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# Selective higher order fiber mode excitation using a monolithic setup of a phase plate at a fiber facet

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**We selectively excited different higher order fiber modes using different setups of a passive binary phase plate in front of the input facet of an optical fiber. The achieved results were analyzed by a complete modal decomposition of the field emitted by the fiber.**

## Motivation

- higher order fiber modes in an optical fiber show a quite strong dependence on external disturbances[1,2]
- for a possible utilization in an uncomplex sensor the excitation of pure higher order modes [HOMs] will be necessary
- passive binary phase[3] plates promise a reproducibly manufacturable, robust, efficient[4,5] and rather cheap setup
- in order to avoid the free space propagation losses in the usually employed free space setups[4–6] we put the phase plate directly in front of the fiber input facet ["monolithic setup"]

## Fiber Modes

- fiber modes are constant field distributions all along the fiber [eigensolutions]
- all guided fields are describable as a superposition of the modes [orthonormal basis]
- for a weakly guiding fiber and in the paraxial case a fiber guides the so called $LP$-modes

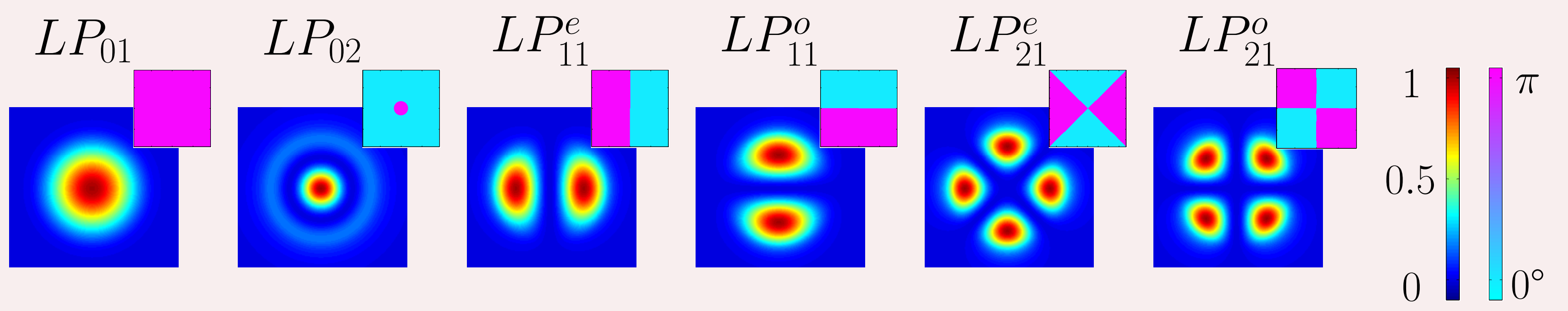

Figure 1: Intensity and phase [insets] profiles of the guided $LP$-modes calculated numerically.

## Passive Binary Phase Plates

- incoming fundamental Gaussian beam with it's waist at the position of the phase plate
- laterally varying thickness induces laterally varying phase shift

