Silicon embedded Dual-Core Photonic Crystal Fiber Based Polarization Splitter

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Abstract—**The aim of this study is to create a small-sized polarization fiber based on a dual-core hexagonal PCF design. To ensure its effectiveness, the coupled mode theory of DC-PCF will be utilized. The proposed structure will be analyzed through the Finite Element Method (FEM), and the PCF's structural parameters will be optimized to achieve a coupling length ratio of 2 at a wavelength of 1.55 um. With its compact size and shorter device length, the device's performance is expected to be enhanced.**

Keywords--Finite Element Method (FEM), Photonic Crystal fiber (PCF), Dual-Core Photonic Crystal fiber (DC-PCF).

I. INTRODUCTION

Photonic Crystal Fibers (PCFs) have garnered significant research interest due to their ability to manipulate their characteristics to suit various applications. These fibers have enabled the development of optical devices such as polarization filters, couplers, and wavelength coupler-splitters, which play a crucial role in integrated optical systems. Dual Core (DC) PCF couplers offer advantages such as design flexibility and shorter coupling length, as compared to conventional optical fiber couplers. These couplers can be used to realize wavelength coupler/splitters, which have significant applications in optical communication systems. By filling the DC-PCF with materials like liquid, metals, and nematic liquid crystals (NLC), the coupling characteristics can be enhanced, resulting in shorter coupling lengths

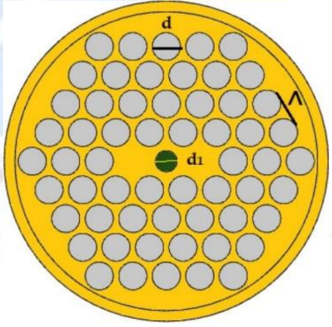
The design and analysis of a polarization splitter based on dual-core PCF involve optimizing the geometrical parameters of the fiber to achieve maximum polarization separation and evaluating the device performance using numerical simulations and experimental measures.[1]

The D-shaped photonic crystal fiber is designed with a flat surface on one side, which is coated with a thin layer of metal to create the surface Plasmon. The device can be used as a filter or a sensor, depending on the application. [2]

This PCF consists of two closely spaced cores with different effective indices, which allows for coupling between the cores through the evanescent field. The polarization-dependent coupling between the two cores leads to a differential phase shift between the polarization states, which can be exploited to separate the two polarization states. The operating principle of the PBS is based on the differential phase shift between the two polarization states. [3]

One of the key advantages of this approach is its compatibility with existing semiconductor processing techniques used to fabricate GA As materials. This enables the integration of the polarization splitter devices with other GA As-based optical components, such as lasers and detectors, in a compact and efficient platform. [4]

An ultra-broadband polarization splitter based on a three-core photonic crystal fiber with a modulation core is a device that can split an incident light beam into its two orthogonal polarization components, such as the transverse electric (TE) and transverse magnetic (TM) modes, over a broad range of wavelengths. The three-core photonic crystal fiber provides a large mode area, which allows for low nonlinearities and high power handling capabilities. [5]



A polarization splitter based on dual-core liquid crystal-filled holey fiber is a device that separates an input light beam into two output beams with orthogonal polarization states. The device is based on a special type of optical fiber, called holey fiber which contains air holes running along its length. These holes create a unique refractive index profile that can be used to guide and manipulate light. They are used in optical sensing and measurement applications, where precise control of polarization is required.[6]

Overall, the ultra-short PCF-based polarization splitter is a compact and efficient device that can be used in various optical communication applications, such as wavelength division multiplexing (WDM) systems and fiber optic gyroscopes. Its small size and high polarization splitting efficiency make it an attractive option for integration with other photonic components on a chip.[7]

A dual-porous fiber-based low-loss broadband terahertz polarization splitter is a device that splits the polarization of a terahertz (THz) wave into two orthogonal polarizations with low loss and broadband operation. The device utilizes *the birefringence property of dual-porous fiber, which has two types of pores arranged in a periodic pattern, to create a difference in the refractive index for the two polarizations.[8] The fiber consists of a porous core surrounded by a periodic arrangement of air holes in the cladding region. The first step in the design process is to determine the optimal parameters for the porous core, such as the diameter, the porosity, and the refractive index. The second step is to determine the optimal parameters for the air holes in the cladding region. Once the optimal structural parameters have been determined, the next step is to evaluate the performance of the fiber as a polarization beam splitter. [9]*

