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Optimal design for crosstalk analysis in 12-core 5-LP mode homogeneous multicore fiber for different lattice structure

Dablu Kumar*, Rakesh Ranjan

Optical Fiber Communication and Photonics Lab, Department of Electronics and Communication Engineering, National Institute of Technology (NIT) Patna, India

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ABSTRACT

12-Core 5-LP mode homogeneous multicore fibers have been proposed for analysis of inter-core crosstalk and dispersion, with four different lattice structures (circular, 2-ring, square lattice, and triangular lattice) having cladding diameter of 200 μm and a fixed cladding thickness of 35 μm. The core-to-core crosstalk impact has been studied numerically with respect to bending radius, core pitch, transmission distance, wavelength, and core diameter for all 5-LP modes. In anticipation of further reduction in crosstalk levels, the trench-assisted cores have been incorporated for all respective designs. Ultra-low crosstalk (-138 dB/100 km) has been achieved through the triangular lattice arrangement, with trench depth $\Delta_2 = -1.40\%$ for fundamental (LP_{01}) mode. It has been noted that the impact of mode polarization on crosstalk behavior is minor, with difference in crosstalk levels between two polarized spatial modes as ≤ 0.2 dB. Moreover, the optimized cladding diameter has been obtained for all 5-LP modes for a target value of crosstalk of -50 dB/100 km, with all the core arrangements. The dispersion characteristic has also been analyzed with respect to wavelength, which is nearly 2.5 ps/nm km at operating wavelength 1550 nm. The relative core multiplicity factor (RCMF) for the proposed design is obtained as 64.

1. Introduction

The Multicore fiber (MCF) is an effective and promising technology to overcome the transmission capacity limitations (100 Tbit/s) [1] of conventional single core single mode fiber (SMF). The MCF with space division multiplexing (SDM) technique can provide a huge bandwidth and very high information carrying capacity [2–4]. Signal transmission for most of the digital modulation schemes (such as, QAM, PSK, and FSK) can be anticipated through the MCFs [5]. A MCF includes more than one core in same cladding region with single mode or few mode [6] propagations in each of these cores. In spite of all these features, the MCF may have some major constraints, such as, crosstalk, non-linearities, dispersion, etc. Researchers, around the world, are trying to minimize these issues in order to achieve an efficient optical fiber technology with extremely low signal distortions. For the design of weakly coupled MCF, the inter-core crosstalk (ICXT) is one of the significant factors. However, ICXT can be controlled within certain limit (usually less than -30 dB/100 km) [7] by precise selection of core pitch and cladding diameter values. The distance between outermost core centre and cladding edge, i.e., cladding thickness (CT), and cladding diameter (CD) are the conclusive parameters of the MCF designs. An appropriate selection of CT and CD values can provide high core density arrangement along with the suppressed the micro-bending losses [8]. However, the large cladding diameter is undesirable in terms of its mechanical reliability issue [9].

In order to obtain the ultra-low ICXT in MCFs with optimal design parameters, the analysis of 12-core homogeneous MCFs for 5-LP (linearly polarized) modes with low dispersion value have been presented in this paper. Four MCF designs, namely, circular, 2-ring, square lattice, and triangular lattice have been investigated to establish the best possible core arrangement in respect of crosstalk performance under the constraints of fixed values of cladding diameter and thickness. The analysis presented can be beneficial for different characterization and fabrication aspects of MCF in order to achieve the enhanced information carrying capacity by fiber optic technology. The 5-LP modes are fundamentally consisting of 8 spatial modes; LP_{01}, LP_{11x}, LP_{11y}, LP_{21x}, LP_{21y}, LP_{02}, LP_{31x}, and LP_{31y} modes, where each mode is degenerated in ‘x’ and ‘y’ polarizations except LP_{01} and LP_{02}. In order to maintain the target crosstalk level, the core diameter and refractive index difference have to be modified depending on the number of modes to be propagated. The trench assisted (TA) core arrangement, which is one of the efficient approach to improve the mode confinement and hence, to reduce the ICXT to extremely-low level, has also been implemented and the crosstalk level up to -138 dB/100 km has been achieved for the

* Corresponding author.
E-mail addresses: dablu.ece15@nitp.ac.in (D. Kumar), rr@nitp.ac.in (R. Ranjan).

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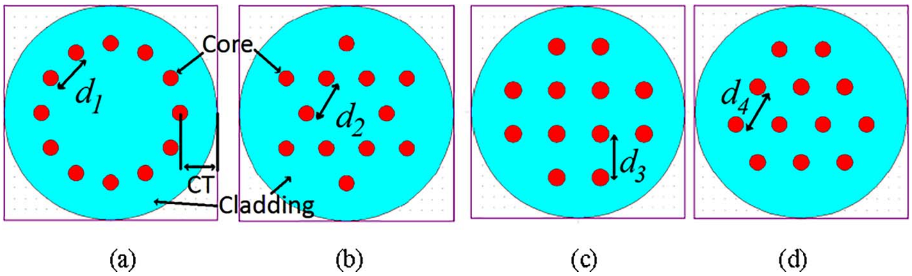

Fig. 1. A 12-core MCF structures (a) Circular design, (b) 2-Ring design, (c) Square lattice and (d) Triangular lattice design.

fundamental mode propagation. The impacts of core pitch, core diameter, fiber bending, wavelength, and transmission distance have been demonstrated on the crosstalk behaviors. Further, the analysis of effective refractive index with respect to wavelength and relative refractive index difference for all 5-LP modes is beneficial to realize the precise crosstalk behavior in MCFs.

