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Laser beam characterization by means of modal decomposition vs. M² method

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We present a *real-time* method to determine the beam propagation ratio M². That is realized by a computer generated hologram which enables the instantaneous measurement of the relative power of the included transverse modes.

Introduction

The laser as enabling technology is a widespread tool in industry and research. Thus, a detailed knowledge of the beam specifications is necessary to achieve the desired results. In laser applications there is an increasing demand for instantaneous measurement and control of the laser beam. One possibility of measurement is the determination of the modal beam composition which describes the beam in a unique form. For that, the beam has to be decomposed into its transverse eigenmodes [1].

Modal decomposition

Modes as eigenfunctions of the Helmholtz equation build a set of orthogonal functions. Thus, modes can be used as basis ψ_{mn} to describe a scalar wave field U:

$$U(x,y) = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} c_{mn}\,\psi_{mn}(x,y)$$

We used Gauss-Hermite (GH) modes ψ_{mn} so that m and n are modal indices. The coefficients c_{mn} are unique

$$c_{mn} = \iint \psi_{mn}^{*}\, U \,\mathrm{d}x\,\mathrm{d}y$$

and the ensemble of all c_{mn} contains the complete information about U. Therefore, the coefficients c_{mn} have to be determined experimentally. As illustrated in Fig. 1 (upper branch) a computer generated hologram (CGH), the so-called **MODAN** (modal analyzer), decomposes the incident beam. An adapted transmission function of the MODAN combined with a 2f-setup enable the simultaneous measurement of all **correlation answers** $|c_{mn}|^2$ of interest [2]. Every $|c_{mn}|^2$ is proportional to the power of one encoded mode. In the MODAN presented here, all GH modes with $(m+n) \leq 5$ are implemented (21 "channels"). Fig. 2 shows the CCD image ("correlogram") for fundamental mode illumination of the MODAN. Therein, the four "alignment channels" in the corners (incident beam) as well as the 21 correlation answers (highlighted pixels) can be seen.

