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Original Research

Design of low crosstalk homogeneous multicore few mode fiber for future high-capacity optical transmission

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Article info

Article history
Received: 3 December 2023
Revised: 12 March 2024
Accepted: 20 April 2024
Published: 21 April 2024

Keywords
Design
Low crosstalk
Homogeneous
Optical fiber
Optical transmission

Abstract

Many researches are diligently striving to develop a multi-core optical fiber with minimal signal distortion and reduced issues. The current study proposed few designs for homogeneous multicore few mode fiber which is characterized by the combination of high index ring and trench. This study also added four air holes surrounding each core. We considered pure silica for both the outer clad and the inner clad of the fiber. To calculate the crosstalk, a two-core model was used and the mode coupling coefficient was determined using coupled-mode and couple-power theory. For the current work we considered only the fundamental mode (LP01) to compute the crosstalk between neighboring cores. The proposed structure was simulated using the wave optics module of COMSOL Multiphysics (Version 6.1), a well-known commercial software tool based on finite element method (FEM). MATLAB (Version R2018a) was used to calculate the mode coupling coefficient and crosstalk after extracting the mode field data from COMSOL. Obtained results revealed that the proposed structure can offer lower crosstalk which was attractive for future high-capacity fiber optic communication using multicore fiber technology.

Introduction

Since the very beginnings of written and spoken communication, we have come a long way. From the earliest phases of speech to the fundamental means of communicating with one another through symbols and pictures, humans have developed into a powerful force in communication. Communication has never been more advanced than it is now, and data has never been transferred more quickly. Over the past century, one of the fastest-growing fields for research and development has been communication technology. As digital switching networks take the place of older systems, optical networks are being upgraded. After inventing this communication system people are using this so much that's why transmission capacity is growing rapidly and will keep growing in the future, multiplying by 100 every ten years (Delezoide *et al.*, 2022).

To address this capacity shortage, every measure has been taken, including extending the transmission window in single-core fibers (SCFs) and utilizing enhanced methods of multiplexing like space-division multiplexing. Despite this, SCFs have a limit of about 100 Tb/s on Shannon transmission capacity. Consequently, the SCF is unable to manage this exponential increase in the need for capacity. To meet the need for transmission capacity, which is always rising. A few innovative technologies, multi-core fibers, or MCFs, have become popular and promising technologies to deal with this capacity need that is only growing the main area of interest for researchers.

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doi: https://doi.org/xxxxx.xxxxx.xxx.x.x.x.x

An optical fiber having many cores is called an MCF. Enabling single-mode or few-mode propagation in each core, all contained inside the same cladding. Research indicates that MCFs utilizing the space-division multiplexing (SDM) method can handle enormous bandwidth and transmission capacity. Consequently, the primary focus of contemporary research on the purpose of MCFs was to mitigate the impacts of dispersion, non-linearities, inter-core crosstalk (ICXT), group lag, etc., that are inherent in their architecture. Scientists are working hard to create a multi-core optical fiber with little signal distortion and fewer problems. The primary issue with weakly coupled MCF designs is ICXT, which harms system performance. Nevertheless, this may be managed by choosing the ideal diameter, and core pitch, and including trenches and air holes. By raising the effective refractive index difference between neighboring modes, we may further minimize the intra-core XT. The trench, heterocore, and air hole are examples of aided structures that may be employed between nearby cores to achieve the low XT and big capacity properties of FM-MCF (Saitoh and Matsuo, 2016; Xie *et al.*, 2020; Xia *et al.*, 2012). Moreover, the air hole would impede the precision of the optical fiber welding process. Because of its greater preparation ability, the trench structure suppresses the overlap of the energy field between cores, lowering the inter-core XT. To reduce inter-core XT, a unique approach consisting of a graded-index core and stairway-index trench structure has been created (Li *et al.*, 2021).

Wavelength division multiplexing (WDM) systems increase the carrying capacity of information using a single fiber. Bi-directional transmission is employed in another manner of WDM in which the multiplexing devices function in two directions. Space division multiplexing is an essential element of the next high-capacity fiber optic networks (Song *et al.*, 2022). The work in this field is strongly driven due to the exceptional significance it has in optical communication. If the construction of a multicore fiber for space division multiplexing with reduced crosstalk is feasible and if it outperforms current fibers, it will function as the fundamental infrastructure for future high-speed fiber-optic transmission systems. The goal of this research was to design and simulate an uncoupled multicore few-mode fiber to reduce inter-core crosstalk. The main objectives of the study were to study multicore optical fiber in general; to propose a better design of uncoupled multicore few-mode fiber for crosstalk reduction and to simulate the proposed structure using Comsol (version 6.1) and Matlab (version 2018).