2. Design parameters

The homogeneous MCFs with 12-cores have been arranged in four different structures as shown in Fig. 1. The first is circular ring arrangement [8], where all the 12 cores are fitted in a ring, the second structure is of 2-rings [8], where 6 cores are fitted in inner ring and remaining 6 cores are placed in outer ring. The third arrangement is of square lattice type, and the fourth arrangement is the triangular lattice or hexagonal close packing (HCP) structure [6]. The main motivation for these designs is to fix the clad thickness (CT = 35 μm), so that the micro-bending loss in outer cores can be minimized as much as possible. A reduction in CT may raise the transmission loss at outermost cores by increasing the bending and confinement losses [18]. The core and cladding diameters are taken as 16 μm and 200 μm, respectively for all four types of MCF arrangements. The analysis of crosstalk (XT) has been done with normal step index core profile and trench assisted (TA) step-index core structure (as shown in Fig. 2).

The refractive index profiles of a step-index core and trench-assisted (TA) step-index cores have been illustrated in Fig. 3, where n_0, n_1, and n_2 are the refractive index of the clad, core and trench respectively, while, Δ_1 and Δ_2 are the relative refractive index difference of core-clad and clad-trench, respectively with n_0= 1.45, $\Delta_1 = 0.70\%$, $\Delta_2 = -0.70\%$ and -1.40%. The distance between two adjacent cores is designated as pitch 'Λ' (i.e., d_1, d_2, d_3, and d_4) as shown in Fig. 1, where, d_1,d_2, d_3 and d_4 are the core-to-core distance between any two adjacent cores in circular, 2-ring, square, and triangular design structures respectively.

In Fig. 3, x_1 is the core radius, x_2 and x_3 is the distance from the inner edge of the trench to the core centre, the distance from the outer edge of the trench to the core centre, respectively. W_t is the trench width, with $W_t = 0.75x_1$, and $x_2 = 1.25x_1$. The refractive index of core is assumed as n_1 for both the case of normal step-index and TA step-index cores. For the analysis of core-to-core crosstalk, the propagation wavelength (λ) is assumed as 1550 nm, and the length of fiber (L) as 100 km. By keeping the clad diameter (CD) and clad thickness (CT) as 200 μm and 35 μm respectively, the values of d_1, and d_2 can be obtained as:

$$d_1 = (CD{-}2 \times CT) \times \sin(15°)\ \mu\text{ m}= 33.65\ \mu\text{m} \quad (1)$$

and

$$d_2 = \frac{(CD{-}2 \times CT)}{2} \times \tan(30°)\ \mu\text{ m}= 37.52\ \mu\text{m} \quad (2)$$

Whereas, the value of $d_3$and d_4 can be calculated as [6]:

$$d_3 = \frac{CD{-}(2 \times CT)}{\sqrt{10}}\mu\text{ m}= 41.11\ \mu\text{m} \quad (3)$$

$$d_4 = \frac{CD{-}(2 \times CT)}{2 \times \sqrt{7/3}}\mu\text{ m}= 42.55\ \mu\text{m} \quad (4)$$

3. Crosstalk analysis

The inter-core crosstalk is a major issue for the weakly-coupled MCF, especially for higher mode transmission. The crosstalk between the neighboring cores can be expressed in terms of power signal, as some amount of the optical signal power transmitting through the one of the core is coupled with its adjacent cores during the signal propagation as illustrated in Fig. 4. The inter-core crosstalk between two cores can be expressed as $XT\,(dB) = 10\log_{10}(P'/P)$, where, is the output power from the core p, and P' is power coupled from neighboring core q [10].

The crosstalk is a random phenomenon, dependent on different parameters of optical fiber/waveguide. The coupled mode theory (CMT) and coupled power theory (CPT) [11,14] have been extensively applied to estimate the average crosstalk in MCFs, including the bending perturbations [21]. The coupled mode equation (CME) for multicore fiber can be obtained as [11],

$$\frac{dA_p}{dz} = -j\sum_{p\neq q} k_{pq}A_q(z)\exp(j\Delta\beta_{pq}z)f(z) \quad (5)$$

where, A_p and A_q is mode amplitude in core p and q respectively, $\Delta\beta_{pq}$ is the propagation constant difference between cores p and q, and z is the direction of propagation, $f(z)$ is the random phase function, and k_{pq} is the mode coupling coefficient, which can be expressed as [12],

$$\kappa_{pq} = \frac{\omega\varepsilon_0\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(N^2{-}N_q^2)E_p^*\cdot E_q\,dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}u_z\cdot(E_p^*\times H_p + E_p\times H_p^*)dxdy} \quad (6)$$

The coupled power equation (CPE) can be obtained as [11],

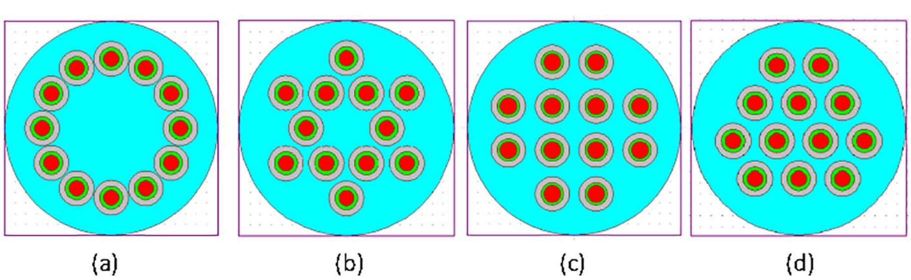

Fig. 2. A 12-core MCF structures with trench-assisted index profile (a) Circular design (b) 2-Ring design, (c) Square lattice and (d) Triangular lattice design.