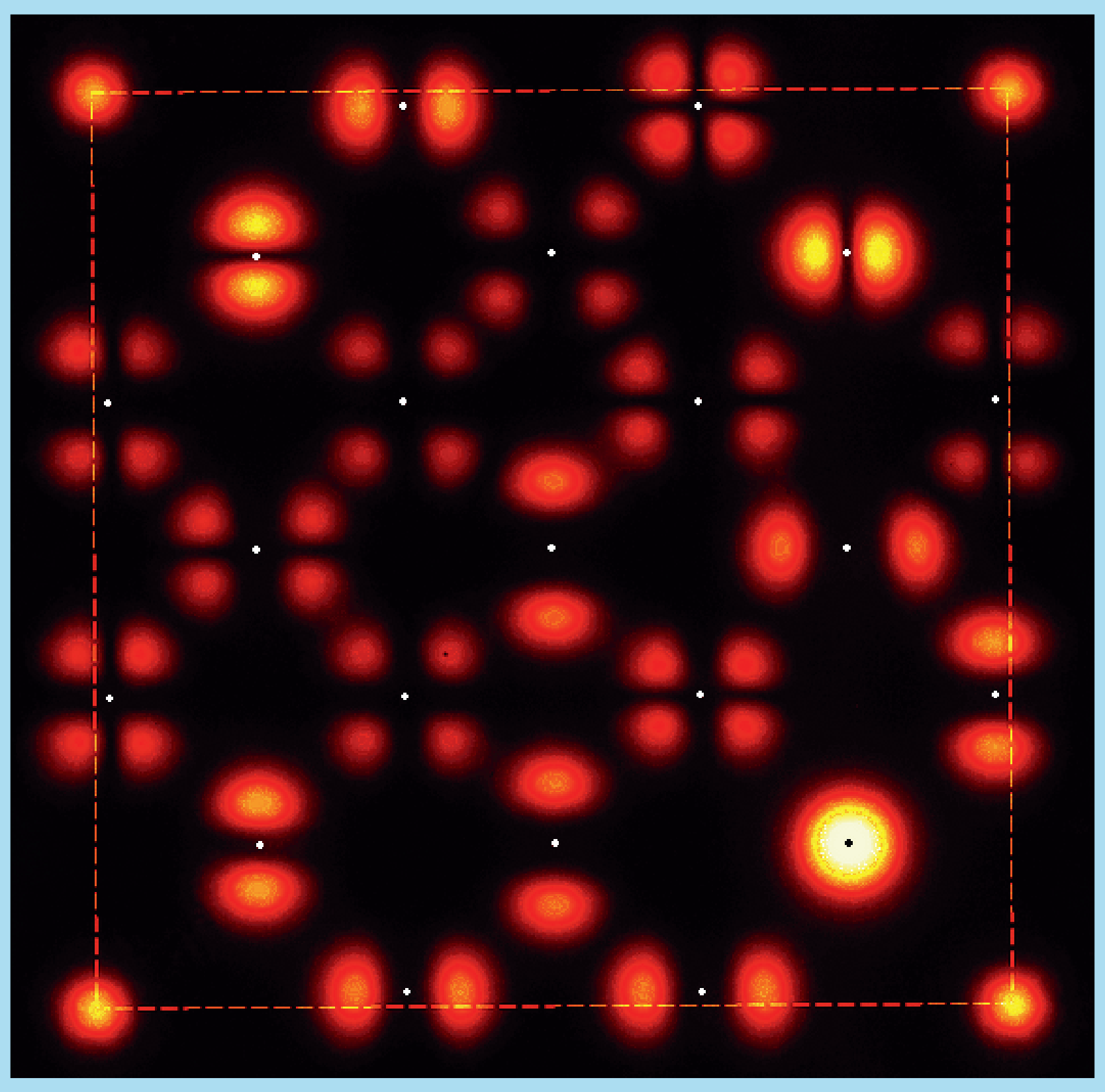

Fig. 2 *Correlogram analysis. Correlation answers are highlighted.*

The correlation answer $|c_{mn}|^2$ for a mode is given by the intensity of one specific CCD pixel. The alignment channels in the corners build a square and enable to find these correlation answer pixels. The simultaneous measurement of all included correlation answers enables the determination of their relative strengths.

