NUMERICAL ALGORITHM FOR WAVEGUIDING PROPERTIES RECONSTRUCTION FROM INTENSITY-ONLY MEASUREMENTS IN MULTICORE FIBERS WITH STRONG MODE COUPLING

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ABSTRACT
A numerical algorithm for reconstruction of supermodes structure and propagation constants in multicore optical fibers with strong core coupling is developed. The method is based on measurements of intensity distribution patterns at the fiber output under excitation of individual cores at the input for several fiber lengths and subsequent solution of the inverse problem. We used our method for a 7-core fiber and showed that the inverse problem can be solved efficiently by the stochastic hill climbing method and all waveguiding properties of the fiber can be retrieved with high accuracy.

Keywords: multi-core fibers, supermodes, numerical modeling, stochastic hill climbing

1. INTRODUCTION

Multi-core optical fibers (MCF) have recently attracted much attention as a promising medium for high-speed data transmission systems, and also as a component of various photonic devices and laser systems (Saitoh and Shoichiro 2016). Of particular interest are MCFs with sufficiently large coupling between the cores, which leads to efficient energy exchange. Such fibers can be used to manipulate the beams of high-power laser radiation, in particular, for coherent combining of radiation from many lasers to increase the peak intensity (Ramirez 2015). In such fibers, parameters of the individual cores and the coupling between the cores must be controlled with great accuracy to ensure predictable interaction, especially in the presence of strong nonlinearity characteristic of high-power laser systems. To carry out a full-scale numerical simulation with realistic parameters of experimentally produced MCFs, it is necessary to know with high accuracy real parameters of their cores and coupling coefficients between cores, which determine the properties of propagating modes. Direct measurement of these parameters with demanded accuracy is a rather difficult task. In this paper, we present an alternative algorithm based on solving the inverse problem of reconstructing the required parameters from measurements of linear light propagation.

2. RETRIEVING FIBER PARAMETERS FROM LINEAR PROPAGATION EXPERIMENT

The MCF can be seen as a system of several coupled single-mode waveguides. Coupling coefficients between the cores depend on the internal structure of the fiber. Assuming that the fiber structure does not change along its length, it is possible to calculate the supermodes (eigenmodes) of the MCF, each of which propagates with its own phase velocity. If only one supermode is excited in the MCF, the power distribution over the cores remains constant during its propagation. In an ideal case, when the internal structure of the fiber (shape and size of the cores and the distance between them) is known, it is possible to calculate the coupling coefficients between the cores and calculate the propagation constants and the supermode profiles. However, even with slight deviations from the ideal fiber structure, the shape of the supermodes and their propagation constants differ from the calculated ones. If several supermodes are excited (for example, when only one MCF core is illuminated at the input), the pattern of the intensity distribution at the fiber output is very sensitive to the deviations of the propagation constants from the ideal case.

Typically, designed core parameters (sizes, refractive index differences), as well as core spacing, are well known for multi-core fibers. However, due to technological issues in the fabrication of a multi-core fiber, the properties of the cores are subject to random perturbations (deformation of the shape, additional mechanical stress that cause some changes in the refractive index); the distances between the cores are also slightly different from the target value. This leads to slight differences in the propagation constant of the individual modes of the cores and the coupling coefficients between the cores and, consequently, the structure and propagation constants of the supermodes of MCF. These usually small changes significantly affect the propagation of laser radiation due to the accumulation of the phase difference over a sufficient propagation length. In experiments that are promising for observing nonlinear effects and studying the coherent combining of laser beams in MCFs, fiber lengths corresponding to several beat lengths (the length of linear energy transfer between cores) are used, which are sufficient to observe a significant difference of the intensity pattern in real and ideal fiber.

Further we show that it is possible to reconstruct the propagation constants and the coupling coefficients of the cores, as well as the profiles of the supermodes, on the basis of several measurements of intensity patterns at the fiber output and optimization algorithm.

The propagation of light in the MCF can be described by the equation

$$\frac{dA}{dz} = i\hat{C}A, \tag{1}$$

where $A=(a_1..a_N)^T$ is the column vector of slowly varying amplitudes in each of N cores, z is the coordinate along the fiber, and $\hat{C}$ is the matrix of the coupling coefficients and the propagation constants of the cores (Chan, Lau and Tam 2012, Koshiba, Saitoh, Takenaga and Matsuo 2011). The eigenvalues of the matrix are propagation constants of N supermodes, and its eigenvectors are profiles of the supermodes.

Based on several intensity measurements in each core $(I_1(z_j)..I_N(z_j))$ at several different propagation lengths z_j and several known initial conditions, the matrix can be retrieved by solving the minimization problem. The difference between calculated and measured intensities

$$\Delta = \sum_{j=1}^{M}\sum_{i=1}^{N} | I_i(z_j) - | a_i(z_j) |^2 |^2 , \tag{2}$$

where M is the number of different points along the fiber at which the measurements were taken, needs to be minimized, which can be done by well-known algorithms.