Materials and Methods

Proposed fiber geometry

The first proposed model was a homogeneous dual-core mode fiber with a core pitch of 42 µm (Figure 1). The few-mode units were structured of a core, high refractive index ring, inner cladding, and trench.

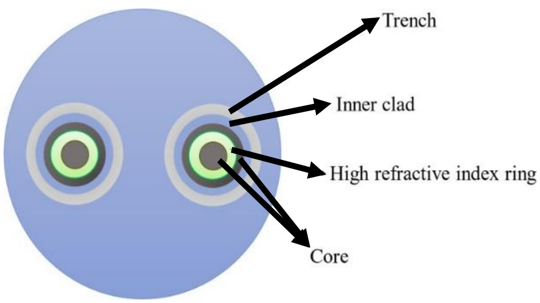

Figure 1. The first proposed geometry.

The distance that exists between any two cores that are adjacent to one another is referred to as core pitch, and each core in MCF has to function as if it were a separate spatial path. In this diagram, 42 µm is selected as the pitch of the core. By taking this approach, it is possible to substantially reduce the amount of internal core-to-core crosstalk. The proposed fiber has a core diameter of 12.16 μm, a cladding diameter of 240 μm, a trench thickness of 4 µm, an outer radius of a high refractive index ring of 4 µm, an inner radius of a high refractive index ring of 3µm, the inner radius of the trench 8 µm. The inner cladding and the outer cladding are composed of pure silica whose refractive index at 1550 nm is 1.444 (Figure 2).

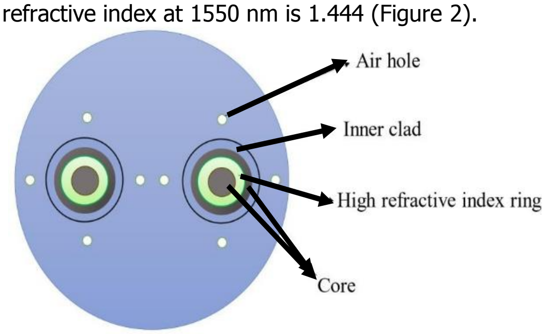

Figure 2. The second proposed geometry.

We had taken the same parameters as we considered in the previous structure. The differences between these two geometries are trench and air holes. We added air holes in the outer cladding with a refractive index of 1 and a diameter of 5.6 µm. We have also removed the trench which was located between the inner clad and the outer clad. So, the core structure consists of a core, ring, and inner clad (Figure 3).

In this figure, we used core, ring, inner clad, and outer clad whose refractive indexes are 1.4574, 1.4603, 1.444, and 1.4339 respectively. We also added air holes with a refractive index is 1 and a diameter is 5.6 µm. To model the proposed multicore fiber using the full vector finite element approach, we applied the widely used commercial software COMSOL Multiphysics (version 6.1). To determine the guided mode of the proposed fiber, we used a radio frequency module. Crosstalk between neighboring cores were compared using MATLAB (version 2018a), after extracting the model

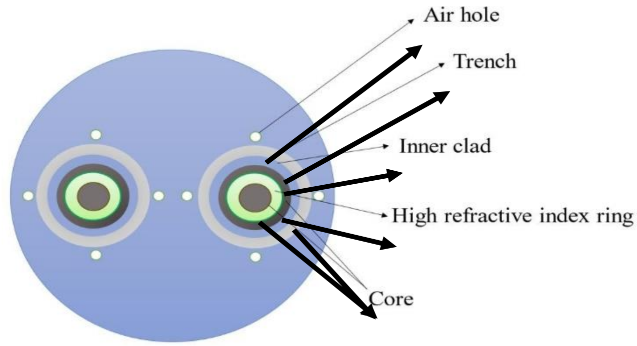

Figure 3. The third proposed geometry.

data from COMSOL. In order to find more accurate results we applied extra fine meshing to describe the simulation domain of our fiber structures (Figure 4).

