Concentric Core Fiber Design for Optical Fiber Communication

Iram Nadeem and Dong-You Choi*, Member, KIICE
Department of Information and Communications Engineering, Chosun University, Gwangju 61452, Korea

Abstract
Because of rapid technological advancements, increased data rate support has become the key criterion for future communication medium selection. Multimode optical fibers and multicore optical fibers are well matched to high data rate throughput requirements because of their tendency to support multiple modes through one core at a time, which results in higher data rates. Using the numerical mode solver OptiFiber, we have designed a concentric core fiber by investigating certain design parameters, namely core diameter (µm), wavelength (nm), and refractive index profile, and as a result, the number of channels, material losses, bending losses, polarization mode dispersion, and the effective nonlinear refractive index have been determined. Space division multiplexing is a promising future technology that uses few-mode fibers in parallel to form a multicore fiber. The experimental tests are conducted using the standard second window wavelength of 1,550 nm and simulated results are presented.

Index Terms: Few-mode fiber, Linear polarized mode, Multicore/multimode optical fiber

I. INTRODUCTION

The motivation behind this work was the EP 0105461 A2 [1], US 4000416 A2 [2] patent designs. A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Therefore, a large transmission rate has been attracting increasing interest because of the rapid spread of Web organizations. The transmission capability of optical fiber connections using single-mode fibers is reaching its confinement. Without developments in the physical foundation, optical transmission frameworks will soon experience a “limit crunch,” because of the increasing demand of a higher data rate in optical fiber networks, a technological breakthrough is required in the near future to meet these high capacity requirements. It is expected that 100-Gbit/s Ethernet will be common in 2017 and carriers will be able to support a data rate of 10 Tbit/s or higher. Therefore, modifications in the existing single-mode fiber design are required to achieve a larger capacity transmission of more than 10 Tbit/s per fiber. One of the promising candidates to expand the capacity of the existing single-mode is to use a multicore fiber (MCF).

To conquer this issue, researchers have proposed other multiplexing procedures such as wave-division multiplexing (WDM), mode-division multiplexing (MDM), and most recently, space-division multiplexing (SDM). The last technique utilizes MCF and few-mode fibers [3-5]. In fact, FM–MCFs, which are a combination of the multicore and few-mode configurations, can be used for achieving a very
high-capacity transmission of the order of 1 peta bit per second (Pbit) or higher, which is equivalent to 100–1,000 times the capacity of the existing optical fiber designs, and are ready to the blast fiber industry with high data transfer rate features [6].

The advent of telegraphy in the 1830s replaced the use of light by electricity and this was the beginning of the era of electricity-based communication. By the use of coding techniques such as Morse code, the bit rate B could be increased to approximately 10 b/s over a long distance of 1,000 km. The invention of telephone in 1876 brought a big change as electric signals were transmitted in an analog form throughout a continuously varying electric current. The primary microwave framework working at the frequency of 4 GHz was put into use in 1948. At that point, both coaxial and microwave frameworks had been developed impressively and could work at bit rates of approximately 100 Mb/s. A serious issue of such frameworks was their little repeater separating (approximately 1 km), which made these frameworks all the more expensive to work with. With the invention of lasers in 1960, more attention was then centered on discovering routes for utilizing laser light over optical communication. In 1966, it was prescribed that optical fibers may be the best choice for communication, as they are fit for the light along a path, e.g., controlling electrons in copper wires. At about the same time, the development of the GaAs semiconductor laser, working reliably at room temperature, was displayed. The synchronous availability of diminished optical sources and a low loss optical fiber provoked a general effort for forming a fiber-optic transmission structure [7, 8].