The main part of the developed method is a modified numerical minimization algorithm for finding the matrix $\hat{C}$, and consequently, the coupling coefficients between the cores and the propagation constants of individual cores. We used modified stochastic hill climbing method (Russel and Norvig 2010, Brownlee 2011), which was tailored for our particular problem.

Since the number of unknown variables in this matrix $\hat{C}$ is sufficiently large (N^2, where N is the number of cores), then the use of direct numerical algorithms to search for minima is not possible for multi-core fibers. It should be noted that not all of the unknowns are independent since we assume the matrix $\hat{C}$ to be Hermitian, which corresponds to the absence of absorption in the fiber. To handle the minimization problem with the above restriction, we built our own implementation of the stochastic minimization algorithm.

As an initial approximation in our method we use the matrix $\hat{C}$, which can be found on the basis of the known geometric structure of the fiber and the refractive indices of the cores and cladding materials by using an appropriate mode-solver. Usually, these data describe the real fiber quite well, except for small deviations, which however lead to significant distortions in the light propagation patterns, and are to be found by our iterative method.

At each iteration, each value in the matrix is changed randomly within certain limits leaving the matrix symmetric, then the value of Δ is computed. At each iteration, several such changes are made to the same matrix, from which the approximation with the smallest value of Δ is selected. If this value is better than the previous one, the approximation is replaced by the matrix that gave this smallest value of Δ. The number of changes at each iteration is of the order of 10-50. It is important to note, that in our implementation of the iterative algorithm the limits of changes decrease with increasing number of iteration, which allows obtaining more accurate results and at the same time reduces computational costs. Namely, at each iteration, which did not lead to an improvement in the approximation, the limit of variation of each matrix element was multiplied by 0.995. In addition, as the iteration number increases, the number of changes at each step increases. For retrieving experimental data for 7-core MCF (see below) we used 10 changes per iteration at the initial stages of the algorithm and 50 changes per iteration at the final stages.

To satisfy the Hermitian condition for the matrix $\hat{C}$, all random variations were chosen so as to preserve its symmetry. It turns out that even in this class of approximations it is possible to significantly improve the initial approximation, calculated from the geometric structure of the fiber. However, the modification of the algorithm, allowing asymmetric, but at the same time Hermitian changes in the matrix $\hat{C}$, did not significantly improved the approximation.

To demonstrate applicability of this method, we experimentally tested it for a seven-core fiber with the structure shown in the inset in Fig. 1.

The laser radiation was alternately launched into each core and the output intensity in each core was measured at several fiber lengths by the cut-back method. Few measured intensity patterns at the fiber output are shown in Fig. 2. The initial approximation for the matrix was calculated on the basis of the fiber structure. With the help of our mode-solver the direct problem of finding propagation constants and coupling coefficients in an idealized fiber was solved and corresponding ideal propagation constants and coupling coefficients were calculated, which were then used as an initial approximation for the matrix $\hat{C}$ at the input of the iterative algorithm. Next, our modified stochastic hill climbing method was used to find the matrix that best approximates the measured intensity dependences. After several iterations we achieved significant reduction in the discrepancy between the measured and calculated dependences compared to the initial approximation (i.e., approximation calculated on the basis of the refractive index profile of the MCF preform), see Fig. 1.

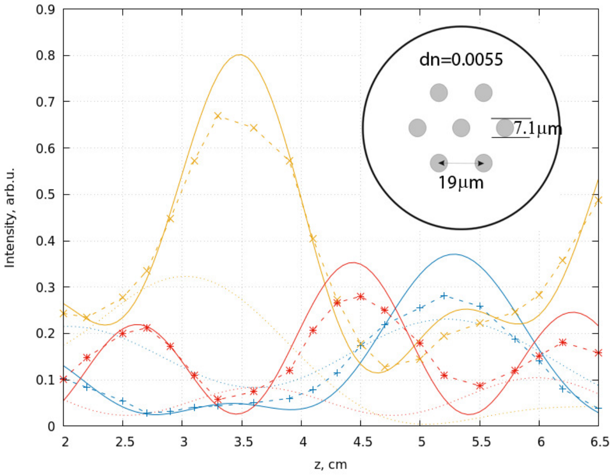

Figure 1: Intensity in some MCF cores measured in experiment (dashed lines with symbols), calculated by our algorithm (solid lines) and calculated based on the refractive index profile (dotted lines).

