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Mode coupling in mode division multiplexing techniques for futuristic high speed optical networks and exploring optical fiber parameters to control mode coupling

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ABSTRACT

Fiber optic communications are inevitable to achieve higher data rates of modern telecom networks. After utilization of Wavelength division multiplexing, higher order modulations and polarization multiplexing, mode division multiplexing is a new dimension to achieve higher transmission capacity for optical fiber communication links. Different spatial distributions of optical energy along cross sectional area of optical fiber allows simultaneous transmission of data by considering each mode as an independent channel. During such simultaneous transmissions, possibility of mixing of signals amongst modes causes signal degradations and acts as limiting factor for bandwidth – distance product of the link. This effect of mode coupling has been explored in this article by presenting its mathematical formulations. A simulation has been performed to study the impact of fiber constructional parameters on mode coupling using optical wavelengths used for telecommunication systems. The observations help to develop fiber for reduced mode coupling for particular group of modes and operating wavelengths. This article paves the way forward for study of mode coupling in micro and macro bending conditions for forthcoming research endeavours.

1. Introduction

Disruptive innovations in information technology systems and devices are pushing the requirements of higher data rates for personal and commercial electronic communications networks. In fixed line telecom networks, digital subscriber lines (DSL) based on twisted pair copper wires are about to reach their limits of bandwidth – distance product to serve modern data intensive applications. Therefore, fixed line networks are migrating their access network from copper lines to fiber to the home. On the other hand, similar reasoning caused development of next generation standards for core and access networks for cellular networks. In a quick duration of less than a decade, commercial deployments moved from third generation cellular systems to data focused fourth and fifth generation cellular systems. Many telecom operators have even deployed their first batch of fifth generation (5G) cellular systems. 5G and onwards cellular systems are designed to meet current and futuristic high data rate requirements of every user. Therefore, optical fiber communication is replacing microwave backhaul of radio access networks in futuristic cellular systems [1]. These scenarios in fixed line and wireless networks indicate the efficient and extensive use of fiber optic communication to avail the high data rate capacity of optical fibers.

Besides use of optical fiber on access networks, core network in telecommunication systems are already using optical fibers for long and short hauls communications. Data traffic from multiple access networks converge on central nodes and consequently pose manifold data rate requirements on transport nodes of telecommunication service providers.

Telecom industry has experienced the utilization of higher order modulation schemes to increase the bit rate on a single fiber as compared to classical method of on-off keying in optical fiber communication. Introduction of coherent communication in light wave systems enabled to achieve higher data rates on any single wavelength. Introduction of wavelength division multiplexing further extended the data carrying capacity of optical fiber in infrared region from 770nm to 1675nm wavelengths [2,3]. Addition of extra degree of polarization multiplexing has also been used for enhancement of single fiber optic capacity. Despite all developments briefly mentioned here, requirement of data rates transmission in backhaul networks is increasing. The Fig. 1 describe the trend and expectations of data rate requirements from optical fiber networks [4].

These requirements are demanding to explore new degree of freedom for data transmission on optical fiber because DWDM and higher order modulations schemes are approaching to Shannon limits of 6 bits/s/Hz in C and L band [5]. Besides efforts of improving data rate with multiple modulation and multiplexing techniques [6], research efforts are made to explore mode division multiplexing (MDM) as potential dimension for increasing capacity of optical fiber channel.

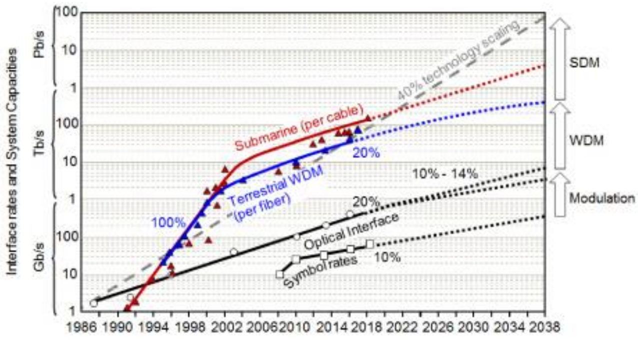

Fig. 1. Evolution of technologies in optical fiber system to achieve higher data rates [4]

Since initial demonstrations of optical fiber for telecommunication systems in 1975, concept of mode division multiplexing has been an intriguing factor. Dominated by dispersion factor, most of the research aligned to explore possibilities in single mode fibers and increased capacity of optical channel by efficient modulation schemes, wavelength division multiplexing and polarization multiplexing. These methods served the industry requirements of channel capacity over single mode fibers for decades. However, current developments in information technology urge telecom operators for continuous upgradation of their transmission networks for higher capacities hence the need emerged to explore additional capacities on single fiber. Therefore, significant research has been directed to explore the utilization of spatial modes as independent channels to increase the fiber capacity.

