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Invited Papers

Few-mode multicore fibers for long-haul transmission line

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ABSTRACT

Few-mode multicore fibers (FM-MCFs) that enable dense space-division multiplexing (DSDM) have the potential to drastically improve the fiber capacity. In designing the FM-MCFs, several issues that originate from multicore fibers and few-mode fibers must be considered. In this paper, these design issues such as inter-core crosstalk (IC-XT) and dispersion mode delay (DMD) are discussed. A three-mode 12-core fiber with low-DMD low-IC-XT achieves long-haul DSDM transmission over 500 km. The design concept, fiber design, and characteristics of the fabricated three-mode 12-core fiber are also described.

1. Introduction

The transmission capacity of optical communication systems using single-mode fibers (SMFs) has been expanded in accordance with the increase of IP traffic. However, there is a limitation of capacity of approximately 100 Tbit/s owing to the fiber fuse phenomenon and Shannon limit [1]. Space-division multiplexing (SDM), realized by multicore fibers (MCFs) and few-mode fibers (FMFs), is expected to overcome the capacity limit of the current optical communication systems. An MCF has multiple cores in a single cladding. An FMF supports multiple transmission modes in a single core. Spatial channel count (SCC) [2] is expanded by using each core or mode of an MCF and an FMF as signal channels, respectively. The MCFs and FMFs have achieved several transmission records. The first transmission capacity over 1 Pbit/s [3] and capacity-distance product over 1 Ebit/s·km were achieved by 12-core SM-MCFs [4,5]. In addition, a 22-core SM-MCF has achieved the highest transmission capacity of 2.15 Pbit/s [6]. A single-core 10-mode fiber has achieved a transmission capacity of 115.2 Tbit/s [7]. However, it is predicted that further improvement in SCC and transmission characteristics will be difficult for the SM-MCFs or FMFs, because inter-core crosstalk (IC-XT) in an SM-MCF increases as the core count increases, and inter-LP-mode crosstalk (IM-XT) in an FMF increases as the mode count increases. These crosstalks also prevent the SDM from realizing long haul transmission. Thus, in order to realize future dense SDM (DSDM) systems, multicore fibers with few-mode cores, known as few-mode multicore fibers (FM-MCFs), are being investigated. The SCC of a fiber can be increased by using an FM-MCF, because the SCC of an FM-MCF is the core count multiplied by the mode count. SCC of over 100 was realized by FM-MCFs [8–10]. However, long-haul FM-MCF transmission over 500 km has only been achieved by a three-mode 12-core fiber with an SCC of 36 [11].

In this paper, we present the design and characteristics of our fabricated three-mode 12-core FM-MCF with a cladding diameter (D_c) of 230 μm, low dispersion mode delay (DMD) of less than |63| ps/km, and low IC-XT of less than −51.6 dB/500 km. First, general issues required for designing an FM-MCF are explained. This is followed by a review of many types of proposed FM-MCFs. Thirdly, techniques to fabricate the fiber are depicted, which include a heterogeneous core arrangement, arranging cores in a square lattice, and a graded index in the core profile. Finally, measured characteristics of the fabricated fiber are reported.

2. FM-MCF design issues

MCFs can be categorized into coupled MCFs and uncoupled MCFs. In the case of coupled MCFs, the transmission LP-modes in each core are strongly coupled among the cores, and super-modes are generated. DMD can be decreased by the use of super-modes. In contrast, uncoupled MCFs use the cores as independent waveguides to reduce the signal processing load. Reported FM-MCFs have been mainly based on uncoupled MCF technology. In designing these uncoupled FM-MCFs, the following issues relating

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to the MCFs and FMFs design must be addressed: (A) IC-XT, (B) core layout, (C) IM-XT, and (D) DMD.

Issue A is a common problem with SM-MCFs. Minimal IC-XT is preferable for long-haul transmission with multilevel modulation. For example, QPSK and 32QAM transmission with a Q-penalty of 0.5 dB require IC-XT values of less than −19 dB and −29 dB, respectively [3]. For SM-MCFs, IC-XT between the LP_{01} modes is the only IC-XT of concern. However, for FM-MCFs, we should also take into account the IC-XT relating to higher-order modes such as between the LP_{11} modes ($XT_{11\text{-}11}$) [12]. There is also IC-XT between different propagating modes such as between the LP_{11} mode and the LP_{01} mode ($XT_{11\text{-}01}$). Fig. 1 shows an example of the calculated core pitch dependencies of IC-XTs after 100 km propagation at 1550 nm and a bending diameter of 210 mm. Power coupling theory is used to calculate the IC-XT [13]. We assumed a core radius of 6.47 μm and a relative refractive index difference of 0.45% with a step index profile that supports LP_{01} and LP_{11} mode transmission over the C + L band (1530 nm–1625 nm) in practical use. The calculated effective areas (A_{eff}s) of the LP_{01} and the LP_{11} modes are 110 μm^2 and 170 μm^2 at 1550 nm, respectively. It is observed that $XT_{11\text{-}11}$ is larger than $XT_{01\text{-}01}$ by approximately 40 dB. This is because that higher-order mode has relatively large A_{eff} compared to that of the LP_{01} mode, and the confinement of higher-order modes is weaker than that of the fundamental mode. The $XT_{01\text{-}11}$ is also small because the difference in the effective indices between the LP_{01} and LP_{11} modes is large [14]. Thus, XT is dominated by $XT_{11\text{-}11}$ and therefore FM-MCFs should be designed with careful consideration of IC-XT related to the highest-order modes.