$$\Delta\Phi = [n_{\mathrm{ph}} - n]\frac{d}{\lambda_0}2\pi$$

- investigated transversal phase profiles

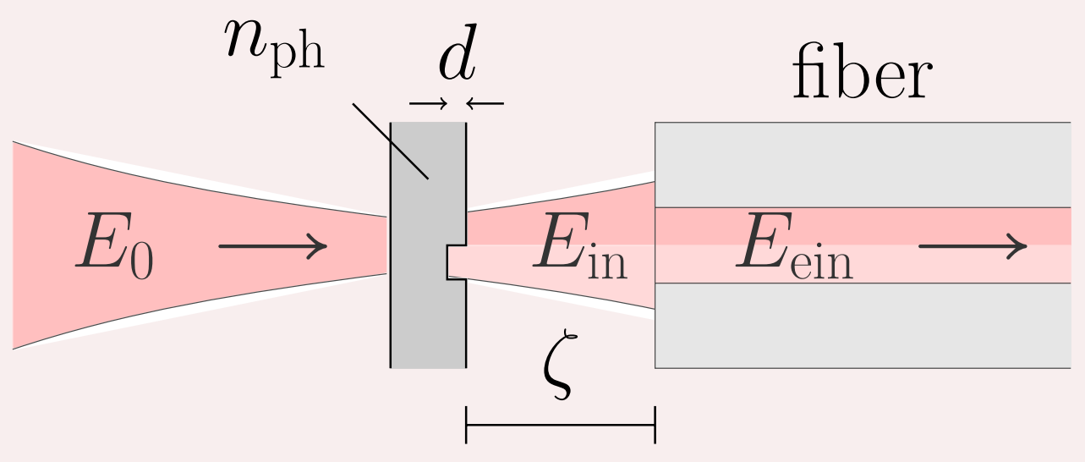

Figure 2: Principle setup of the monolithic binary phase plate in front of the fiber input facet.

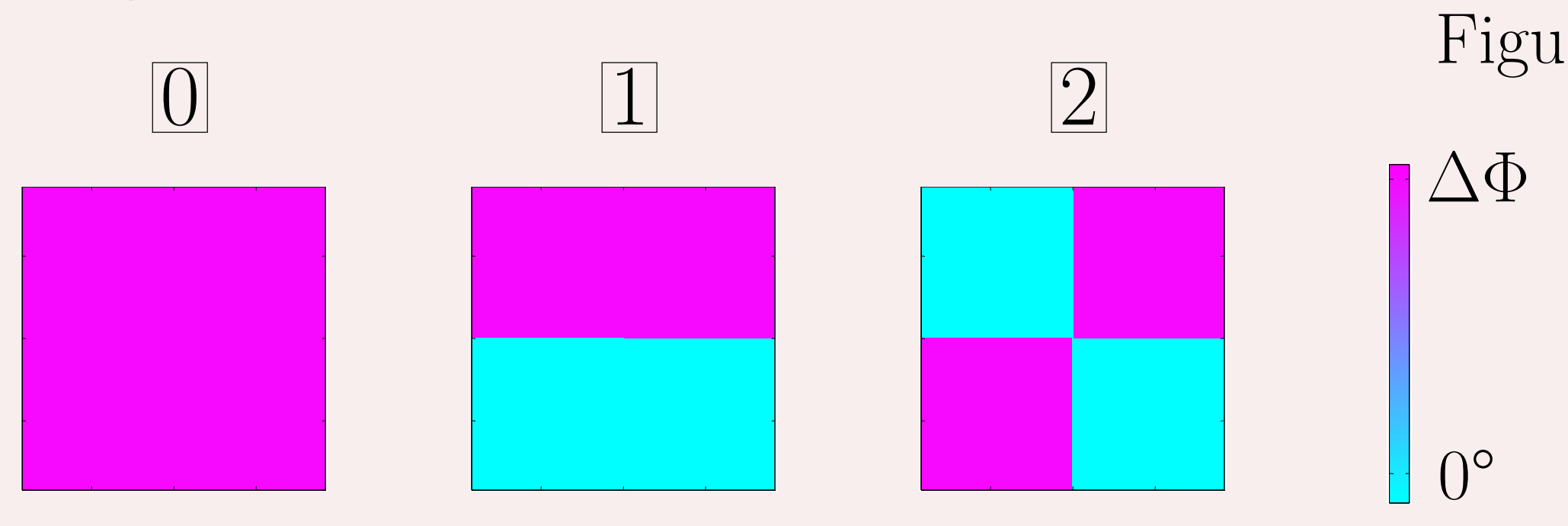

Figure 3: Transversal profiles of the used phase plates.