Modes interference, also known as mode coupling has been a serious and unavoidable phenomenon in optical fiber communication. Recent advancements of coherent receptions and improved signal processing techniques has raised the probability of finding a workable mode division multiplexing in long distance and high speed fiber communication.

According to the well-known Shannon theorem, capacity of the optical fiber observe upper bound of 100 T bits/s corresponding to filling the C and L band for optical fiber channel. Deployment of additional fibers for increasing the system capacity is cost oriented project and raise the concerns of cost per bit and power consumption in ever growing telecom networks. In this scenario adding an additional degree of freedom in the fiber communication will help to extract the additional capacity from fiber networks.

After brief description of significance of mode division multiplexing in telecom networks in section I of introduction, we will proceed to explore the effects of mode coupling as limiting factor in optical networks. In Section II, we summarize the relevant research endeavors which describe the significance of MDM and role of mode coupling. In Section III, we present the mathematical model to demonstrate the factors of mode coupling. A simulation on selected parameters and their impact on mode coupling has been presented in section IV. Article concludes by presentation of final remarks in section V.

2. Related Works and Literature

In Mode division multiplexing (MDM), signals transmitted on different modes have spatial overlaps therefore modes exchange the energy during transmission. This exchange of energy amongst modes is the mode coupling effect. Besides intermodal interference or cross talk, energy of some mode may couple back to the parent mode due to difference of group velocities. Such mode coupling causes inter-symbol interference in mode division multiplexing. Alike wireless communications, MIMO signal processing can be used at receiver to mitigate the effects of cross talk and inter-symbol interference. In case of conventional multi-mode fiber, larger number of modes pose higher mode coupling and Differential Mode Group Delays (DMGD). These higher level of mixed signals require complex signal processing for equalization. The signal processing complexity makes multi-mode communication unfeasible for large distance communication [7]. However, few mode fiber add additional capacity with comparable signal processing capacity.

Besides the consideration of inter-symbol interference and cross talk, strong mode coupling can exhibit a potentially useful phenomenon. Strong mode coupling makes temporal dispersion to scale with square root of fiber length as compared to linear scaling in case of weak coupling. In [8], the authors argued that strong coupling invokes an opportunity in reduction of signal processing effort of correct recovery of signal.

Different researchers have reported the mode division multiplexing to achieve high data rates. A demonstration of 100Gbps over two modes have been reported by [9] over the distance of 40Km. Three mode experiment to achieve 2Tbps exploiting all degrees of freedom in wavelength, polarization, and space [10]

The few mode transmission has been used in passive optical access network to increase the information carrying capacity of optical network. In [11], the work demonstrated the experimental evaluation of linear mode coupling and its impact on MIMO equalization performance. This work used an experimental model to compare the performance of graded index multi-mode fiber, step index multi-mode fiber and step index single mode fiber. It reports successful MDM-WDM PON over a distance of 10Km.

Besides the reports of successful demonstration of MDM in optical networks, there are useful research endeavors to understand the impact of mode coupling on overall performance of MDM based optical links. As reported in [12], the researchers explored the impact of mode coupling due to mechanical movements and vibrations in optical fibers. This model examined the mode coupling in an experimental mode for various types of fiber. This work does not mention the mathematical model of mode coupling.

In [13] the mode coupling phenomena has been presented for graded index fibers. This article focused on the study of mode coupling due to micro bends in graded index fiber only. It does not elaborate the concept of mode division multiplexing rather this classical study focused to build the argument for development of single mode fibers instead of multimode fibers used in the early age of optical fiber communication.

An interesting study of spatial and polarization mode coupling in multimode fibers for graded index fibers has been presented in [14]. They developed a model to find principal modes in the presence of modal and polarization coupling.