It can be seen that the overall structure of the reconstructed supermodes is close to the structure of the supermodes, calculated from the ideal refractive index profile of the MCF (Fig. 3). The propagation constants of the supermodes obtained by our algorithm show only a small difference at the relative level of 10^{-5} from the values calculated on the basis of the MCF refractive index profile. Nevertheless, this gave a much better matching of measured and calculated dependences of the intensities in the cores along the fiber. Since the obtained matrix determines all the waveguiding properties of the MCF, the propagation constants in individual cores can be readily obtained. Thus, our algorithm allows retrieving with high accuracy small corrections to the propagation constants (at the level of 10^{-5}), arising from imperfectness of the fiber manufacturing technology.

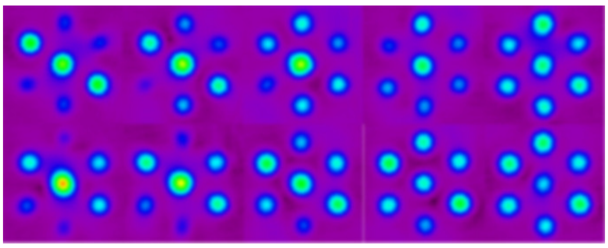

Figure 2: Measured intensity patterns at the output of different lengths of 7-core MCF while the central core was excited at the input.

Compared with the known method for reconstruction of mode properties in multimode and multi-core fibers based on the observation of spectral interference of a broadband signal and subsequent Fourier processing (Nicholson, Yablon, Fini and Mermelstein 2009), our method does not require a broadband light source. Another known method utilizes similar idea that underlies our method and based on the measurements of the output intensity patterns and corresponding iterative algorithm (Mosley, Gris-Sánchez, Stone, Francis-Jones, Ashton and Birks 2014). However, we believe that our method has much better convergence and greater reliability due to utilization of multiple data sets at several fiber lengths.

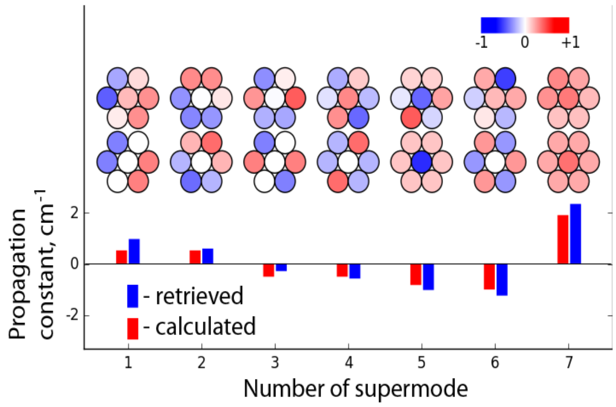

Figure 3: Structure of supermodes and propagation constants (relative to propagation constant of single core) retrieved by our algorithm (upper row) and calculated on the basis of refractive index profile (lower row).

Typically, to reconstruct the parameters of 7-core fiber, about 30000 to 50000 iterations were required, depending on the quality of the initial approximation. Our C++ implementation of the algorithm took about one minute to perform the reconstruction on a typical laptop computer. Thus, our algorithm is significantly faster than previously reported iterative algorithm utilizing intensity-only measurements for reconstructing parameters of multi-core fibers (Mosley, Gris-Sánchez, Stone, Francis-Jones, Ashton and Birks 2014).

3. ACCURACY AND STABILITY OF THE ALGORITHM

According to the results obtained from the processing of the measurement data for the 7-core fiber, it can be seen that our method allowed us to find corrections to the coupling coefficients and propagation constants, which give a much better coincidence of the radiation propagation pattern to the measured one, than the pattern calculated on the basis of the ideal fiber structure.

However, it was not possible to achieve perfect coincidence of the measured intensity and intensity calculated by our algorithm. This can be caused by various factors, for example, additional changes in the structure of the fiber and the coupling coefficients along the fiber, unaccounted dynamics of the polarization and nonmonochromaticity of propagating radiation, and inaccuracies in the experimental measurement of intensities. In addition, this could be caused by the inefficiency of our method. In order to test the efficiency of the method, the following numerical study was carried out.

Our method works under the assumption that the propagation of light in a multi-core fiber is described by the matrix $\hat{C}$, which contains the coupling coefficients between the cores and the propagation constants of individual cores (Eq. 1). It is reasonable to check numerically the efficiency and the limits of our method. To do this, the matrix $\hat{C}$ calculated on the basis of the refractive index profile of a certain fiber, for example, shown in the inset in Fig. 1, was changed randomly. Then, using the solution of the direct propagation problem (Eq. 1), the intensities at several points along the fiber were calculated upon excitation of various cores at the fiber input, i.e. experimental measurements were simulated numerically. After that, our method was applied to solve the inverse problem using simulated intensity values. As a result, the original and reconstructed values of the coupling coefficients and propagation constants were compared.

