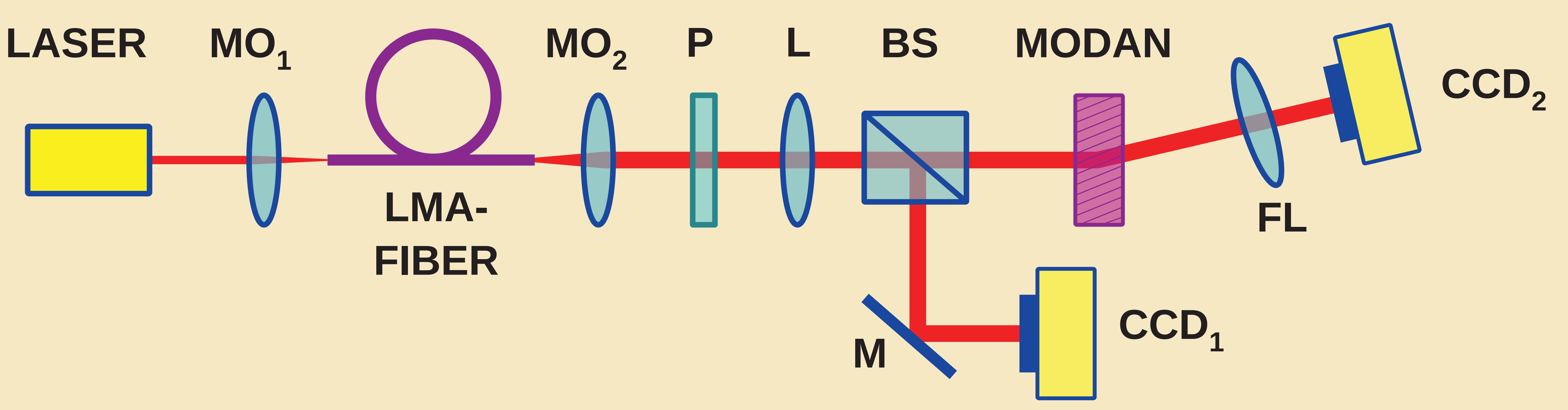

Fig. 3: Experimental setup: $MO_{1/2}$ - microscope objectives, P - polarizer, L - imaging lens, BS - beam-splitter, FL - *Fourier*-lens, M - mirror

Experimental results

As experimental results different near-field beam profiles have been measured by CCD_1, modally decomposed (by MODAN, FL & CCD_2) and numerically reconstructed according to ***Eq. 1***.

In ***Fig. 4*** a single-mode like profile is displayed. However, the mode analysis exhibits, that ≈ 17% higher order mode content exists. The correlation coefficient r between measured and reconstructed intensity distribution is higher than 0.98.

An optical field, consisting of a large amount of higher order modes can be seen in ***Fig. 5***. Here, the modes LP_{21e} and LP_{21o} together are guiding about 60% of the total power.

Fig. 6 demonstrates the ability of the method to achieve the full information about the optical field. The intensity and the reconstructed phase distribution - in this case a vortex-structure - is pictured.