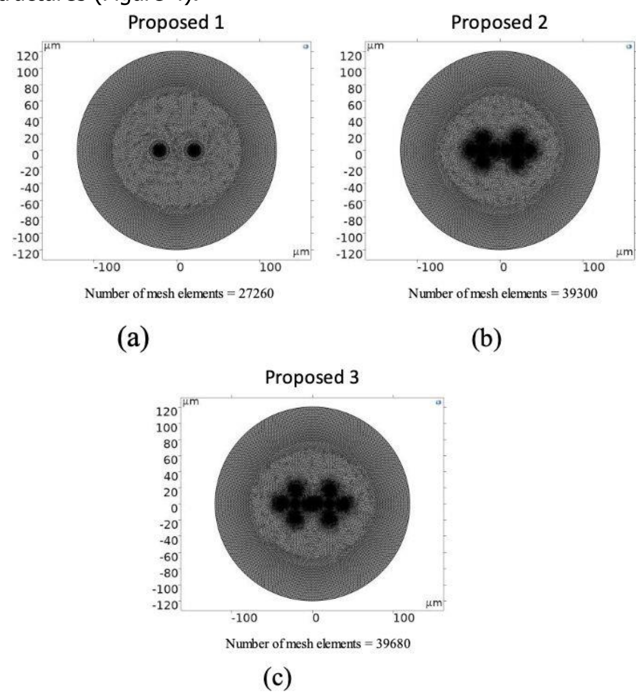

Figure 4. The mesh view of (a) the first proposed geometry (b) the second proposed geometry (c) the third proposed geometry.

Figure 5 presents a flow diagram where our overall working procedures have been displayed. To find the modes of our proposed fiber we first draw the geometry in COMSOL and set the necessary parameters. The total cross-section was then discretized into triangular finite element mesh and a modal solution was obtained. The field data was then extracted to compute crosstalk using MATLAB. Table 1 shows the parameters of the proposed fiber model which were used in simulation.

Numerical analysis

First, we calculated the all layers refractive index by using the following expression,

$$\Delta = \frac{n1 - n2}{n1}$$

Where Δ represented the relative refractive index difference and $n1$ and $n2$ were the refractive index of core and clad. Then we extracted the data from the COMSOL. Those data were the electric field of the adjacent core, the magnetic field of the adjacent core, and the refractive index profile. Afterward, we executed the following formula for mode coupling between neighboring cores with the extracted data using MATLAB,

$$k_{12} = \frac{\omega\varepsilon_o \int_{-\infty}^{+\infty} \cdot \int_{-\infty}^{+\infty} (N^2 - N_2^2)\, E_1^* E_2 dxdy}{\int_{-\infty}^{+\infty} \cdot \int_{-\infty}^{+\infty} u_z (E_1^* \times H_1 + E_1 \times H_1^*) dxdy}$$

$$k_{21} = \frac{\omega\varepsilon_o \int_{-\infty}^{+\infty} \cdot \int_{-\infty}^{+\infty} (N^2 - N_1^2)\, E_2^* E_1 dxdy}{\int_{-\infty}^{+\infty} \cdot \int_{-\infty}^{+\infty} u_z (E_2^* \times H_2 + E_2 \times H_2^*) dxdy}$$

Where,
ω = the angular frequency
εo = Permittivity of free space
uz = outwardly directed unit vector
E1 = Electric field of core 1
E2 = Electric field of core 2
H1 = Magnetic field of core 1
H2 = Magnetic field of core 2
E1* = Complex conjugate of the electric field of core 1
E2*= Complex conjugate of the electric field of core 2
H1*= Complex conjugate of the magnetic field of core 1
H2*= Complex conjugate magnetic field of core 2
N = refractive index distribution in the entire coupled region
N1 = Refractive index distribution of core 1
N2 = Refractive index distribution of core 2

Then the average coupling coefficient was computed as,

$$K_{12} = \frac{k_{12} + k_{21}}{2}$$

Later on, we calculated the power coupling coefficient using the following equation,

$$h_{12} \cong \frac{2K_{12}^2 R_b}{\beta\Lambda}$$

Where Rb and β were the bending radius of the fiber and the propagation constant of fiber modes, respectively. Finally, we got the crosstalk over a length of L by solving the following equation,

$$XT = 10 \text{ log10 } [\tanh{(h12L)}]\ [dB]$$

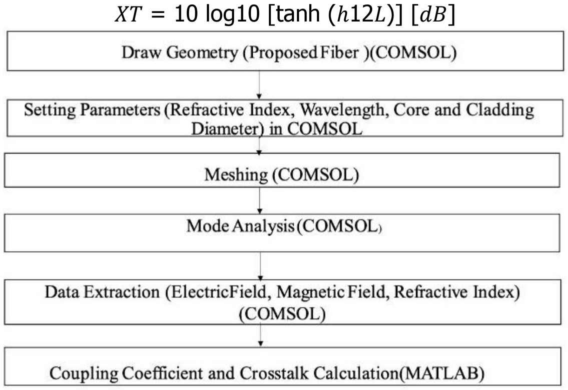

Figure 5. Flow diagram of working procedure.

