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Design of low crosstalk and bend insensitive optical interconnect using rectangular array multicore fiber

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ABSTRACT

A design strategy for achieving minimum crosstalk in a space division multiplexed 2×4 multicore fiber (MCF) for application in next generation exa-bandwidth optical interconnects is proposed. To evaluate crosstalk in adjacent cores of MCF, a semi-analytical approach based on finite element method and coupled power theory is applied. The dependence of crosstalk on various MCF parameters – such as index profile parameter, core to core pitch and bending radius – is investigated. It is shown that optical interconnects based on heterogeneous core MCF with triangular index profile and optimum core to core pitch, can be configured to have minimum crosstalk per unit length. Moreover, such interconnects show high degree of bend tolerance for both small and large bending radii.

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1. Introduction

Due to steadily increasing data rate requirements and to overcome bandwidth density drives, optical interconnect (OI) has become a key technology to realize signal transmission in box-to-box, rack-to-rack, board-to-board, and chip-to-chip interconnect applications [1]. It has triggered research interest as a promising network choice to achieve future exaflop (10^{18}) high performance computing systems [2]. For next generation supercomputing as well as data centers, key issue for design of OI is to increase the channel density with minimum escalation in link cost and power budget [3]. OI configuration based on multicore fiber (MCF) shows promise to cope with ever increasing demands on bandwidth within data centers, terabit switches, core routers, digital cross connect systems and high performance computers [4,5]. MCF supports multichannel transmission compatible with 2D arrays of vertical cavity surface emitting laser (VCSEL) transmitter [6]. Although, fiber ribbons or individual fibers increase the fiber density [7], they are costly, bulky, consume more power and do not meet the very high density requirement of end to end optical interconnects for data transmission. Hence they cannot be an alternative to MCF with space division multiplexing capacity to overcome the exponentially growing demand in data traffic of current optical communication system [8].

MCF which was proposed couple of decades ago [9], due to its space division multiplexing capability has become a strong candidate to configure novel OI [10] which can exploit huge optoelectronic bandwidth disparity between requirement and availability. For efficient usage of MCF as OI, one of the major issues that has to be addressed is crosstalk between cores which depends on refractive index profile of individual cores and distance between neighboring cores. Moreover as bends are inevitable for interconnects, bend induced index perturbations and core density strongly affects the crosstalk characteristics in MCF [11,12]. To estimate crosstalk between adjacent cores in a MCF, coupled mode theory [13,14] and coupled power theory [14] are applied. Furthermore, to reduce the crosstalk in a MCF, research work on homogeneous MCFs [15], heterogeneous MCFs [16], trench assisted MCFs [17] as well as hole assisted MCFs [18] has been recently published. These novel MCFs maximize channel density and reduce crosstalk but their use as an optical interconnect is relatively less investigated. Recently, α index profile hexagonal seven core single mode MCF has been reported to reduce intercore crosstalk [19]. In order to realize low crosstalk and high core density, a holey microstructured MCF based optical interconnect is also reported recently [20]. The hexagonal arrangement of cores in MCF discussed in Refs. [19,20] is more closely packed but not compatible with edge coupling requirement of silicon photonic transceiver. More compatible is rectangular arrangements of four and eight core fiber proposed for optical interconnects in which crosstalk is calculated by the coupled mode theory followed by experimental results [21,22].

In this paper, quantitative and qualitative design parameters of an optical interconnect are being reported. The optical interconnect consists of 2×4 rectangular arrayed heterogeneous MCF. Individual cores have α index profile that can be made compatible with edge coupling to silicon photonic transceiver chips. The optimal design is based on minimizing crosstalk obtained by coupled power theory [23,24] for index parameter α, intercore distance Λ, and bending radius. The results are compared with

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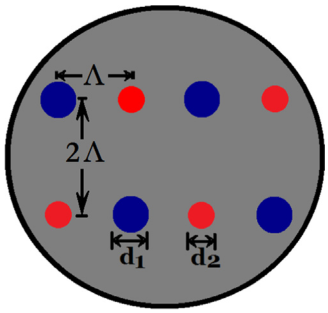

Fig. 1. Schematic of 2 × 4 rectangular array heterogeneous MCF.

that of linear 1 × 4 core geometry of MCF and hexagonal seven core MCF [25]. The paper is organized as follows: in Section 2, the geometry and design of heterogeneous 2 × 4 MCF with α index profile is discussed. For sake of continuity, mathematical approach based on coupled power theory [25] to obtain crosstalk in MCF is briefly discussed. The fiber propagation parameters required to implement coupled power theory are obtained through commercial software FemSIM. In Section 3, simulation results and design approach of a bend-insensitive heterogeneous MCF for optical interconnect applications are elucidated. Finally, Section 4 concludes the paper.