The impact of mode coupling in form of group delays for graded index fibers has been explored in [15]. They focused on study of micro bends. Their work excludes the variation of index of fiber and diameter of core in terms of their relationship of coupling caused delays.

In another research article [16], authors used power flow equations to study mode coupling in plastic fibers and compared the signal distributions in glass fibers. They described numerical solution using explicit finite different method.

There is significant research going on to explore spatial diversity by using the multi cores in a single clad formation. Although Multi core fibers exhibit good potential of increase in transmission capacity, it requires a new formation of optical fiber cables hence increase in network deployment costs. On the other hand, multi-mode fibers are amongst the early technology variants of optical fiber cables. Multi-mode fibers are better in terms of cost of productions and deployments as compared to introduction of new type of multi core fibers.

In light of presented references in this section, we established the significance of mode division multiplexing in optical networks to achieve high transmission capacity. Various experiments has been reported in research circles. Some has been cited here for sake of reference. Besides the demonstrations of MDM in optical transmission a sizeable research effort is available to study mode coupling in MDM links. Some most relevant articles has been cited here. Majority of the articles argue the presence of mode coupling, its impact on transmission capacity and relation to operational parameters of optical fiber. In our article we have chosen to explore the impact of mode coupling in step index fibers with respect to constructional parameters of fiber. This effort induces the uniqueness of this article as compared to reported works in this domain of knowledge.

3. Mode Coupling Model

In Optical fibers, light is an electromagnetic signal which is modelled as an electric field with amplitude and phase. Transverse modes behave as orthonormal signals hence resultant electric field in optical fiber is sum of orthonormal modes as expressed in Eq. (1)

$$E = \sum_m A_m\, E_m(x,y)\, \exp\,(j(\omega t - \beta_m z) \qquad (1)$$

Here $E_m(x,y)$ represent the electric field on fiber cross section for m^{th} mode and its propagation constant is β_m [17]. Here A_m models the amplitude of m^{th} mode. In absence of any undesired perturbation, the modes expressed in Eq. (1) exhibit the orthonormal behavior by satisfying the relationship in Eq. (2)

$$\int E_n^*(x,y).E_m(x,y)dxdy = \frac{2\omega\mu}{|\beta_m|}\delta_{mn} \qquad (2)$$

Overlap of electric fields of mode m and n is dependent on δ_{mn} which accounts the signal mixing between both modes. In ideal fibers with no undesired perturbations, these modes traverse through the longitudinal axis of fiber, the length of fiber, without intermixing. However, there are always some practical considerations in terms of manufacturing variations in core clad geometry, some undesired micro bends and index variations. These practical factors causes the mixing of normal modes along the fiber length. Therefore, amplitude of electric field represented in Eq. (1) is converted to a function of fiber longitudinal axis. This new form of total electric field in optical fiber is expressed in Eq. (3)

$$E = \sum_m A_m(z)E_m(x,y)\exp(j(\omega t - \beta_m z) \qquad (3)$$

Here $A_m(z)$ represent the variation of amplitude in normal mode m due coupling with other modes as electric field travel through fiber length. Now these modes cannot be considered as Eigen modes.

According to the coupled mode theory presented in [18], a wave Eq. representing the variations of amplitude of in mode m with respect to fiber length describe the coupling coefficient of mode ‘m’ with mode ‘n’

$$\frac{dA_m}{dz} = \sum_n K_{mn}A_n \exp(j(\beta_m - \beta_n)z) \qquad (4)$$

Eq. (4) neglects the backward scattering waves for sack of simplicity and focus on forward travelling waves only. Here K_{mn} in Eq. (4) represent the coupling coefficient. Under few considerations of $n^2 - n_0^2 = n_1^2 - n_2^2$ *and* $n_1^2/n_2^2 \sim 1$ and $f(z) = r(x,y,z) - a$, K_{mn} can be expressed in Eq. (5)

$$K_{mn} = \frac{-j\omega a\varepsilon_0(n_c^2 - n_g^2)}{4P}\int_0^{2\pi}(r(x,y,z)-a)\left[E_{mt}^*.E_{nt} + E_{mz}^*.E_{nz}\right]d\phi \qquad (5)$$

Here $r(x,y,z)$ models the radius of perturbed fiber along z axis whereas ‘a’ is the radius of ideal fiber. Eq. (5) exhibit the relationship of mode ‘m’ and mode ‘n’ on their transverse components inform of E_{mt} and E_{nt} as well as the coupling due to longitudinal components in form of E_{mz} and E_{nz}.

