Fiber optic waveguide arrays as an artificial medium for discrete optics

U. Röpke, H. Bartelt, S. Unger, K. Schuster , J. Kobelke

Institute of Photonic Technology, Albert-Einstein-Str. 9, D-07745 Jena, Germany

mailto:ulrich.roepke@ipht-jena.de

Periodic arrays of weakly coupled waveguides are considered as new artificial optical media with a "discrete diffraction". Using a high precision fiber technology, arrays with a low coherent diffraction were fabricated and investigated with regard to linear light propagation. The achieved array quality will make it possible to study non-linear propagation phenomena (light-bullets).

1 Background

A periodic array of weakly coupled waveguides represents an optical medium with a discrete spatial structure transversely to the light propagation direction and with specific diffraction properties („discrete diffraction"). This medium (metamaterial) provides the basis of the field of linear and non-linear "discrete optics" [1]. Applications are expected in optical signal processing and laser technology.

Waveguide arrays can be fabricated using photorefractive effects (volatile arrays), fs-writing or fiber technology. Fiber optic arrays benefit from the high damage threshold of silica, a possible high number of circularly shaped cores and large array length. However, challenging requirements must be met for material and structural properties of the array to allow the interplay of nonlinear, dispersive and coupling effects [2]. Furthermore, measurement techniques to investigate the optical quality of real waveguide arrays are not yet available.

2 Fabrication

The waveguides are made from high-quality silica and F-doped silica materials (Hereaus F300/F320) with an index step Δn_0 = 0.0012 (NA = 0.06).

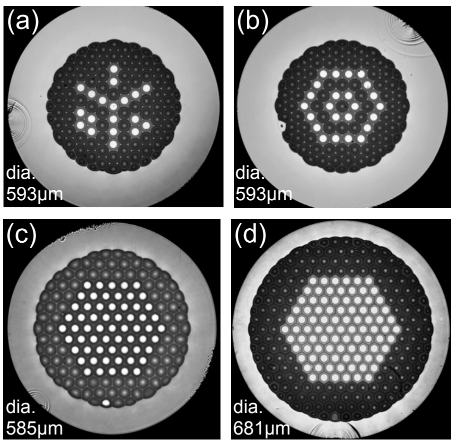

Fig. 1 *White light transmission micrographs of elementary (a), 1-dimensional, circular (b), 2-dimens. / 61 cores (c) and 91 cores (d) arrays; Outer diameters are stated.*

A core radius r_0 = 19 µm and core distance $\Lambda \approx$ 3.6 r_0 was chosen to obtain singlemode operation and a weak coupling at a design wavelength of λ = 1.55 nm.

The array was fabricated using the stack-and-draw technique (assembly, consolidation and drawing of a packed preform). Package rods with a close tolerance range are crucial (rod-in-tube technique, grinding and drawing with diameter tolerance < 0.1%). A buffer area encloses the array to optimize its structural and optical properties (minimal influence of surroundings and optical background).

The drawn fiber optic arrays show a regular hexagonal structure, including the array boundary. Variations of the circular shaped cores were not found. Different array structures were fabricated for the study of light propagation, Fig. 1. Furthermore, different array pitch values Λ were realized by fabrication of different outer diameters.

3 Measurements

The linear propagation characteristics of light in the array are investigated by excitation of a specific core at the input facet of the array; the light distribution at the output facet is captured by a camera and processed by a computer to determine the relative core powers (i.e. core power / total power).

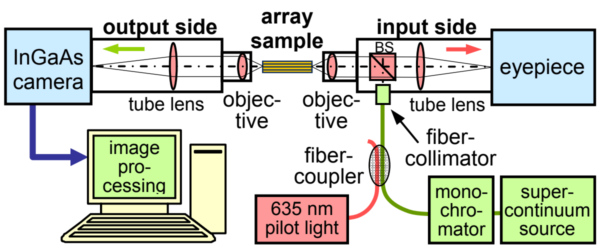

Fig. 2 *Measuring set-up with a tunable light source*

In the experiment the waveguide coupling was changed by a wavelength tuning (supercontinuum source Fianium SC400, monochromator Oriel 77250), Fig. 2. The tuning range was 1.08 - 1.8 µm and the spectral width ≅ 20 nm. Samples with different diameters and lengths can be investigated.

4 Modelling of light propagation in ideal arrays

The model uses the scalar coupled mode theory of the amplitudes u_i of the core modes (next-neighbors approximation) [3]. With the amplitude vector $u = \{u_i\}$ and the coupling matrix M_C ($M_{C;i\,k}$ = 1 if i, k refer to adjacent cores, $M_{C;i\,k}$ = 0 otherwise), the undisturbed propagation is expressed by

$$\frac{d\,u(\varsigma)}{d\varsigma} = \mathrm{i}\,\frac{\pi}{2} M_C\, u(\varsigma)\,. \qquad (1)$$

Here, $\zeta = z / L_C$ is the propagation length z normalized with the (linear) coupling length $L_C(\lambda, \Lambda)$ of two cores. Eq. (1) is solved by the calculation of array eigenmodes (supermodes) and its superposition according to the initial condition $u_0 = \{u_i(\zeta = 0)\}$ at the sample input facet. The relative power of the core i at $z = L$ (sample output facet) is obtained by

$$p_i(\varsigma_L) = \left|u_i(\varsigma_L)\right|^2 \Big/ \sum_k \left|u_k(\varsigma_L)\right|^2 , \qquad (2)$$

with $\zeta_L(\lambda, \Lambda) = L / L_C$ (normalized sample length).