2. Theory

The schematic cross section of proposed optical interconnect with rectangular arrayed MCF is shown in Fig. 1. It is designed such that MCF with rectangular array of eight cores [5] is well matched to the computer compatible parallel communication links. The cores can have α index profile tailored and can have same or different core diameters. The refractive index profile of the core is expressed as

$$n(r) = n_c\sqrt{\{1-2\Delta(r/a)^{\alpha}\}} \quad a \geq r \geq 0 \tag{1}$$

here, $n(r)$ is refractive index at a radial distance r from fiber axis, a is the core radius, n_c is the refractive index of the core at $r=0$, n_{cl} is homogeneous ($n(r)=n_{cl}$ for $r \geq a$) refractive index of the cladding, Δ represents relative refractive index difference between core and cladding and α defines the shape of the profile. To reduce crosstalk, there should be a large phase difference between modes of the adjacent cores and moreover power in the core should be tightly confined to reduce effect of perturbations. One way to increase the difference in propagation constant and power confinement is to increase the relative index difference. However, to maintain the single mode propagation, core diameter is proportionately reduced. For homogenous MCF, individual cores are of diameter $d_1 = 5$ μm with relative refractive index difference $\Delta = 0.8\%$ and cladding refractive index 1.45. Inhomogeneous MCF is designed with adjacent cores of different diameter and Δ. Relative refractive index differences considered are $\Delta_1 = 0.8\%$ and $\Delta_2 = 0.6\%$ with core diameters $d_1 = 5$ μm and $d_2 = 4.8$ μm for bigger and smaller cores respectively. With the above parameters, in FemSIM, all cores in rectangular array are arranged with pitch and separation between the linear arrays of two rows is 2Λ. The operating wavelength is assumed to be 1.55 μm. The cladding diameter depends on number of cores and core to core pitch. When spacing between cores is large, the flexibility of fiber reduces having a serious impact on mechanical reliability due to large cladding diameter. For present analysis, the cladding diameter is assumed to be 200 μm [20].

In order to analyze intercore crosstalk in MCFs, coupled power theory [23,24] is employed. First, mode coupling coefficient κ and power coupling coefficient h between two neighboring cores of MCFs with α index profile is investigated. The expression of κ between two cores is given as [26]

$$\kappa_{mn} = \frac{\omega\varepsilon_0 \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}(N^2-N_n)E_m^{*}.E_n dxdy}{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} u_z.(E_m^{*}\times H_m + E_m \times H_m^{*})dxdy} \tag{2}$$

where, ω is angular frequency of sinusoidally varying electromagnetic field, ε_0 is permittivity of the medium, and u_z represents outwardly directed unit vector. The pair m and n is either (1, 2) or (2, 1). E and H represent the electric and magnetic fields respectively. The refractive-index distribution in the entire coupled region is expressed as [17].

$$N^2 = N_1^2 + N_2^2 - n^2 \tag{3}$$

where N_1 and N_2 represent the refractive index distribution of each core with α index profile, and n represents the refractive index distribution outside the cores. $N^2 - N_2^2$ is zero except inside the core 1, while $N^2 - N_1^2$ is zero everywhere except inside core 2. To calculate coupling coefficient κ full vector finite element method have been proposed [27]. In this paper finite element method based commercial mode solver FemSIM is used to evaluate effective index and electric field distribution of both MCF models. The data thus obtained is numerically integrated in MATLAB to calculate κ between adjacent cores.

Analytical approaches based on exponential, Gaussian, and triangular autocorrelation functions were proposed to evaluate the power coupling coefficient h for bend fibers [14]. However, for bending radius larger than a threshold value R_{th} the crosstalk behaviors are not well simulated with Gaussian autocorrelation function in phase mismatched region [11,12,14]. Moreover, value of h predicted by triangular autocorrelation function is not accurate [14]. The reason for discrepancy of the two autocorrelation functions is that they work satisfactorily when crosstalk is independent of segment length [14]. It is true for homogenous core straight MCF when modes are phase matched. The two correlation functions do not give appropriate results in case of index mismatch for small bending radius when crosstalk is strongly dependent on the segment length [14]. Therefore, to realize accurate estimation of intercore crosstalk for phase mismatch configurations in MCF exponential autocorrelation is more efficient [25]. The power coupling coefficient for exponential autocorrelation is expressed as [25]

$$h_{mn} = \frac{2K_{mn}^2 d_c}{1+(\Delta\beta_{mn} d_c)^2} \tag{4}$$

where m, n represent the core m and n, K_{mn} is the average value of κ_{mn} and κ_{nm} and satisfies the law of power conservation [14], $\Delta\beta_{mn}$ is the difference of equivalent propagation constant between cores m and n, and d_c is the correlation length. The simulation results with d_c=0.05 m agree well with the measurement data [28], and it is the preferred value for the estimation of crosstalk in this paper. The crosstalk between two α index profile cores of MCF over a length L and average power coupling coefficient $\overline{h}_{mn}$ is estimated by coupled power theory as [25]

$$X_T = \tanh(\overline{h}_{mn} L) \tag{5}$$

The above expression is independent of the twist rate of the fiber which has to be considered otherwise [11,14,28].

3. Results and discussion

For calculation, core to core pitch Λ and spacing 2Λ between two linear arrays of core as shown in Fig. 1, is assumed to be 30 μm

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