Variations on fiber geometry include the deviation of geometry from circular to elliptical form, bends causing clad boundary variations. So, a radius of fiber can be written in form of Eq. (6)

$$r(x,y,z) = a + f(z)\cos(q\phi) \qquad (6)$$

Replacing $r(x,y,z) - a$ with $f(z)\cos(q\phi)$, we can summarize the Eq. (5) as $K_{mn} = K'_{mn}.f(z)$

With K'_{mn} expressed in Eq. (7)

$$K'_{mn} = \frac{-j\omega\varepsilon_0(n_c^2 - n_g^2)a}{4P}\int_0^{2\pi}(E_{mt}^*.E_{nt}c\text{os}\,q\phi)d\phi \qquad (7)$$

To explore the details of mode coupling between mode ‘m’ and mode ‘n’, we replaced the function $f(z)$ by its Fourier component at spatial frequency $(\beta_m - \beta_n)$ [19]

$$K_{mn} = K'_{mn}.\frac{df(z)}{dz}.\left(\frac{1}{j(\beta_m - \beta_n)}\right) \qquad (8)$$

and

$$K_{mn} = K'_{mn}.\frac{d^2f(z)}{dz^2}.\left(\frac{-1}{(\beta_m - \beta_n)^2}\right) \qquad (9)$$

Here we learn that coupling between mode ‘m’ and mode ‘n’ is also influenced by Fourier components of function $f(z)$ at $(\beta_m - \beta_n)$.

The study so far indicate that reduction in mode coupling of guided modes require either reducing the coupling coefficient or the Fourier component at particular frequency. Fourier components are difficult to control because it is related to random constructional variations or deviations from ideal parameters. It turns into a suggestion for better control on fiber drawing process to ensure geometrical accuracy and avoiding micro bends and surface bubbles [20]. On the other hand coupling coefficient described in terms of K'_{mn} is an integral of overlapping fields of spatial modes. The straight forward solution to reduce the integral overlap is use of target modes in cross polarization. However, this would not be a suitable option for transmission sing QAM with polarization mode multiplexing in addition to mode division multiplexing. Besides above-mentioned factors of controlling coupling parameter, physical parameters of fiber can also be considered for control on coupling coefficient [21]

4. Simulation and Results

In this section, we use the relationship expressed in Eq. (7) and (8) to simulate the impact of structural parameters on coupling coefficient (K'_{mn}). Physical parameters of index difference Δ and normalized frequency has been considered as variables of this study. Coupling amongst neighboring modes for a prospective communication in few mode fibers has been selected.

For this experiment, we have selected the fiber core with refractive index of 1.444 and refractive index of clad is set on 1.4363 as initial values. The wavelength 1550 nm has been selected due to usual application of this wavelength in telecommunication networks. The range of normalized frequency of the fiber has been achieved by changes in the radius of core.

Fig. 2 displays the relationship of coupling coefficient between modes LP01 and LP11; LP11 and LP21; LP21 and LP3. The coupling coefficients exponentially decrease for values of V greater than cut-off values of modes.

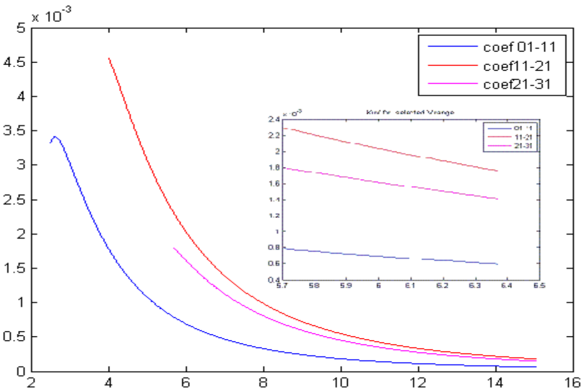

Fig. 2. K'mn by changing V number of fibers

This happens due to meager longitudinal component of coupled modes for the values of V greater than their cut-off values [22]. As we have discussed that few mode fibers are prospective candidate for mode division multiplexing with smaller number of modes, the range of V=5.4 to V=6.4 can allow four linearly polarized modes. Their interaction in terms of coupling coefficients has been demonstrated in sub frame of Fig. (2). Different values of coupling coefficient for LP21 and LP31 as compared to other combination are due to shape of deviation functions of electrical fields on crass section of fiber [22].