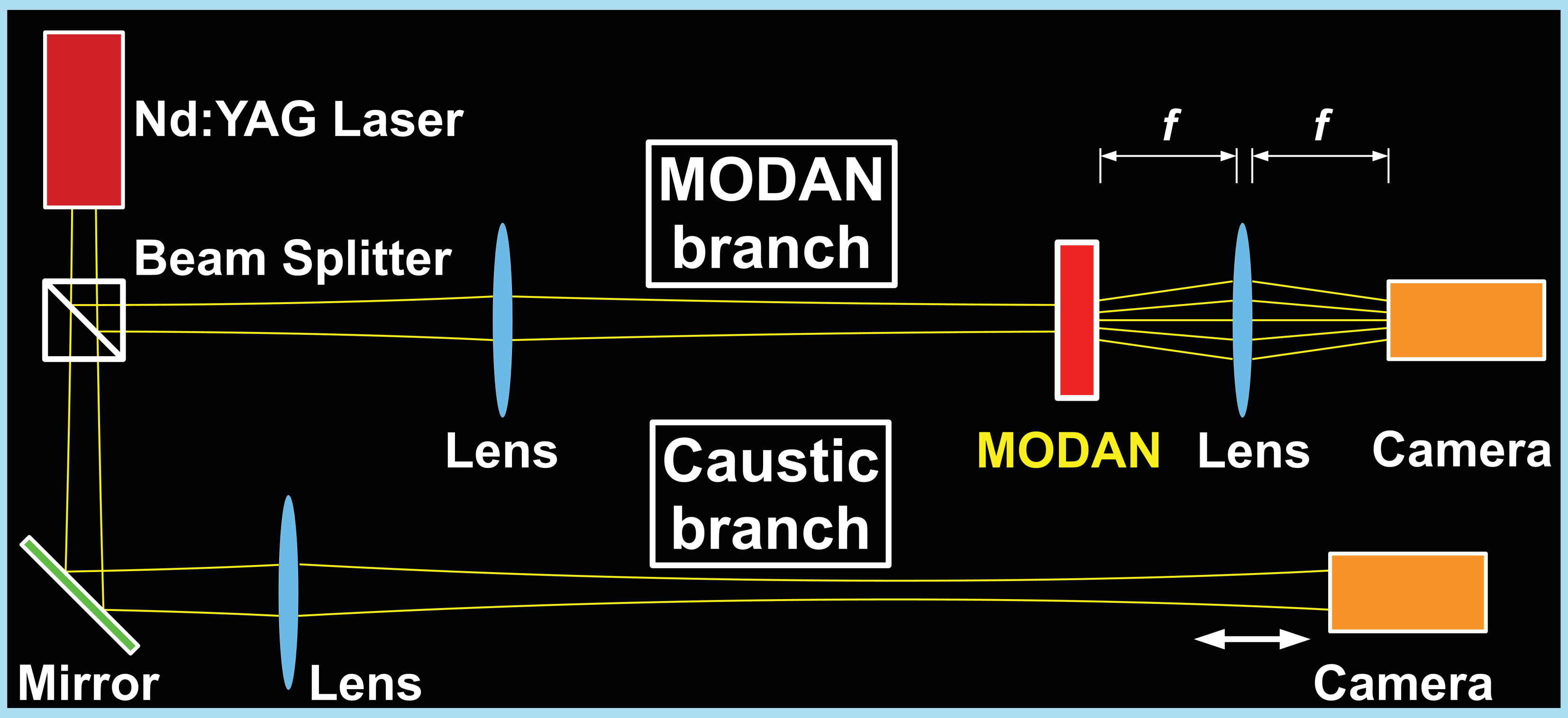

Fig. 1 *Scheme of experimental setup. Lower branch for reference.*

Results

Starting from the ISO standard 11146 [3], the beam propagation ratio can be expressed in a modal decomposed form:

$$M_x^2 \approx \sum_{m=0}^{5}\sum_{n=0}^{5-m}(2m+1)\,|c_{mn}|^2$$

$$M_y^2 \approx \sum_{n=0}^{5}\sum_{m=0}^{5-n}(2n+1)\,|c_{mn}|^2$$

In the derivation we assumed an incoherent superposition of the modes [4]. In this case the beam propagation ratio only depends on the relative power of the modes which can be determined in real-time.

The results for almost fundamental mode illumination are listed in Table 1. The ISO conformable "caustic" measurement results here in smaller M² values than the MODAN method. This effect can be traced back to adjustment inaccuracies.

Caustic		MODAN	
M_x^2	M_y^2	M_x^2	M_y^2
1.04	1.07	1.20	1.18

Tab. 1 *Fundamental mode results.*

For higher order modes of type ψ_{m0} or mixtures of such modes, the "GH20" correlogram is shown exemplarily in Fig. 3. As expected, the beam propagation ratios in y-direction are similar to the case of the fundamental mode. The achieved M² values in x-direction are visualized as bar charts in Fig. 4. The upper bar chart demonstrates the potential of the MODAN technique, whereas in the lower chart deviations occur due to the limited number of encoded modes.