A common approach for reducing IC-XT is enlarging core pitch, which leads to a large D_c and deterioration of the mechanical reliability of a fiber. Reducing effective core area (A_{eff}) can also suppress IC-XT. However, reduced A_{eff} is inadequate for long-haul transmission systems owing to non-linear effects. In general, A_{eff} differs according to the propagation mode, and the A_{eff} of the LP_{01} mode is the smallest of all modes. It is desirable for the A_{eff} of the LP_{01} mode to be larger than that of conventional SMFs of around 80 μm^2 at 1550 nm.

Two methods have been proposed to reduce IC-XT without enlarging core pitch or reducing A_{eff}. One approach is to introduce a low-index layer, such as index trenches [15] or air holes [16], to surround each core. Air-holes have the largest index contrast and confine light more strongly than an index trench. However, it can be difficult during the drawing process to maintain their size. In addition, air-holes at a splice point can easily collapse, causing variation of the mode field diameter (MFD) and large splice loss. Index-trench technique is widely used in bending insensitive fibers to improve the bending-loss characteristics of a fiber. It can be fabricated by doping fluorine into the cladding. One issue with this structure is that the cutoff wavelength of the inner core lengthens rapidly if the core pitch becomes smaller than a certain threshold [15], because the confinement of the modes in the inner core is increased by the index trench of the surrounding cores. Fig. 2 shows the calculated LP_{21}-mode 22-m cutoff wavelength ($\lambda_{cc\text{-}21}$) of the center core of a two-LP-mode seven-core fiber as a function of core pitch [17]. The core parameters are shown in Fig. 3. A full vector finite element method was used for the calculation [18]. The $\lambda_{cc\text{-}21}$ increases rapidly when the core pitch is less than 45 μm. The core pitch of a trench assisted FM-MCF is thus also limited by the cutoff wavelength, not only by the IC-XT.

Another approach involves employing a heterogeneous core arrangement with cores of different relative effective index (n_{eff}). Fig. 4 illustrates the IC-XT behavior between the same propagation modes of a homogeneous MCF and a heterogeneous MCF as a function of the bending radius. The IC-XT of a homogeneous MCF changes proportionally as the bending radius increases. In the case of a heterogeneous MCF, the IC-XT changes radically at a threshold bending radius (R_{pk}) given by

$$R_{pk} = \frac{n_{eff}}{n_{eff}}\Lambda,$$

where n_{eff} is the effective index of a propagating mode in a core, Δn_{eff} is the difference of n_{eff} between cores, and Λ is the core pitch [13]. In the range of bending radius greater than R_{pk}, IC-XT is drastically reduced compared to a homogeneous MCF because the phases do not match. We can thus reduce the IC-XT of an MCF by setting R_{pk} below the effective bending radii in the cables. However, heterogeneous A_{eff} is not preferable because it leads to equalizing splice loss and optical signal-to-noise ratio (OSNR) over all cores, An SM-MCF with heterogeneous n_{eff} and homogeneous A_{eff} that has overcome these issues was reported [19].

Issue B is related to issue A. In the case of using an MCF in an actual transmission line, all cores are assumed to be excited equally and each core receives IC-XT from all neighboring cores. The aggregated IC-XT, $\text{IC-XT}_{\mathrm{worst}}$, is calculated by

$$\text{IC-XT}_{\mathrm{worst}} = \text{IC-XT} + 10 \cdot \log n,$$

where n is the number of neighboring cores surrounding each core. A small n is preferable to suppress $\text{IC-XT}_{\mathrm{worst}}$. In order to both maximize the core count of an MCF and reduce n, various core layouts have been proposed for SM-MCFs, and some of these are also used for FM-MCFs. Fig. 5 summarizes the MCF core layouts presented to date: hexagonal close-packed structure (HCPS), one-ring structure (ORS) [20], dual-ring structure (DRS) [21], and square lattice structure (SLS) [22].

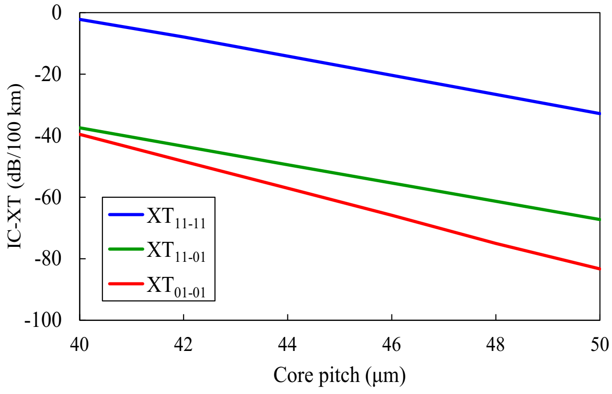

Fig. 1. Calculated IC-XT as a function of core pitch after 100 km propagation. Bending diameter is 210 mm, and wavelength is 1550 nm.

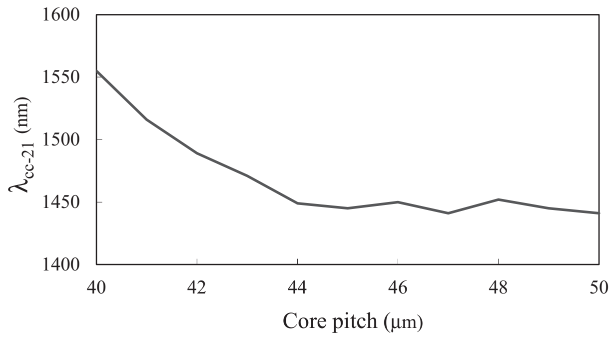

Fig. 2. Calculated 22-m LP_{21}-mode cutoff wavelength ($\lambda_{cc\text{-}21}$) of the center core of a two-LP-mode seven-core fiber as a function of core pitch.