These calculations were performed for the various amount of random changes of the matrix $\hat{C}$. We introduced parameter p, and each matrix element was changed by a random value not exceeding p% of its original value while maintaining the symmetry of the matrix. It turned out that correct retrieval of the matrix $\hat{C}$ strongly depends on the value of p. For example, for our 7-core fiber, the refractive index profile of which is shown in the inset in Fig. 1, the correct parameters are retrieved for p not exceeding 80. For large values of p, the initial approximation for the algorithm is not accurate enough, and the reconstructed values differ substantially from the correct ones. To estimate the accuracy, we used the parameter Δ, as well as the average deviation of the elements of the reconstructed matrix from their correct values

$$e = \frac{1}{N^2}\sum_{j=1}^{N}\sum_{i=1}^{N}|C_{ij} - C_{ij}^*| \ , \qquad (3)$$

where $\hat{C}^*$ is the retrieved matrix.

The obtained dependencies of the reconstruction quality e and Δ on the parameter p for a different number of the fiber cores N are shown in Figs. 4 and 5, respectively. For values of p giving an unstable result, several realizations showing the spread are displayed in the figures. In this case, we consider results with the parameter $\Delta<10^{-2}$ and the parameter $e<0.1$ as sufficiently good reconstruction. It can be seen that for MCFs with a smaller number of cores, the reconstruction quality is improved.

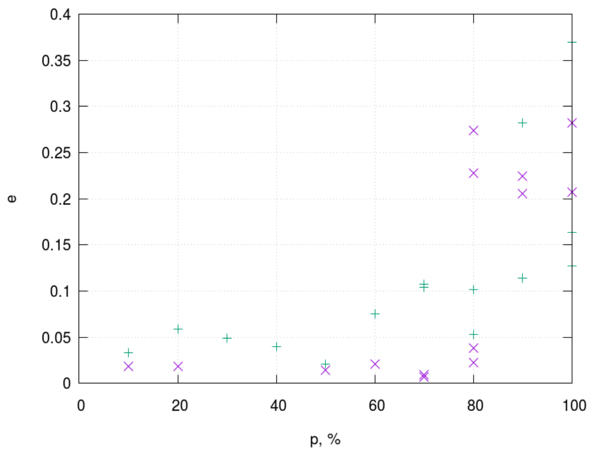

Figure 4: Dependence of the quality of reconstruction e on the parameter p for 7-core fiber (x) and 4-core fiber (+).

4. MINIMUM DATA SET FOR SUCCESSFUL RECONSTRUCTION

Our method uses data on the intensity of light in different cores at different propagation distances with several variants of excitation at the fiber input.

In the experimental measurement of the intensity and in numerical simulations, we used N variants of different input excitation; in each variant one of the N cores was illuminated at the input. We used from $2N$ to $3N$ different lengths of the fiber within the interval corresponding to several beat lengths. Such choice made it possible to obtain good results with a sufficiently small number of initial data and a small amount of computation. We also note, that if only half of the variants of the fiber input excitation was utilized, the accuracy of the reconstruction degrades only slightly. However, the choice of several fiber lengths at which intensity patterns are measured is important for successful reconstruction. If all the lengths are too close (their spread is less than one beat length), then the accuracy of the method degrades significantly.

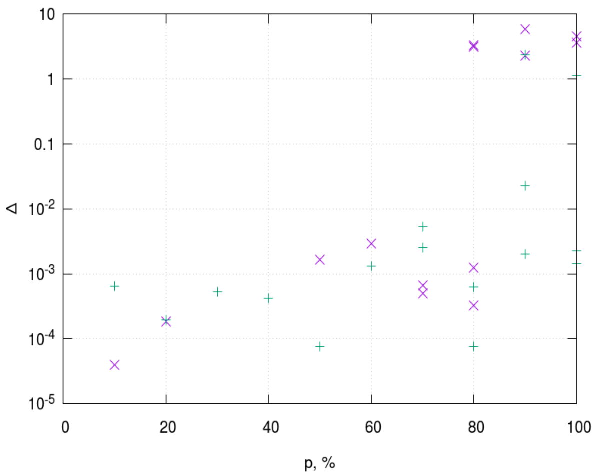

Figure 5: Dependence of the minimization error Δ on the parameter p for 7-core fiber (x) and 4-core fiber (+).

It is also worth noting that our method can be successfully applied even if some individual measurements are missing, since the method considers each measurement independently of the others.

5. CONCLUSION

In conclusion, we proposed a new method for reconstruction of supermodes structure and propagation constants in MCF with strong core coupling based on the intensity-only measurements. The method was successfully applied to 7-core MCF and allowed us to retrieve propagation constants of supermodes and modes of individual cores with high accuracy.

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