- one should note that the upper limit of the $\Delta\Phi$-scale in figure 3 is due to experimental difficulties not mandatorily 180°
- the power percentage of the field $E_{\mathrm{in}}$ [see figure 2], after a phase plate $\boxed{l}$ with phase shift $\Delta\Phi$, adapted to the mode group $LP_{lm}$ corresponds to

$$\tilde{\rho}_l^2 = \frac{1}{2}[1 - \cos(\Delta\Phi)] \qquad , \qquad \tilde{\rho}_0^2 = \frac{1}{2}[1 + \cos(\Delta\Phi)]$$

## Experimental Setup

- the decomposition of the fields excited in the fiber was achieved by analyzing the output beam via the correlation filter method [CFM][7]

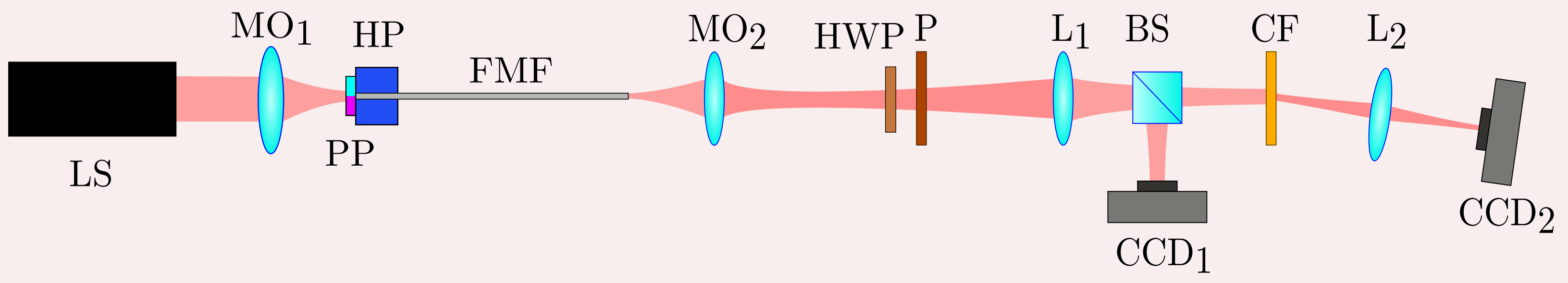

Figure 4: Scheme of the experimental setup [ LS - laser source, $MO_{1,2}$ - microscope objectives, PP - phase plate, HP - Hexapod, FMF - few mode fiber, HWP - $\frac{3\lambda}{2}$ waveplate, P - polarizer, $L_{1,2}$ - lenses, BS - beam splitter, $CCD_{1,2}$ - cameras, CF - correlation filter].

## Results

- for the investigated phase plates the remaining free space propagation distance $\zeta$ [see figure 2] between the phase plate and the fiber input facet of less than 100 µm showed to be negligible
- the numerical experiments show a high efficiency and an achievable mode purity of 100 %

Table 1: Numerically determined parameters of the monolithic setups assuming $\Delta\Phi = 180°$

| phase plate | efficiency | $\sigma_{\max}$ | FWHM |
|---|---|---|---|
| $\boxed{0}$ | 99.3 % | 10.0 µm | 16.6 µm |
| $\boxed{1}$ | 72.9 % | 12.7 µm | 18.2 µm |
| $\boxed{2}$ | 67.2 % | 15.1 µm | 24.6 µm |

- dependence of the modal content on the transversal displacement of the incident beam, exemplarily seen in figure 5 for phase plate $\boxed{1}$, shows a quite good agreement