The year 1996 marked the advent of the fourth era of light wave frameworks that were economically easy to implement, which made use of the optical improvement for expanding the repeater separating and of wavelength-division multiplexing (WDM) for expanding the bit rate [9]. In most WDM techniques, the fiber frame occasionally uses erbium-doped fiber amplifiers separated at 60–80 km. The transmission rates of 21,000 km at 2.5 Gb/s and in excess of 14,300 km at 5 Gb/s were observed. Then, a positively worldwide system coating 250,000 km with the limit of 2.56-Tb/s (64-WDM) channels at 10 Gb/s in excess of four fiber sets came into operation. In 2000, the worldwide system of submarine frameworks having a 27,000-km fiber optic connection became operational, interfacing numerous Asian and European nations [8]. A few WDM frameworks were sent crosswise over the Atlantic and Pacific Sea throughout 1998–2001. Accordingly, the web information movement is expanded; they have expanded the aggregate limit by requests of extent [10, 11]. The limit of the existing standard single-mode fiber is reaching its major point of confinement paying little attention to the critical acknowledgment of transmission innovations, which consider high efficiencies. SDM focused around MCFs has lead to an answer for the issue of the immersion of the limit of optical transmission frameworks. This article exhibits the late advancement on the MCF, which is a concentric core fiber for future long communication systems. From [12], we can say that the operating wavelength windows utilized for optical communication are 0.8, 1.3, and 1.55 μm. At the wavelength of 1.55 μm, the fiber has the most reduced loss of 0.25 dB/km, whereas at the 1.3-μm band, it has a loss of 0.5 dB/km.

II. RELATED WORK

WDM has been implemented in the recent years to meet the ever-increasing demand of the bandwidth for a single-mode fiber system, but another approach to further increase the transmission capacity of the optical fiber communication system is to use SDM [5].

In [13], WDM, MDM, and PDM (polarization-division multiplexing) transmission tests over a more than seven-core MCF of 76.8 km and 16.8 km are shown alongside the experimental setup. The data transmission rate of 109 Tbit/s has been observed for 16.8 km, which can be enhanced further, but the multimode fiber (MMF) transmission experiences intermodal scattering. SDM is over a single-mode fiber might be accomplished in two ways. The principal approach consists of utilizing waveguides that help numerous waveguide modes, i.e., MMF. The transmission distance reached up to 137 km at a channel data transfer capacity of 240 Gbit/s. The waveguide modes could not be particularly energized and distinguishable in the standard MMF. The second approach to execute SDM consists of numerous spatially differentiated parallel waveguides shaped inside the fiber. The least difficult provision is to be is MCF. This consists of different cores that communicate within the accurate fiber area. By this methodology, we can minimize the crosstalk among the cores. Each core can have a separate channel, and thus, the communication frame could be more separate [14-16]. Core division and the distance between cores are very important parameters; however, low crosstalk in the seven-center fibers has been found where core area >45 μm and cladding area >150 μm [17].

The few-mode fiber is a fiber with one core having a suitably large cross-sectional area to support a number of independent guiding modes. Recent advancements have led to fibers supporting a few modes, the so-called “few-mode fibers” (FMFs), with low losses. In these fibers, each bounded mode has as a totally independent data channel and its own multiplexing scheme. One of the greatest challenges in such a mode multiplexing system is to maintain individual excitation and the detection of each mode.
III. DESIGN PARAMETERS

Capacity broadening is an important demand for future technologies, multicore fiber works on more number of cores as a result it can support huge amount of data as compare to single mode fiber. So, multicore fibers most preferable Concentric Core (type of MCF) is a very promising research area for future communication networks because of its greater number of cores and its capacity.

