学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Study on Spatial Mode Conversion Technique for Space Division Multiplexing
（空間分割多重通信における空間モード変換技術に関する研究）

Optical fiber communication systems can carry enormous traffic volumes, which support large-capacity and long-distance communications owing to their large available bandwidths and extremely low propagation losses. With the increasing demand for internet, traffic demands have reached their capacity limits for single-mode fibers (SMFs) owing to the nonlinear Shannon effects and fiber fuse phenomenon. To satisfy the increasing communication traffic demands, space-division multiplexing (SDM) transmission systems have been investigated as potential candidates for a breakthrough technology to offset this capacity crunch. SDMs typically include two approaches: mode-division multiplexing (MDM) using few-mode fibers (FMFs) or multi-mode fibers (MMFs) and core multiplexing using multi-core fibers (MCFs). They treat each core/mode as an independent optical path; thus, the capacity can be improved in proportion to the number of cores/modes. Besides, few-mode multicore fibers (FM-MCFs), known as combined MDM and core multiplexing techniques, have considerable potential for meeting the large capacity and spatial-channel counts. However, as an optical network is not as simple as using only one type of fiber, SMF is preferred for long-distance and SDM fiber is used for short-distance transmissions. Thus, mode conversion techniques are critical for different modes and fibers conversion, which support SDM components and links to be added to the existing non-SDM infrastructure.

To realize simplified cost-efficient SDM optical networks with switching flexibility and scaling potential, we propose two spatial mode conversion schemes: the spatial mode exchange technique using volume holograms (VHET) for MDM systems and the spatial light modulator (SLM) based optical-fiber joint switch (OFJS) for FM-MCFs systems. In MDM systems, the transmission quality is restricted by the differential mode delay (DMD), which is defined as the relative group delay between the propagating modes. This delay is related to the computational cost of the multi-input-multiple-output digital signal processing (MIMO-DSP) technique developed for compensating crosstalk. In MIMO-DSP, the computation required to recover the signals at the receiver becomes more complex as the DMD between the propagation modes increases, which restricts the transmission distance. Moreover, the power consumption of the system also increases as the MIMO-DSP calculation increases. Thus, a reduction in DMD is essential to facilitate long-haul transmissions in MDM transmission systems. We propose and develop the VHET as the main technology to reduce the DMD by exchanging the spatial modes with different transmission speeds. VHET utilizes multiplexed volume holograms to exchange multiplexed spatial modes simultaneously; the cost and size of the optical systems are markedly lower because this scheme requires only a single holographic medium, which is independent of the number of multiplexed modes.

On the other hand, although MIMO-DSP techniques can compensate for crosstalk, it is essential to ensure that all spatial channels are routed together as a unit from the transmitter to receiver. Thus, integration and implementation cost of the switching elements are decisive factors in SDM networks. A SLM-based OFJS is proposed herein for FM-MCFs conversion. This scheme is a cost-effective integration technique with a simple configuration that can switch all signal paths of the FM-MFC as a unit in an optical free space to obtain a greater throughput; in addition, it can achieve selective operation by changing the SLM display patterns. On the other hand, unlike the mode conversion techniques applied in SMF transmission systems, crosstalk is a serious issue that must be considered in SDM transmission systems since integration generally comes at the expense of crosstalk among parallel optical paths. Thus, based on the above schemes, we further propose improved methods to suppress cross-talks. Chapter outlines are shown as follows.

Chapter 1: We review the development of optical communications, and introduce the research background and the purpose of this study.

Chapter 2: We mainly introduce the configuration and key technologies of SDM transmission systems. We first introduce the structure and classification of the optical fibers, and then describe the configuration of MDM transmission systems. The principle and characteristics of Volume Holograms (VHs) and SLMs as the primary components used for mode conversion are finally introduced in detail. Besides, the classification of crosstalk is discussed, which is an important parameter to evaluate the performance of systems.

Chapter 3: VHET as a spatial mode conversion technique is proposed in this chapter to suppress the DMD. The basic principle and characteristics of VHET are introduced in detail. Subsequently, numerical simulations and experiments are conducted by using a linearly polarized (LP) mode group comprised of LP01, LP11, and LP21. A dual-wavelength method that enables VHET applied in the optical transmission bands is lastly discussed.

Chapter 4: The conversion performance is severely degraded by crosstalk owing to the non-target holograms. To address this issue, VHET combined with phase plates is proposed in this chapter to suppress the crosstalk by modulating the intensity distribution of light signals. To confirm the basic operation of the proposed methods, numerical simulations of a specific LP mode group are performed. The simulation results of three improved methods are then discussed.

Chapter 5: An SLM-based OFJS for FM-MCFs is proposed in this chapter to realize SDM networks with routing flexibility and scaling potential. This scheme can switch all signal paths of the FM-MCF as a unit and achieve selective operation by changing the SLM display patterns. Subsequently, numerical simulations and experiments by jointly switching optical signals and routing them in a specified direction are demonstrated. Further, the method of changing the position of the output port to reduce the port crosstalk is described and performed.

Chapter 6: We summarize the research results of this study and describe the prospects of our research.