Moving forward we develop Fig. 3 to see the relationship of coupling co-efficient with delta values of fiber. For this analysis, we observed the relationship of LP01 with LP11. Fig. 3 express that coupling coefficient for weakly guiding fibers (delta =0.065) is lesser. The reason for this behavior lies in more linear polarization of fields inside the core of fiber. An important factor associated with few mode fibers is dispersion due to group delays and its relation with different values of V number of the fiber.

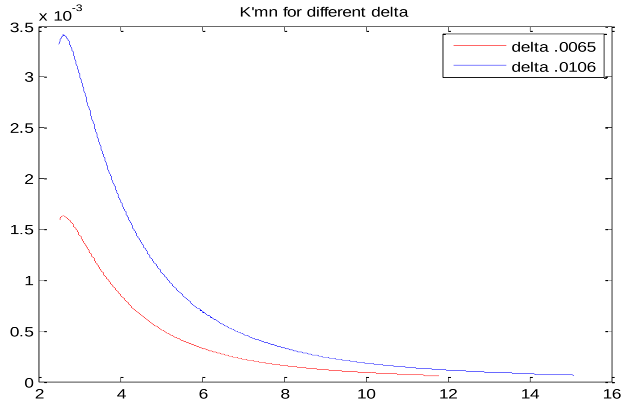

Fig. 3. Mode coupling coefficient constant (K'_{mn}) for LP01-LP11 for different delta

In mode division multiplexing, complex signal processing is required for neutralization of mode coupling effects. The group delay difference is one of the factor to determine the complexity of signal processing. Therefore, we observed the relationship of group delay difference with variations of already adopted scale of v number of fiber [23]. In few mode fibers, group delay of guided modes is expressed in Eq. (10) and the group delay difference between two modes has been displayed in Eq. (11).

$$t_g = \frac{n_2}{c}\left[1+\Delta\frac{d(bV)}{dV}\right] \quad (10)$$

$$gdd = t_{g(ij)} - t_{g(k,l)} \quad (11)$$

Fig. 4 represent the variations of group delay difference amongst various modes for different values V number of fiber. V number of fiber optic indicate the formation of core and clad hence these results help to understand effects of fiber construction on modal group delays.

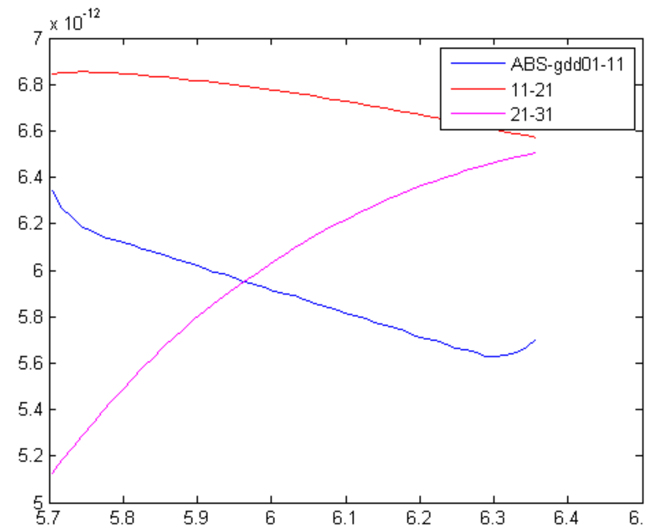

Fig. 4. Absolute value of group delay difference (seconds per unit length) of selected modes in few mode fiber with changing values of 'V'

Observations of Fig. (3) and Fig. (4) reveal the range of V number of optical fiber for better coupling performance and group delay differences amongst coexisting modes. The selection of appropriate V number of fiber will ease the MIMO signal processing constraints at the receiver. Middle values of V are suitable to accommodate the reverse patter of group delay difference of LP21 and LP31 with pattern of LP01 and LP11.

5. Conclusion

In this article, we explained the requirement of mode division multiplexing and explored the impact of mode coupling in mode division multiplexed signals. Coupling coefficient in few mode fibers can be reduced by careful selection of constructional parameters of fiber for operational wavelengths. Group delays of different modes can be managed by constructional parameters to control the signal processing capacity for optical link.

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