Table 1. Parameters of proposed geometry.

Parameters	Meaning	Value
ncl	Cladding refractive index	1.444
wl	wavelength	1550 (nm)
rcl	Cladding radius	120 (μm)
nc	Core refractive index	1.4574
nr	Ring refractive index	1.4603
ntr	Trench refractive index	1.4339
nair	Air hole refractive index	1
D_air	Air hole diameter	5.6 (μm)
r1	Inner radius of high refractive index ring	3.00 (μm)
r2	Outer radius of high refractive index ring	4.00 (μm)
r3	Core radius	6.08 (μm)
rt	Inner radius of the trench	8.00 (μm)
h	Trench thickness	4.00 (μm)
Λ	Core pitch	42.00 (μm)
Δ1	High refractive index ring -core index contrast	0.20%
Δ2	Core – cladding index contrast	0.92%

Results and Discussion

Refractive index profiles

In Figure 6(a), we observed that after crossing the outer clad, the refractive index dropped to 1.434 due to the presence of a trench, while in the core section, a high refractive index ring caused it to rise to 1.4603. We noticed a slight difference between Figure 6(a) and Figure 6(c), which was caused by the air holes surrounding each core. Without this change, all aspects remained similar to before. In Figure 6(b), the graph showed that after crossing the outer clad, it crumpled to the refractive index of the air holes, then climbed up to the index of the inner clad.

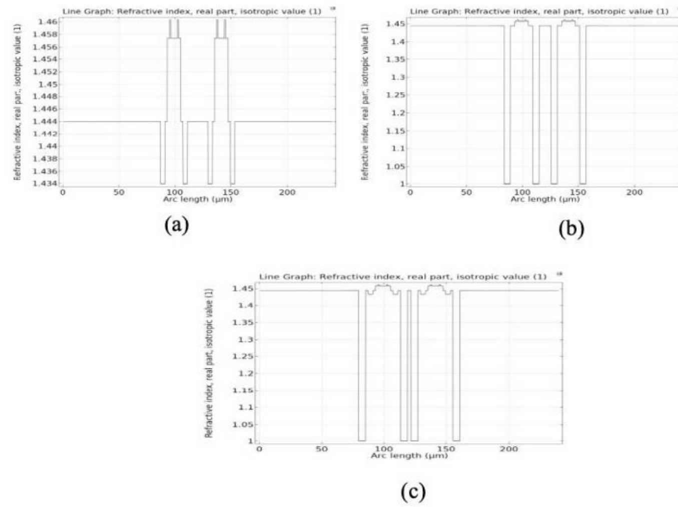

Figure 6. Reflective index profile of (a) the first proposed geometry (b) the second proposed geometry (c) the third proposed geometry.

Electric field profile of LP01 mode

After solving the Maxwell equations, COMSOL computed the modal solution of the fiber structure. We focused solely on the fundamental mode of the fiber. Figure 7 displays the electric field profile of the LP01 mode for only one of the cores of the proposed fibers. We observed strong confinement of light in the core, following a typical Gaussian shape, as evidenced by its line graph.

Magnetic field profile of LP01 mode

The magnetic field profile of the LP01 mode for our proposed fiber is displayed in Figure 8. Similar to the electric field, this profile also clearly showed that the mode was strongly confined in the core with its typical Gaussian-like shape.

Power profile of LP01 mode

Figure 9 displays the power profile of the LP01 mode for the proposed structure. Essentially, this was the pointing vector of the electromagnetic wave, obtained from the cross-product of its electric and magnetic fields. It was observed that the power was strongly confined inside the cores of each structure.

Relationship between XT and Rb

Figure 10 illustrates the relationship between the crosstalk and the bending radius for the proposed multicore fibers. We set the wavelength to 1550 nm and the length to 1 km. Subsequently, we varied the bending radius and computed the crosstalk. It was observed from the figure that the crosstalk value increased with the bending radius of the fiber.