1) Fundamental concepts: Core-clad refractive index is the most important parameter when we refer to light propagating through optical fibers. Mathematically, it is expressed as follows:

\[ n = \frac{C}{v}, \]

(1)

where \( C \) denotes the velocity of light and \( v \) indicates the velocity of the medium. Another basic and important parameter used in all types of fiber design is the parameter \( V \), which is usually known as the normalized frequency parameter or the normalized optical frequency. It is used for determining the number of modes that are guided by a fiber mathematically and is defined as:

\[ V = \frac{2\pi}{\lambda} a NA = \frac{2\pi}{\lambda} a \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2}. \]

(2)

where \( a \) denotes the fiber core radius, \( n_{\text{core}} \) represents the refraction index of the core (\( n_{\text{core}} > n_{\text{clad}} \)), \( n_{\text{clad}} \) indicates the refraction index of the cladding, and \( \lambda \) refers to the wavelength, which is 1,550 nm in our case. It is important to know different key optical properties for a fiber design. For the single-mode operation, the values of the parameter \( V \) should be below 2.405, and a fiber can support only one mode per polarization direction. For the multimode operation, \( V \) should have values greater than or equal to 2.405 [17]. For large \( V \) values, modes guided by the fiber can be calculated as follows:

\[ M = \frac{4}{\pi^2} |V|^2. \]

(3)

2) OptiFiber: The optimal design software by optiwave for an optical communication system is used. It depends directly on the choice of fiber parameters. This is basically a numerical mode solver and has other models for calculating dispersion, losses, birefringence, and polarization mode dispersion (PMD) specifically for fibers.

One of the design goals when constructing a fiber is to minimize its nonlinearities. The effective nonlinear coefficients of optical fibers depend on the nonlinear indices of the bulk materials used for making the fiber and on its wave-guiding properties: the shape of modes, degree of confinement, etc. As a result, it can vary within broad limits.

IV. CONCENTRIC-CORE FIBER DESIGN

Fig. 1 and Table 1 shows a fiber design and parametric values used. This design has four concentric cores in which each core has a radius of 7 \( \mu \text{m} \) and each cladding part has a radius of 2 \( \mu \text{m} \), making the total radius 114 \( \mu \text{m} \). The refractive index of each core is much higher than that of the cladding. The material used for making this fiber is pure silica, and the wavelength of 1,550 nm is used for a length of 1,000 m/1 km.

1) Confinement diagram of different modes: Confinement means that the signal flow is parallel to the channel, bounded on both sides, and that no mode is unnecessarily covering the core area from the outside.

In Fig. 2, the blue lines that represent the mode inside the core (red line area) are completely confined within the core. No blue line is scattered outside or strikes outside the claddings. This means that there are very few chances of crosstalk between the cores and the claddings.

![Fig. 1. Fiber design profile.](http://jicce.org)

Table 1. Design specifications of the four-core concentric fiber

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refractive index of core</td>
<td>1.64692</td>
</tr>
<tr>
<td>Refractive index of cladding</td>
<td>1.44692</td>
</tr>
<tr>
<td>Radial distance of each core</td>
<td>7 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Radial distance of each cladding</td>
<td>2 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Total radial area</td>
<td>114 ( \mu \text{m} )</td>
</tr>
</tbody>
</table>
V. RESULTS

1) Mode field area of some modes: The transverse degree of the optical force circulation of a mode (e.g., of an optical hole or a waveguide) is typically indicated as a mode radius. The mode diameter (sometimes also called the mode field diameter [MFD]) is simply twice the mode radius. MFD is a critical parameter identified with the optical field (electric and magnetic) distribution in the fiber. MFD has been demonstrated to provide valuable data about the cabling characteristics, i.e., the conceivable joint, macro-bending, and micro-bending losses. Fig. 3 represents the MFD of some modes. The effective area of the fiber has an immediate connection with the nonlinear bends in long fiber joints.

2) Material losses: The optical signal coupled between fiber optic parts is transmitted with no loss of light. However, there is constantly some sort of imperfection present at the fiber optic connections that causes some loss of light. Basically, it is a measure of the optical power lost at the fiber optic connections, which is a concern of the
system designers. Fiber loss is defined as the ratio of the optical output power $P_{\text{out}}$ from a fiber of length $L$ to the optical input power $P_{\text{in}}$.

