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Analysis of the Intensity Distribution at the Output of a Few-mode Fibre

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BRIEF REPORT

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The resurgence of interest in multi-mode fibers and in Few-mode Fibers (FMFs), in particular, in telecommunications is mainly due to the recognition of the fact that only the application of parallel channels can cope with the fast-growing demand on capacity of communication systems. Spatial mode-division multiplexing is one of the actively studied approaches to provide for high capacity optical links. FMFs are widely believed to provide the optimal practical balance between the highly important possibility to increase the communication capacity compared to single-mode fibers and the growing complexity of signal processing when dealing with many transversal modes. Few-mode fibre is also an attractive platform for non-telecom application fields such as imaging, microwave photonics, optical sensing, and fundamental studies of the complex nonlinear spatiotemporal dynamics including spatiotemporal solutions and optical beam self-cleaning. Larger mode areas (as compared to SMF) provided by FMFs suppress nonlinear effects and improve damage threshold, making a pathway to the development of novel high-power laser systems. Control and measurement of the optical phase at the FMF output is important for many scientific and industrial applications.

Implementation of spatial division multiplexing in modern coherent communication systems that use both the amplitude and phase of the optical signal is based on the sophisticated and relatively expensive multiple-input multiple-output (MIMO) processing schemes, which rely on bulk optics. The technical challenge in using multi-core and FMFs to increase system capacity is related to the need to use adaptive MIMO processing techniques for spatial de-multiplexing and to dynamically compensate for the differential mode group delays. The complexity of signal processing is growing quickly with the number of modes. Alternative approaches to mode de-multiplexing with a reduced complexity even for few mode fibers are of great interest for both telecom and other applications. Highly attractive solution, from a practical viewpoint, would be the phase retrieval for optical beams or pulses from intensity-only measurements. Recently, fiber transmission in three-modes-both-polarization using direct detection (intensity-only measurements) was demonstrated.

Carrier less phase-retrieving coherent measurements in single mode fibers using a multimode scrambler were also demonstrated using a two-dimensional photodiode array. It should be stressed that phase retrieval techniques are important for various current and future applications of multi-mode or FMFs in imaging, sensing, delivery of high-power coherent beams, nonlinear fiber optics, neuro morphic photonics, medical applications, and others. In this work, our focus is not on a particular application, but on the development of an advanced signal processing algorithm that can be applied across these fields.

Growing interest in FMF stimulates the demand for efficient beam characterization algorithms at the fiber output. The simplest approach is to measure the M2 factor of the beam, which, however, considers only the beam divergence. A full description of the beam includes a characterization of the amplitudes and phases of the waveguide Eigen modes. This problem is known as mode decomposition (MD).

Several approaches based on use of a reference beam such as digital whole graph and multi-plane light conversions have been proposed. However, implementation of these methods requires a coherent radiation source on the receiver side that limits their applicability.

A number of methods without a reference beam have been proposed to solve the MD problem. Numerical computing-based MD methods include the classical Gerchberg–Saxton technique line-search and stochastic parallel gradient descent. Methods include iterative procedures such as gradient descent or genetic algorithms. Although iterative methods show a high accuracy and a performance that makes it possible to decompose several times a second, they are still sensitive to the initial value and can become stuck at local minima.

Non-iterative methods for MD include using the fractional Fourier system or machine learning methods. Several neural networks architectures have been proposed either to enhance performance of iterative methods by guessing the initial mode weights distribution or for direct application for the MD problem in FMFs. MD methods using neural networks outperform iterative methods in decomposition speed; however, they require high-performance computers, a large amount of memory, and a long time for training the neural networks. In addition, they cope poorly when a fiber supports more than five modes.

The iterative algorithm based on stochastic parallel gradient descent presented in ref makes it possible to decompose nine images per second in a three-mode fiber. A hybrid genetic global optimization algorithm allows only one decomposition per 150 s for six-mode fiber in noiseless case, although it does not get stuck at local minima.