Relationship between XT and L

To get the relationship between XT and L we had to set the wavelength 1550 nm and the bending radius 100 mm. After that, we varied the length parameter and got the following Figure 11 which shows that the crosstalk value becomes higher if we increase the fiber length.

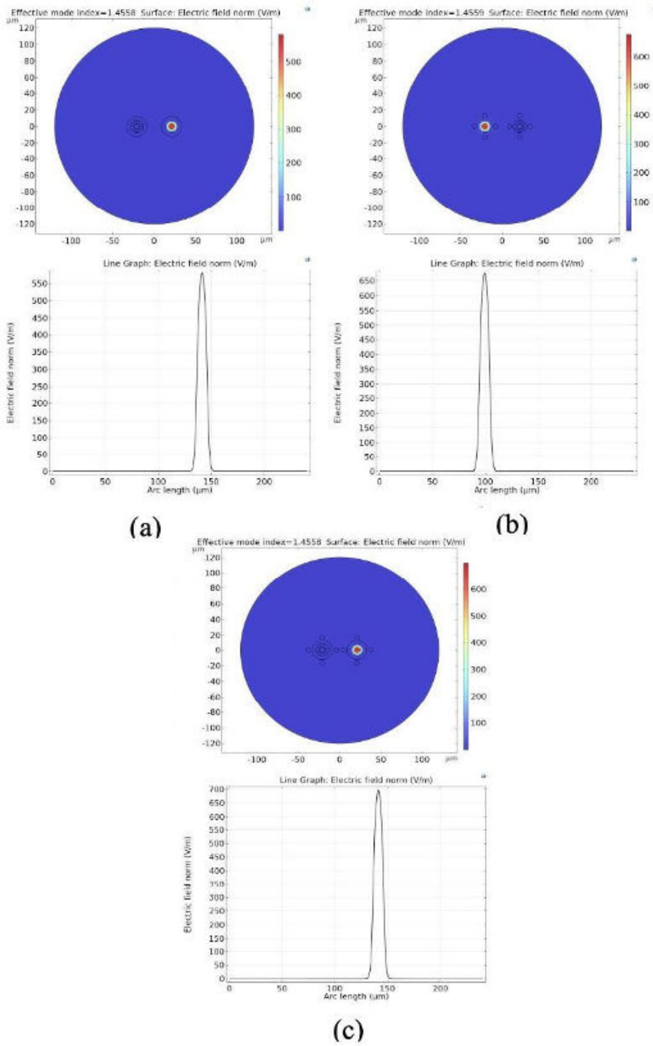

Figure 7. Electric field surface profile and line graph profile of (a) the first proposed geometry (b) the second proposed geometry (c) the third proposed geometry.

The summary of the crosstalk values of our proposed multicore fibers is shown in Table 2.

Table 2. The resultant crosstalk.

Multicore fiber	Crosstalk (dB/km)
The first proposed geometry	-162.31
The second proposed geometry	-173.40
The third proposed geometry	-183.90
Ref. paper	-156
Simple and homogeneous structure without any trench	-138

From table 3, we have seen that the lowest crosstalk was achieved from the third proposed geometry. After that, we got -173.40 dB/km which is for the second geometry. Lastly, -162.31 dB/km is computed from the first proposed geometry. These three proposed geometries are structured based on the reference paper where the authors got the crosstalk -156 dB/km.

Conclusions

Space division multiplexing (SDM) was deemed necessary to satisfy the increasing demand for next-generation data. Multicore fiber emerged as the most viable approach for implementing SDM. The primary challenge in implementing multicore fiber was inter-core crosstalk. At present, there is a significant emphasis on this topic in the field of optical fiber communication research. Various types of multicore fibers with techniques to suppress crosstalk have already been demonstrated. The objective of this study was to create a step-index multicore optical fiber for space division multiplexing (SDM) in a fiber optic link with high capacity. The goal was to achieve reduced crosstalk compared to current fiber structures. We specifically examined the crosstalk exclusively for the LP01 mode between two cores. We evaluated the fiber's performance and conducted comparisons with the existing framework. The simulation results indicated that the proposed structure exhibited superior performance in terms of crosstalk. The design of the fiber geometry was accomplished using COMSOL (Version 6.1), a software tool that employed a full vector finite element method. MATLAB (R2018a) was utilized to compute the coupling coefficient and crosstalk between neighboring cores. In the current work, we only focused on the LP01 mode. For future work, it was hoped to extend the simulation and analysis by exploring other higher-order modes. Simulation-based research considering various kinds of graded refractive index profiles of the fiber core could also be explored.

