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Few-mode fiber technology for mode division multiplexing

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ABSTRACT

We review recent progress on few-mode fiber (FMF) technologies for mode-division multiplexing (MDM) transmission. First, we introduce fibers for use without and with multiple-input multiple-output (MIMO) digital signal processing (DSP) to compensate for modal crosstalk, and briefly report recent work on FMF for use without/with a MIMO DSP system. We next discuss in detail a fiber for MIMO transmission systems, and show numerically that a graded-index core can flexibly tune the differential mode group delay (DMD) and a cladding trench can flexibly control the guiding mode number. We optimized the spacing of the core and trench. Accordingly, we can achieve a 6 LP (10 spatial) mode operation and a low DMD while preventing the high index difference that leads to manufacturing difficulties and any loss increase. We finally describe our experimental results for a 6 LP (10 spatial) mode transmission line for use in a C + L band wavelength-division multiplexing (WDM) MDM transmission with MIMO DSP.

1. Introduction

Internet traffic has been growing rapidly and we must greatly increase the transmission capacity to accommodate a huge amount of traffic in the near future [1]. To deal with this capacity crunch, newly proposed multiplexing technologies such as space-division multiplexing (SDM) using multi-core fiber (MCF) [2–4], multi-mode fiber (MMF) [5–7], and multi-core multi-mode fiber [8–10] are being intensively investigated. By using MCF as a transmission line, we were able to increase the transmission capacity compared with that of conventional single-core fiber since multiple cores were arranged in a single fiber. On the other hand, by using MMF as a transmission line, we were able to increase the transmission capacity compared with that of conventional single-mode fiber since higher-order modes are utilized as transmitted channels. Early proposals for mode-division multiplexing (MDM) [11,12] focused on using conventional MMF with core diameters of 50–62.5 μm for short distances. However, these fibers may support 100 or more modes that couple with each other during transmission over even a moderate distance in a random manner due to environmental perturbation. As a result, practical demonstrations of MDM in MMF are restricted to the use of a limited number of modes and some form of spatial filtering, for example using MMF fused couplers [13,14] or butt-coupling [15].

Therefore, few-mode fibers (FMFs) designed to guide just a few modes were proposed for MDM transmission. Although in the broad sense FMF can be categorized as an MMF, it is called “few-mode fiber” to distinguish it from conventional GI-MMFs. One important difference between FMF and conventional GI-MMF is the number of propagation modes. Conventional GI-MMF typically accommodates several tens of modes. On the other hand, FMF has fewer modes (typically fewer than ten LP modes). Another important difference is their application area. GI-MMF has been widely deployed over short to medium distances (e.g. in data centers or local area networks). In contrast, FMF has been mainly investigated for use in large capacity networks to overcome the capacity limit of conventional single-mode fiber (SMF). FMF has the potential to provide high mode selectivity and low attenuation.

There are two main approaches for MDM transmission without/with multiple-input multiple-output (MIMO) digital signal processing (DSP) [16] to compensate for the crosstalk (XT) between non-degenerate modes (NDM-XT). MIMO DSP can also be used to deal with the LP modes degeneracies (spatial and polarization). In this paper, we defined the mode as LP mode (LP_{01}, LP_{11}, LP_{21}...), not spatial mode which includes the degenerate mode (LP_{01}, LP_{11a}, LP_{11b}, LP_{21a}, LP_{21b}...).

1. MDM transmission system without MIMO DSP for NDM-XT compensation
   Fiber and mode MUX/DEMUX with low modal XT is utilized. It consists of minimizing mode coupling so that each mode can be detected separately with a mode multiplexer/demultiplexer

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(MUX/DEMUX). The DSP complexity can remain close to that of a single mode fiber (SMF) transmission. However, insufficient modal XT suppression causes signal degradation.

2. MDM transmission system with MIMO DSP for NDM-XT compensation
   Multiple-input multiple-output (MIMO) DSP on the receiver side fully compensates for such linear impairments as dispersion and XT even if there is strong mode coupling in the fiber and/or MUX/DEMUX. The DSP complexity increment is a major issue as the number of modes and the transmission distance increase. If we are to reduce DSP complexity, we must reduce the differential mode group delay (DMD) in transmission fibers.

In the former case, 3 or 4 LP (5 or 6 spatial) mode transmission has been demonstrated with low DSP complexity using a transmission line consisting of a 40 km span of weakly-coupled four LP mode step index (SI) fiber [17–19]. On the other hand, for the latter case, it has been shown that a 6 × 6 MIMO transmission over 1000 km [6,20–22], 12 × 12 MIMO transmission over 708 km [7], 20 × 20 MIMO transmission over 125 km [23] and 30 × 30 MIMO transmission over 22.8 km [24] can be achieved by using optimized transmission line with graded index (GI) fiber.

In this paper, we focus on single-core few-mode fiber technologies and review recent progress on fibers for systems without and with MIMO DSP to compensate for modal XT. We next clarify how we design 6 LP (10 spatial) mode fiber with a low DMD to reduce the complexity of MIMO processing. Finally, we report experimental results for our 6 LP (10 spatial) mode transmission line and its applicability to MDM transmission with MIMO DSP.

2. State of the art of few-mode fiber

Various FMFs have already been proposed. They fall roughly into two categories; FMF for an MDM transmission system without MIMO DSP and with MIMO DSP. In this section, we introduce the state-of-the-art few mode fibers and design.