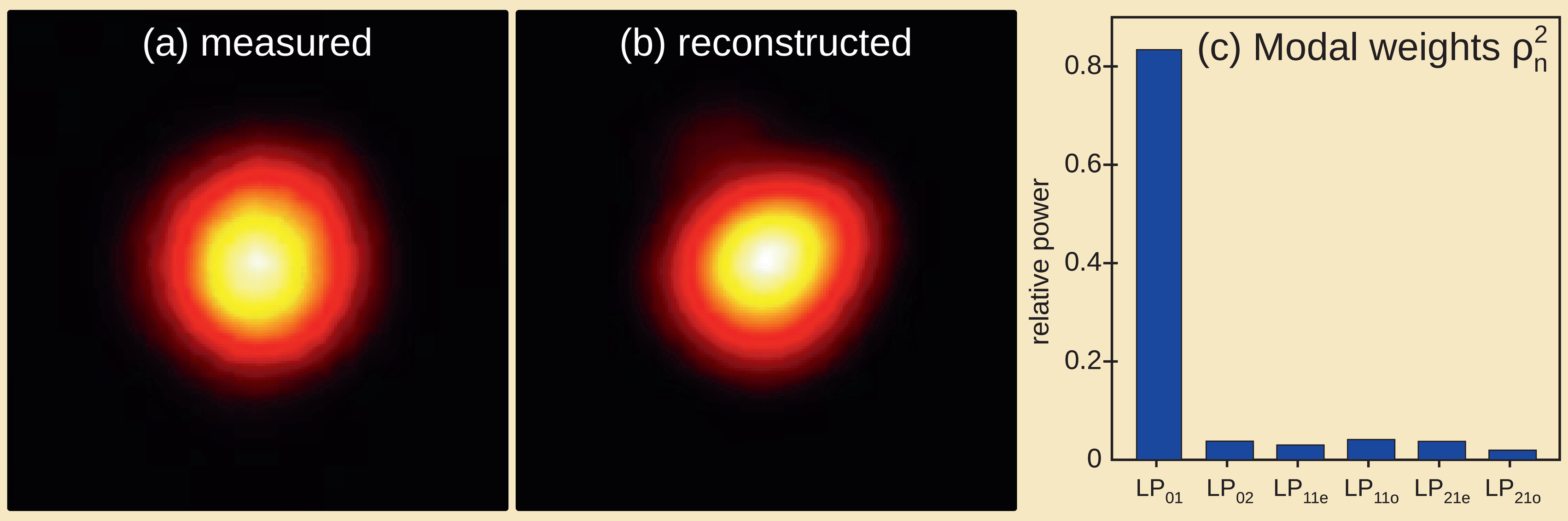

Fig. 4: (a) measured near-field, (b) reconstruction result, (c) modal statistics

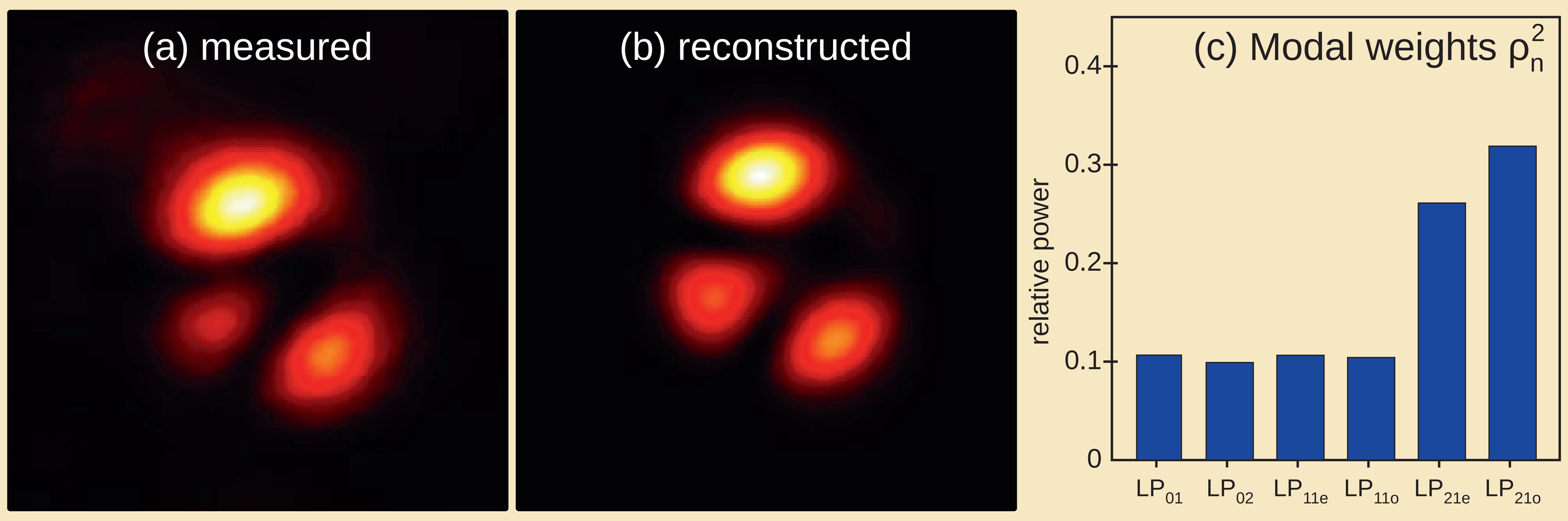

Fig. 5: (a) measured near-field, (b) reconstruction result, (c) modal statistics

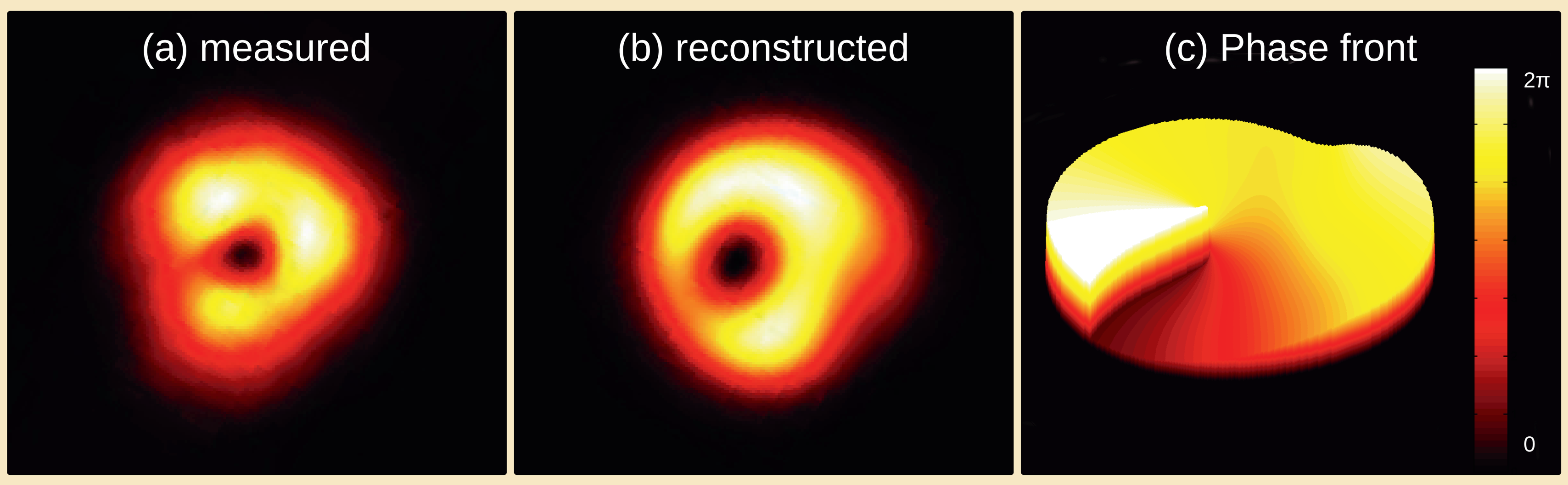

Fig. 6: (a) measured near-field, (b) reconstruction result, (c) 3D-phase front. Modal weights: $P(LP_{01}) \approx 15$ %, $P(LP_{11e}) \approx 36$ %, $P(LP_{11o}) \approx 17$ %

Conclusion and Outlook

We introduced an in-situ characterization method for measuring the full field information about optical fields. With a low cost experimental realization it is possible to determine the fractional power of excited modes and their phase distributions - even for unusual beam profiles, e.g. ring-like structures. For this reason it is also conceivable to characterize the step-index fiber fields by the beam-quality factor (M²-parameter) [1]. Furthermore the mode propagating properties of disturbed and bended fibers, that are changing their mode contents (mode-decoupling, polarization effects, power-loss) can be investigated.

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