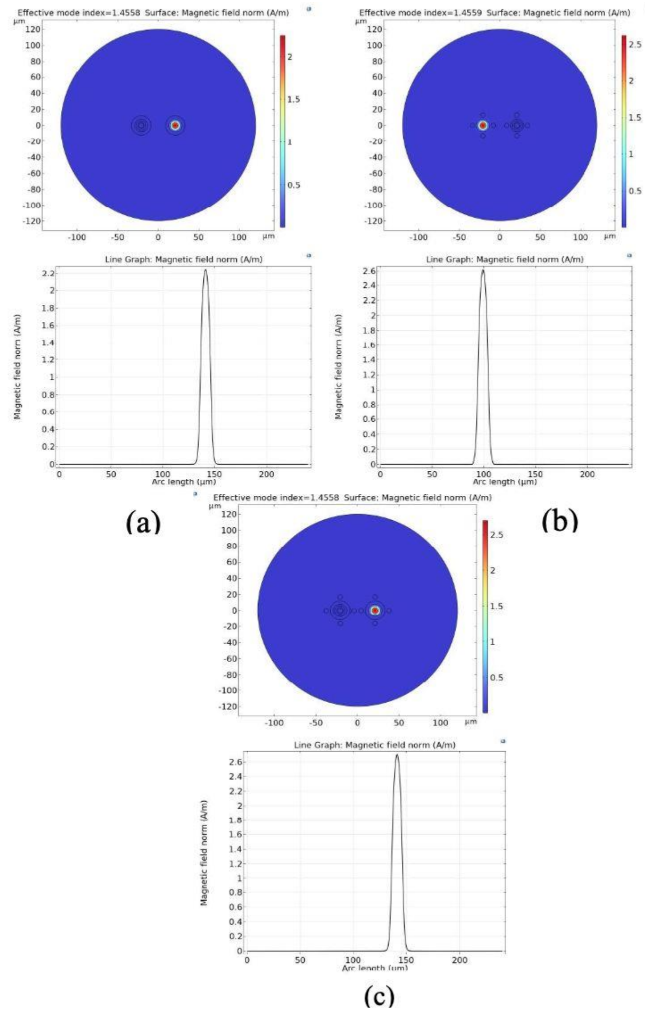

Figure 8. Magnetic surface profile and line graph of LP01 mode for (a) the first proposed geometry (b) the second proposed geometry (c) the third proposed geometry.