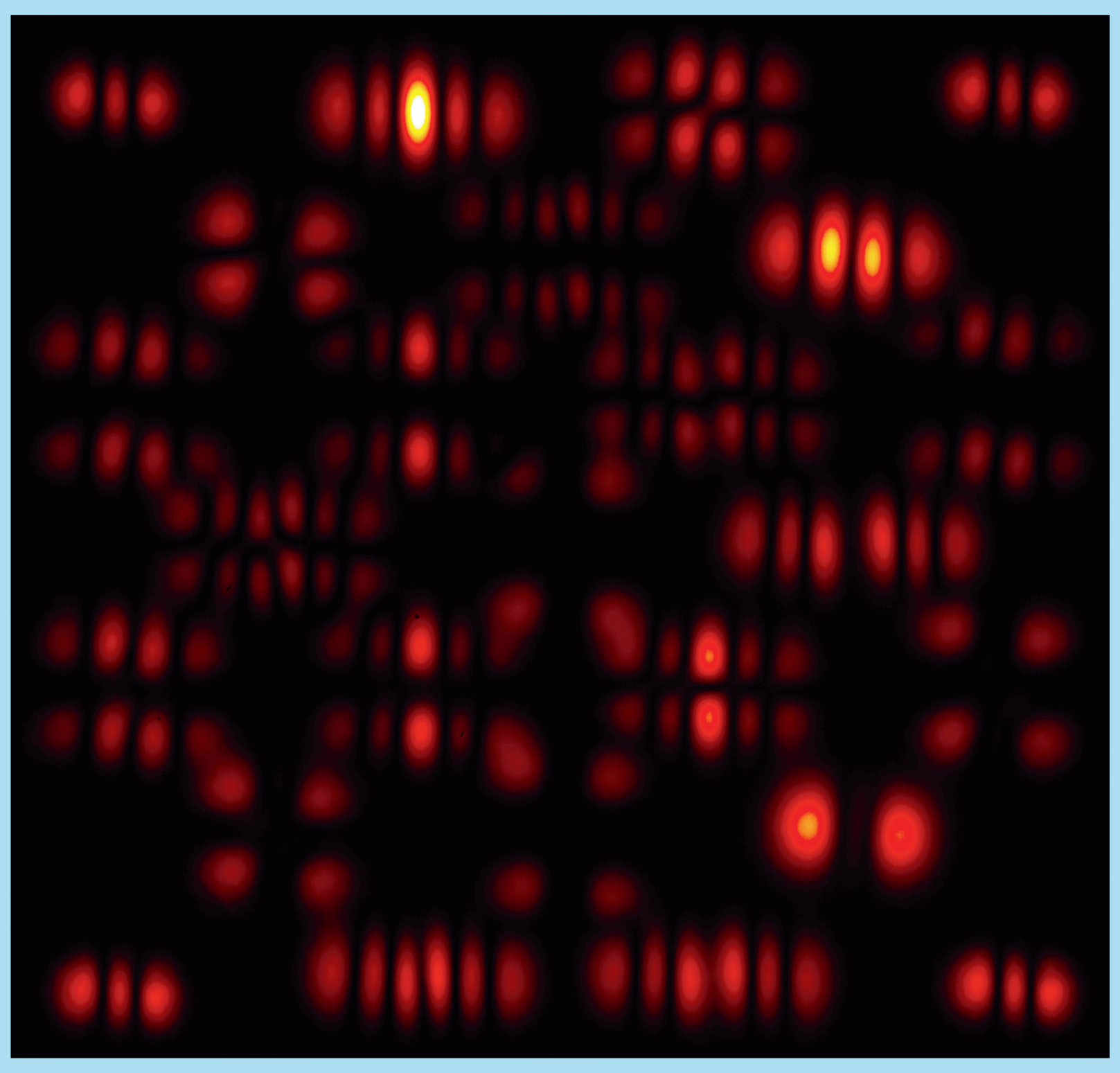

Fig. 3 *Correlogram for "GH$_{20}$" illumination.*

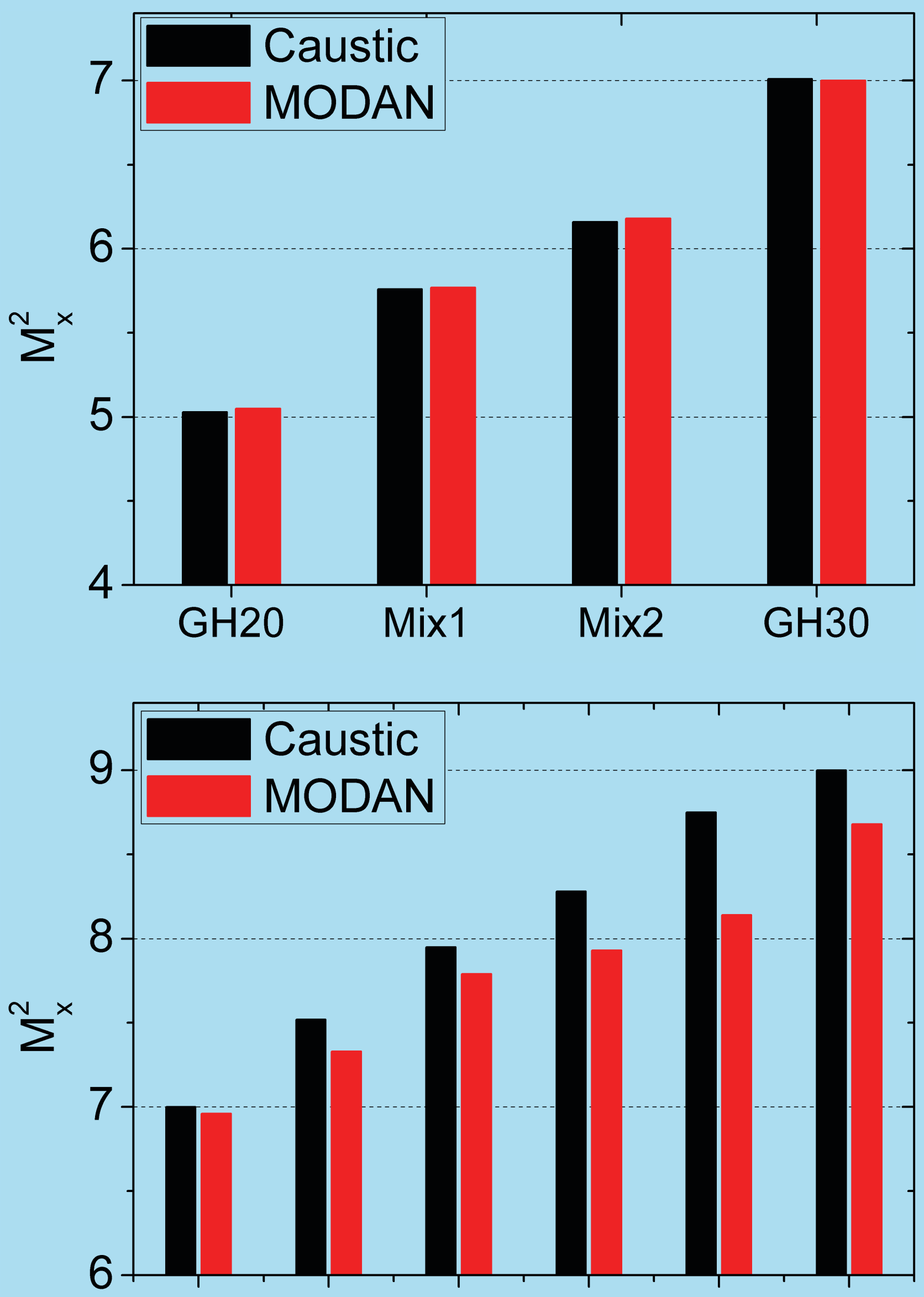

Fig. 4 *Bar charts of the results in x-direction.*

Conclusion

We demonstrated an in-situ approach to determine the relative power of encoded transverse modes. Using a computer generated hologram (MODAN) in a simple 2f-setup, this method enables a real-time determination of the beam propagation ratio M². The obtained results are compared with ISO standard measurements and show principal conformity. Sources of error will be investigated in detail in the future; but the potential of this approach can be seen clearly already today: The MODAN method enables an instantaneous characterization of laser beams including the power content of each mode. Even an intermodal phase measurement (for coherent superposition of modes!) is possible by implementing interferometric channels into the MODAN (see Poster P79).

References:

[1] V. A. Soifer and M. A. Golub, *Laser Beam Mode Selection by Computer Generated Holograms* (CRC Press, 1994).

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[4] H. Kogelnik and T. Li, "Laser beams and resonators," Appl. Opt. 5(10), 1550–1567 (1966).

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