2.1. For MDM transmission system without MIMO DSP for NDM-XT compensation

FMF for an MDM transmission system without MIMO DSP should be carefully designed taking the following into account;

1. Bending loss of propagation mode.
2. Cut-off wavelength for undesirable mode.
3. Effective index difference (Δn_{eff}).

One way to reduce DSP complexity is to reduce the modal XT in the fiber and employ a less complex MIMO DSP. It is considered that FMF with a large effective index difference between modes Δn_{eff} is successful in preventing each mode from coupling owing to structural perturbations [25,26]. We assumed certain requirements for the fiber for *N* mode operation. Here, we define "*N* mode operation" as the propagation of *N* specific modes in a fiber for the target wavelength. Simple SI fiber was proposed for use without MIMO DSP because it is easy to design and manufacture [27,28]. For example, we set 2 LP mode operation with a target wavelength range of 1530–1565 nm corresponding to the C band. In this case, the cut-off wavelength of the LP_{21} mode as the third LP mode should be less than 1530 nm. In addition, the bending losses for the LP_{01} and the LP_{11} modes should be suppressed, and so we assumed a permissible bending loss of 0.1 dB/100 turns at a bending radius of 30 mm [29]. Fig. 1 shows the core radius *a* and relative index difference Δ relations of SI fiber that satisfies the requirements for *N* mode operation in the C band. Here, the solid curves correspond to a structure designed to realize a cut-off

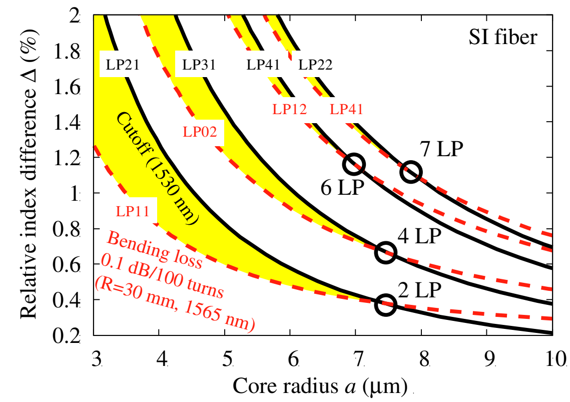

Fig. 1. SI fiber design for 2 LP, 4 LP, 6 LP, and 7 LP mode operation in C band.

condition at 1530 nm for the undesirable mode (LP_{21} mode in the case of 2 LP mode operation). The dashed curve corresponds to a structure designed to realize a bending loss of 0.1 dB/100 turns at a bending radius of 30 mm for the highest order propagation mode (LP_{11} mode for 2 LP mode operation). The bending losses at 1565 nm are the largest in the target wavelength range. Here, we calculated the bending loss of the wavelength using the Marcuse formula [30]. Thus, the desired structure was obtained in the area surrounded by the two curves. The effective area A_{eff} of the SIF is maximized at the intersection of the solid and dashed curves (a = 7.5 μm, Δ = 0.37% for 2 LP mode operation) while satisfying the requirements for *N* mode operation. For 4 LP, 6 LP, and 7 LP mode operation, we consider the bending losses of the LP_{02}, LP_{12}, and LP_{41} modes and the cutoffs of the LP_{31}, LP_{41}, and LP_{22} modes, respectively. Fig. 2 shows the index profiles of the proposed 2 LP mode [25] and 4 LP mode [27] and the designed 6 and 7 LP mode SI fiber. High concentration doping is needed so that the number of modes increases, whereas the core radius does not change very much. Fig. 3 shows the *N* LP mode operation dependence of SI fiber with minimum Δn_{eff} between all neighbor LP modes and A_{eff} in the LP_{01} mode at 1550 nm. With more than 2 LP modes, we can realize a Δn_{eff} between neighbor LP modes of around 1.0×10^{-3} and an A_{eff} for the LP_{01} mode of more than 100 μm^2, which is larger than that of conventional SMF because the core diameter is larger than that of SMF. Fig. 4 shows the effective index difference Δn_{eff} and A_{eff} of the LP_{01} mode at 1550 nm as a function of the relative index difference of 2 LP mode operation SI fiber with a *V* parameter of 3.6. Here, *V* parameter is defined as

$$V = \frac{2\pi}{\lambda} a n_{core} \sqrt{2\Delta} \quad (1)$$

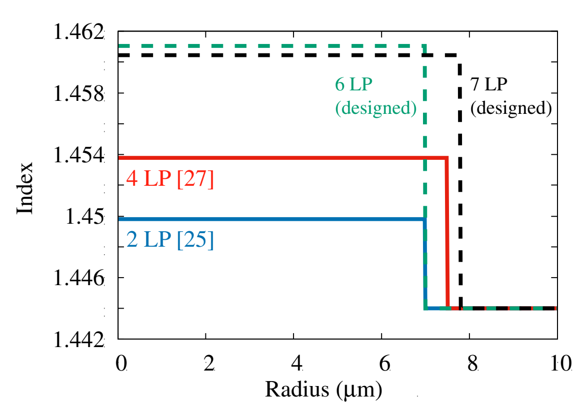

Fig. 2. Index profiles of SI fiber for 2 LP, 4 LP, 6 LP, and 7 LP modes.

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