5 Results of light propagation in real arrays

The relation of the parameters ζ_L and λ was derived by excitation of the central core and comparison of the measured and computed power distributions (output patterns) as exemplified in Fig. 3.

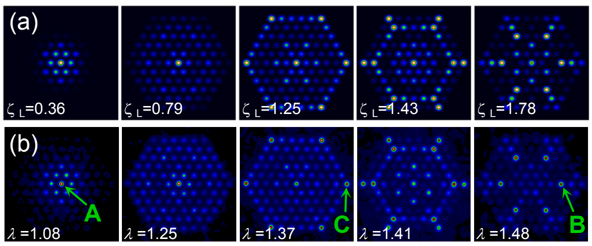

Fig. 3 *Output patterns in pseudocolor representation: (a) model, (b) experiment; (array with 91 cores, sample length L= 55 mm, pitch Λ = 29.6 µm, λ in µm)*

In Fig. 4, values ζ_L and λ belonging together are shown as points. Lines represent the results of computer simulations of $\zeta_L(\lambda, \Lambda) = L / L_C$ with L = 55 mm, and $L_C(\lambda$ = 1.55 µm, Λ = 34.8 µm) = 58 mm as a best-fit value.

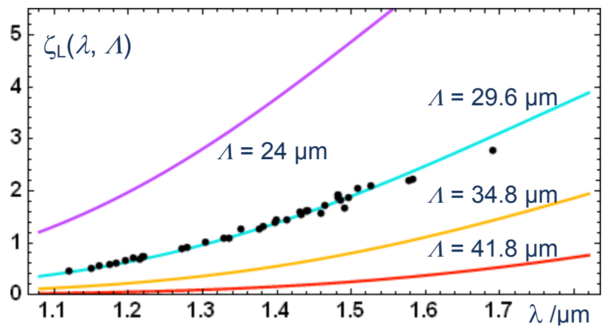

Fig. 4 *Normalized sample length $\zeta_L = L / L_C$ as a function of the wavelength λ and array pitch Λ*

To study the light propagation in detail, the relative powers $p_i(\lambda)$ of symmetrically equivalent core positions were measured and compared with the model. Fig. 5 shows curves referring to positions (A), (B) and (C) in Fig. 3. Random (discrepancies of cores) and systematic (e.g. next-nearest neighbors coupling) deviations at λ > 1.5 µm are observed.

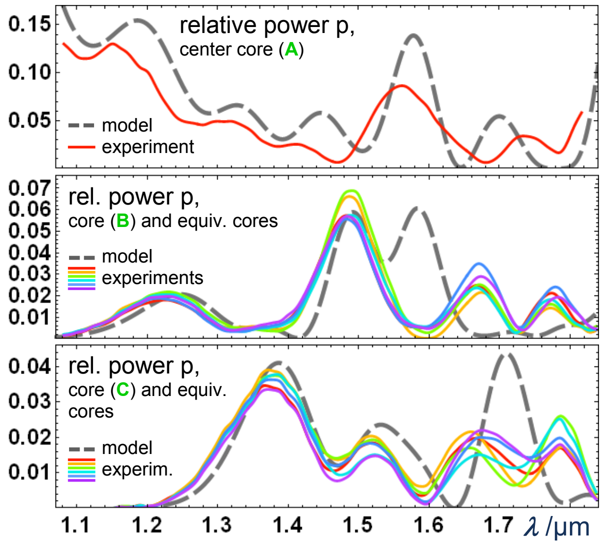

Fig. 5 *Relative output power of selected cores (A), (B), (C) and cores in symmetrically equivalent positions*

Conditions for a core-to-core imaging of an input to an output core were found as shown in Fig. 6. This feature can be described as a reflecting property of the regular margin of the array.

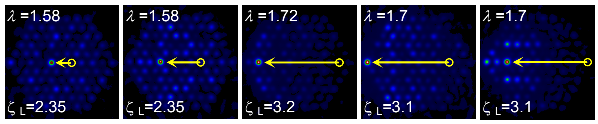

Fig. 6 *Output patterns with imaging features (the circles indicate the positions of the exited cores)*

6 Summary

Different fiber optic arrays with excellent structural quality were fabricated and investigated. Model calculations and experimental results concerning coherent light propagation are well in agreement. The optical quality of the medium is expected to meet the requirements of future experiments in nonlinear discrete optics.

References and Acknowledgment

[1] J. W. Fleischer, et al., “Spatial photonics in nonlinear waveguide arrays,” Opt. Expr. **13**: 1780 (2005)

[2] T. Pertsch, et al., “Nonlinearity and Disorder in Fiber Arrays,“ Phys. Rev. Lett. **93**, 053901 (2004)

[3] U. Röpke, et al., "Two-dimensional high-precision fiber waveguide arrays for coherent light propagation," Opt. Express **15**: 6894-6899 (2007)

This work was funded by the DFG within the research unit 532 “Nonlinear Dynamics”.