The symbol $\alpha$ is commonly used for expressing the loss in decibels per kilometer. Material losses include Rayleigh scattering, ultraviolet (UV), infrared (IR) absorption, and hydroxyl (OH) absorption losses. For example, the OH radical of the H$_2$O molecule vibrates at the fundamental frequency corresponding to the IR. Since the OH radical is slightly harmonic, “overtones” may occur. This causes the OH absorption lines to form at $\lambda = 1.39$, 0.95, and 0.725 $\mu$m, i.e., the second, third, and fourth harmonics of the fundamental frequencies, respectively. IR absorption is associated with the characteristic vibration frequency of a particular chemical bond between the atoms of the material that the fiber is composed of. An interaction between the vibrating bond and the electromagnetic field of the optical signal results in a transfer of energy from the field to the bond, thereby causing absorption. Fig. 4 shows that at 1,550 nm, all types of material losses are less than 0.25 dB/m. From Fig. 5, we can infer that the material loss (blue line) at 1.55 $\mu$m is $-9$ ps/km-nm, the waveguide loss (green line) is approximately 5 ps/km-nm, and the total loss, which is represented by the red line, is $-2$ ps/km-nm. Fig. 6 shows that the mean value of PMD is $4.05$ ps/$\sqrt{\text{km}}$ for the first order. From Fig. 7, we can infer that the value of the effective group delay for 1,550 nm is 1.645, which is denoted by the red line. On the other hand, the value of the group delay is $4.909 \times 10^6$ ps/km in Fig. 8. The effective nonlinear coefficients of the optical fibers depend on the nonlinear indices of the bulk materials used for making the fiber and on its wave-guiding properties: shape of the modes, degree of confinement, etc. As a result, it can vary within broad limits. Therefore, in our case, this value of $3.74 \times 10^{-16}$ has been observed in Fig. 9. A summary of the results of all these parameters is presented in Table 2.
VI. CONCLUSION

In this study, we developed another type of fiber design, namely a concentric core fiber supporting LP01, LP02, LP11, and many other modes simultaneously. These concentric rings can help to couple more light into the optical fiber. By having three or more of modes simultaneously through the fiber core, the high data rate requirement can be satisfied. Thus, we have observed different types of losses in the designed profiles. These are...
only the simulated results on the OptiFiber software obtained using patent design. However, in the future, such type of designs focus the research interest on the shape of the core, i.e., circular, cylindrical, and panda-shaped cores can be designed within a single cladding to obtain a wider bandwidth as the performance of the optical link highly depends on the distance between the cores and the arrangement of the cores within the single cladding. The proposed concentric-core single-mode fiber (CCSMF) having a diameter of <125 µm can enhance the bandwidth of the fiber and can be used for military purposes for secure and fast communication; here, the inner core can be used for message signals, whereas the outer cladding will keep an alarm signal in it as protection. The proposed study parameters shall be the preliminary steps to understand fiber construction. Furthermore, the relevant method and comparison can be done as further enhancement.

REFERENCES

Iram Nadeem
received her M.S. in Telecommunication Engineering (Major: Optical Fiber Communication) from University of Engineering and Technology (UET), Taxila, Pakistan, in 2014 and her B.S. in Electrical Engineering from the same institute in 2010. She is currently pursuing her Masters in Information and Communication Engineering from Chosun University. She had worked as Lecturer and Lab Engineer in different engineering institutes of Pakistan. Her research interests include optical fiber communication, microwave and satellite communication, antenna design, and wave propagation.

Dong-You Choi
received his B.S., M.S., and Ph.D. degrees from the Department of Electronic Engineering, Chosun University, Gwangju, Korea, in 1999, 2001, and 2004, respectively. Since 2006, he has been a researcher and teaching as a full professor. His research interests include rain attenuation, antenna design, wave propagation, and microwave and satellite communication. He is a member of the IEEE, IEICE, JCN, KEES, IEEK, KICS, and ASK.