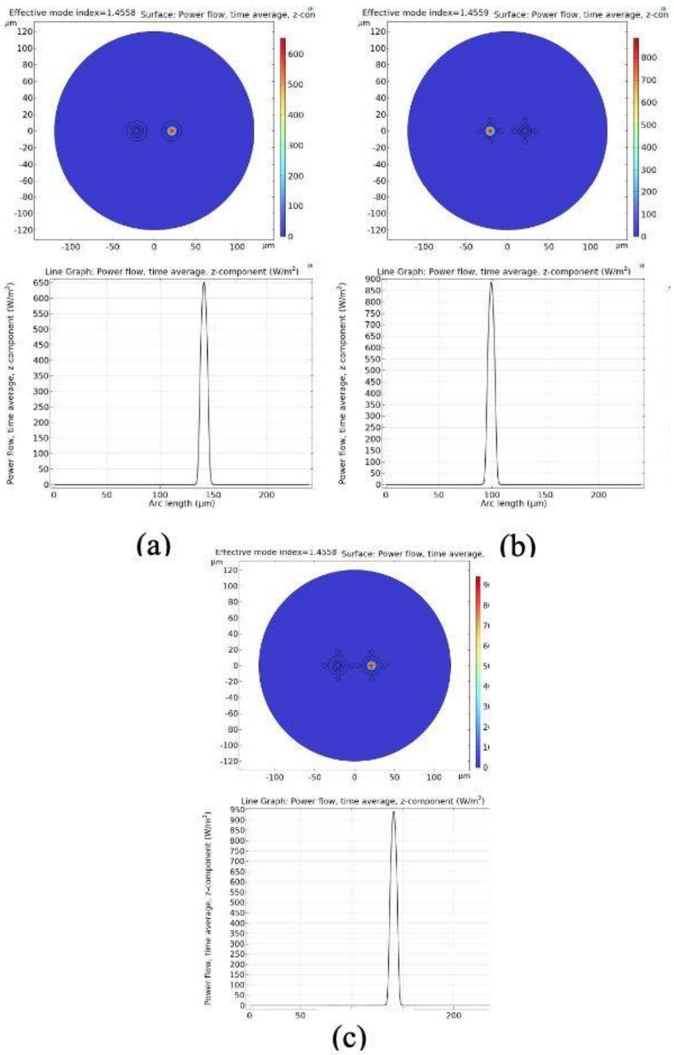

Figure 9. Power profile and line graph of (a) the first proposed geometry (b) the second proposed geometry (c) the third proposed geometry.

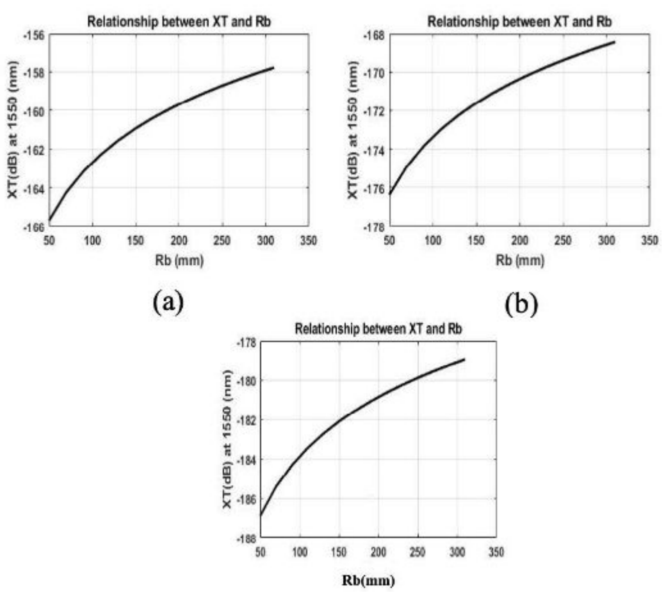

Figure 10. Relationship between XT and Rb of (a) the first proposed MCF (b) the second proposed MCF (c) the third proposed MCF.

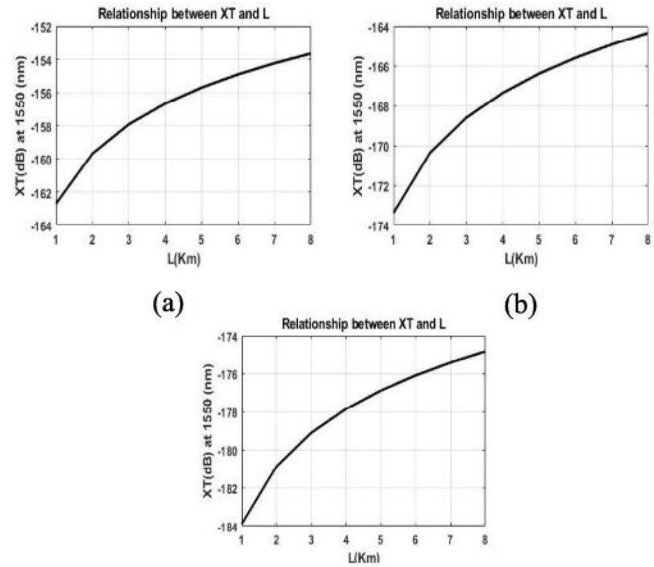

Figure 11. Relationship between XT and L of (a) the first proposed MCF (b) the second proposed MCF (c) the third proposed MCF.

Acknowledgments

The author would like to thank the technical and logistic support of the Electronics and Communication Engineering Discipline, Engineering and Technology School, Khulna University, Bangladesh.

Data availability

Not applicable.

Informed consent statement

Not applicable.

Conflict of interest

The author(s) declare no competing interests.

Authors' contribution

S.M. Waquar Shams: conceptualization, formal analysis; **Md. Jakaria:** writing-original draft preparation, review and editing; **Md. Sohel Mahmud Sher:** formal analysis**,** writing-original draft preparation; **Shakila Naznin:** formal analysis**,** writing-original draft preparation; **S.M. Saiful Alom:** formal analysis**,** writing-original draft preparation, review and editing. All enlisted authors has read and approved the final version of the published article.

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