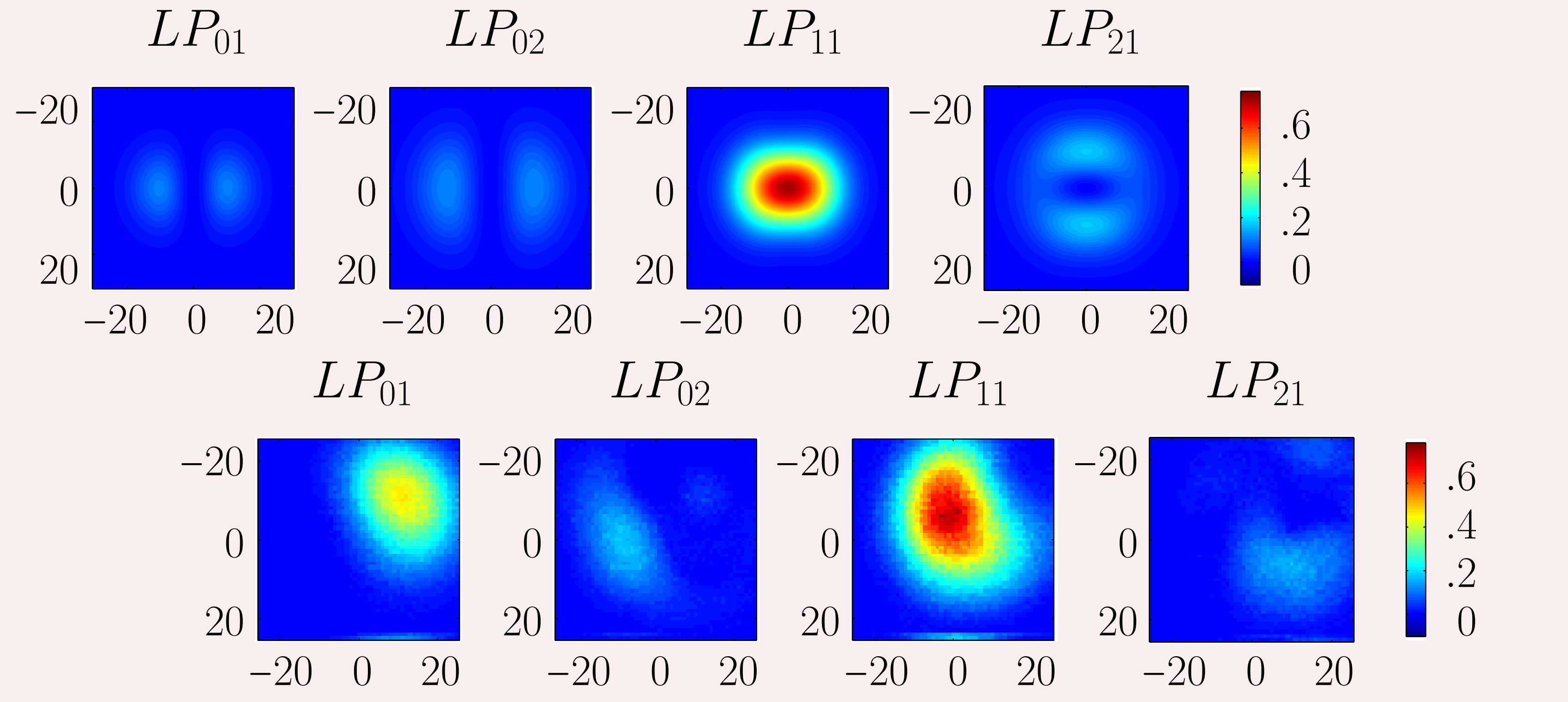

Figure 5: Modal coupling efficiency for the numerical [$\Delta\Phi = 180°$,top] and the optical [bottom] experiments as function of the transversal displacement of the incoming beam relative to the concentric position of incident beam and fiber for phase plate $\boxed{1}$.

## Comparison

- the non-monolithic setup showed to be slightly more frail to misalignments or disturbances
- the optimal coupling efficiencies show the monolithic setup to be more efficient [approximately by a factor of 2, $\Delta\Phi_{\text{free space}} = 180°$, $\Delta\Phi_{\text{monolithic}} \lesssim 150°$]

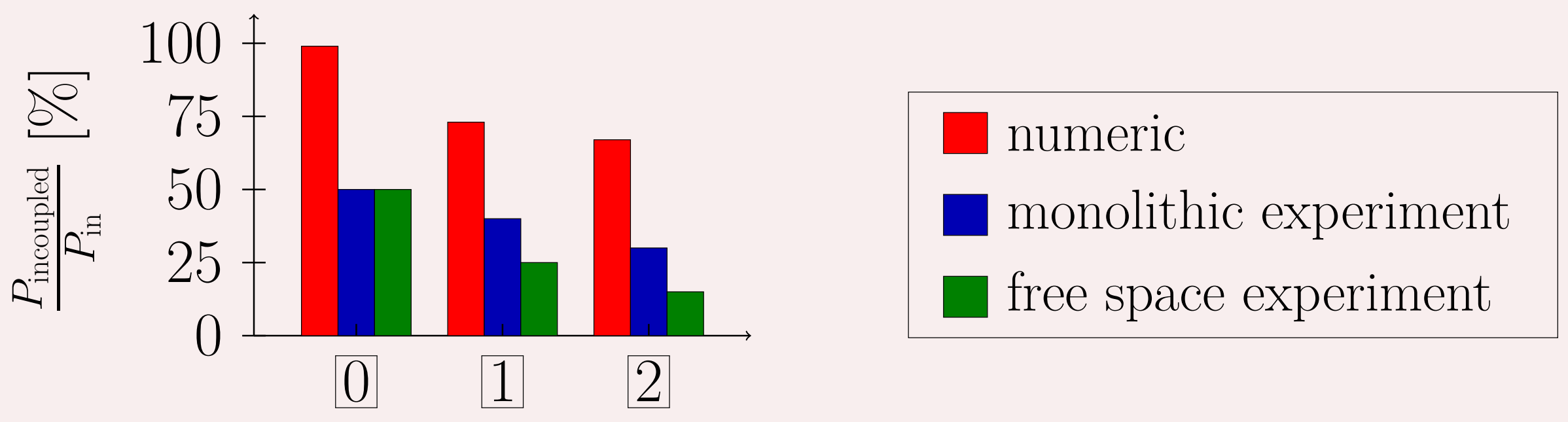

Figure 6: Numerical and experimental optimal coupling efficiencies.

## Conclusion

- a proof of principle for the monolithic setup is given
- allthough the phase shift of the phase plate was not optimal, the monolithic setup was already more efficient
- outlook:
  - optimization of the phase shift $\Delta\Phi$
  - investigation of the influence of a possible tilt of the incident beam
  - determination of external effects [e.g. pressure, strain or temperature] on the different fiber modes in order to be able to use it as a sensor

## References

[1] Schulze, C., Lorenz, A., Flamm, D., Hartung, A., Schröter, S., Bartelt, H., and Duparré, M., "Mode resolved bend loss in few-mode optical fibers", *Opt. Express* **21**, 3170–3181 (Feb 2013).

[2] Schulze, C., Wilde, J., Brüning, R., Schröter, S., and Duparré, M., "Measurement of effective refractive index differences in multimode optical fibers based on modal decomposition", *Optics Letters* **39**, 5810–5813 (July 2014).

[3] Gavrilov, A. V., Karpeev, S. V., Kazanskiy, N. L., Pavelyev, V. S., Duparré, M., Lüdge, B., and Schröter, S., "Selective excitation of step-index fiber modes", *Proc. SPIE* **6605**, 660508–660508–6 (2007).

[4] von Hoyningen-Huene, J., Ryf, R., Winzer, P., et al., "Lcos-based mode shaper for few-mode fiber", *Optics Express* **21**(15), 18097–18110 (2013).

[5] Stepniak, G., Maksymiuk, L., and Siuzdak, J., "Binary-phase spatial light filters for mode-selective excitation of multimode fibers", *Journal of lightwave technology* **29**(13), 1980–1987 (2011).

[6] Flamm, D., Schulze, C., Naidoo, D., Schröter, S., Forbes, A., and Duparré, M., "All-digital holographic tool for mode excitation and analysis in optical fibers", *Journal of Lightwave Technology* **31**(7), 1023–1032 (2013).

[7] Kaiser, T., *Field Reconstruction In Optical Fibers By Complete Modal Decomposition Using Computer-Generated Holograms*, diploma thesis, Friedrich-Schiller-Universität Jena (2008).