A dual-core photonic crystal fiber (PCF)-based terahertz (THz) polarization beam splitter (PBS) with broad bandwidth and ultra-high extinction ratio is a device that splits an input THz beam into two orthogonal polarizations with high efficiency over a wide range of frequencies. Its high efficiency and wide operating range make it an attractive option for high-speed THz communication systems and other applications that require high-quality polarization splitting of THz waves. [10]

A polarization splitter based on dual-core soft glass photonic crystal fiber (PCF) with micron-scale gold wire is a device that splits an input light beam into two orthogonal polarizations with high efficiency. The device utilizes a dual-core soft glass PCF structure that is modified by embedding a micron-scale gold wire between the two cores. In the simulation, the optical properties of the dual-core soft glass PCF are modeled using the FEM or FDTD methods. The simulation results can provide valuable insight into the electromagnetic fields and optical properties of the fiber, as well as help identify ways to improve the device's performance. [11]

II. MATERIAL AND DESIGN

This diagram depicts the proposed design for a polarization splitter based on photonic crystal fiber. The structure is composed of air holes arranged in a hexagonal pattern, with the removal of two side air holes in the first cladding layer to achieve a DC configuration. After analysis, the optimal values for the structural parameters were determined to be the diameter for the air hole (d=1.2µm), a pitch between the air holes (Λ = 2.15µm), and an air filling fraction of (d/Λ = 0.56). To increase the birefringence of the structure, the air hole in the core can be replaced with a silicon material with a diameter of (d1 = 0.18 µm).

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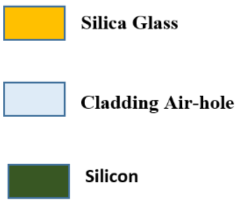


Fig (1) Schematic layout of the proposed PCF-based polarization splitter.

d =Diameter of the cladding air hole

d1 =Diameter of the material in the core

Λ = Pitch (distance between two consecutive air holes)

III. NUMERICAL ANALYSIS

To determine the effective refractive index and field distribution of the proposed photonic crystal fiber (PCF), Maxwell's wave equation is solved.

$$\boldsymbol{\nabla} * (\boldsymbol{\nabla} \times \boldsymbol{p}) - \boldsymbol{k_0^2 \varepsilon_r E} = \mathbf{0} \qquad \mathbf{(1)}$$

This equation involves the curl of the electric field, the Eigenvalue ($\boldsymbol{k_0^2}$), and the relative permittivity ($\boldsymbol{\varepsilon_r}$)

The mode field of a DC-PCF can be represented as a combination of an odd mode and an even mode, as per the coupled mode theory. The CL refers to the minimum length at which the optimal power transfer takes place between the two cores. Its mathematical expression is given by

$$\mathbf{CL}(\boldsymbol{\lambda})_{\mathbf{i}} = \frac{\pi}{\beta_i^{\mathrm{even}} - \beta_i^{\mathrm{o\,dd}}} = \frac{\lambda}{2(n_i^{\mathrm{even}} - n_i^{\mathrm{0dd}})} \qquad \mathbf{(2)}$$

In this equation, the variable" i " represents the polarization mode (X or Y), while λ refers to the wavelength of the incident light. The effective refractive indices of the even mode and odd mode for the X or Y polarization mode are denoted by $\boldsymbol{n_i^{even}}$ and $\boldsymbol{n_i^{0dd}}$ respectively.

To express the relationship between the CL of the X-polarized mode and that of the Y-polarized mode at a wavelength of 1.55 µm, we use the term CLR, which stands for the CL ratio. The formula to calculate CLR is given as:

$$\boldsymbol{CLR_\lambda} = \frac{\boldsymbol{(CL)_X}}{\boldsymbol{(CL)_Y}} \qquad \mathbf{(3)}$$

The CT refers to the amplitude of the undesired wavelength that persists at the output of the core along with the desired wavelength. It can be expressed as:

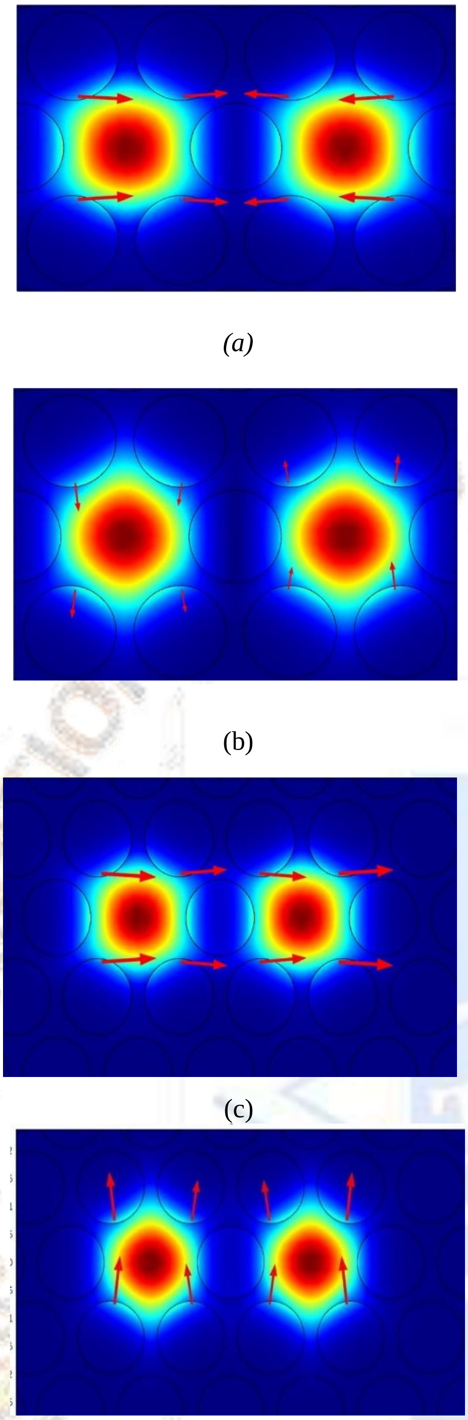
$$\boldsymbol{CT} = \mathbf{10}\, \boldsymbol{log_{10}} \frac{\boldsymbol{P_x out}}{\boldsymbol{P_y out}} \qquad \mathbf{(4)}$$

IV. RESULT AND DISCUSSION

To analyze the proposed polarization splitter based on photonic crystal fiber, the researchers employed the finite element method-based software, COMSOL Multiphysics 5.2a. By applying the coupled-mode theory, they were able to observe the superposition of two core modes in the DC PCF, resulting in four distinct super modes: X-even, Y-even, X-odd, and Y-odd. The even super modes, such as X-even and Y-even, are created by the superposition of two core modes with the same phase. Conversely, the odd super modes, such as X-odd and Y-odd, are generated by the superposition of two core modes with opposite phases. The resulting modal field distribution of these four super modes is illustrated in the analysis in Fig. (2)

4.1 <u>Optimization of the PCF Design Parameters:</u>

In order to achieve a coupling ratio of 2, which allows for the separation of the input wavelength with a short cladding length at the output of two cores, the design parameters of the proposed photonic crystal fiber needed to be optimized. Specifically, the pitch (Λ), the diameter of the air hole (d), and the diameter of silicon (d1) were analyzed to determine their optimal values. Through this analysis, the researchers sought to achieve the desired coupling ratio of 2 for the input light launched into the DC fiber, which experiences different phase shifts during propagation that cause power to couple from one core to another.



(a)

(b)

(c)

(d)

Fig (2) Modal field distribution of super modes (a) X-odd; (b) Y-odd; (c) X-even; and (d) Y-even.

4.1.1 *Influence of pitch (Λ):*

To assess the impact of the pitch value on the coupling ratio (CLR) at a wavelength of 1.55 μm for X- and Y-polarization, the researchers varied the pitch value between 1.51 and 1.63 μm, while keeping the diameter of the air hole constant at 1.2 μm. The resulting CLR values were presented in Figure 3. An increase in the pitch value leads to an increase in the distance between the two cores, resulting in a longer propagation length, which leads to an increase in both CL and CLR.

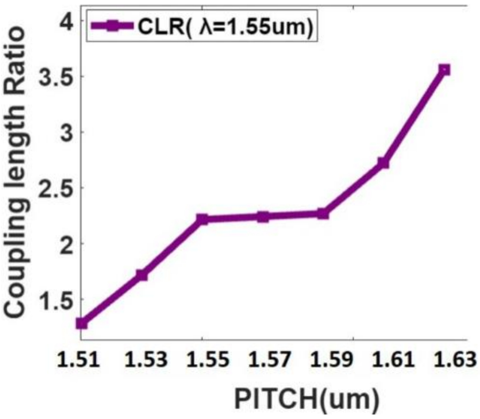


Fig (3) Influence of pitch on CLR

4.1.2 *Influence of Cladding Air-hole with the diameter (d):*

In order to determine the optimal value of the cladding air hole diameter (d) to achieve a coupling ratio (CLR) of 2 while maintaining a constant pitch of 2.15 μm, the researchers varied the value of d between 3.15 and 3.25 μm. The resulting values of CLR were calculated at a wavelength of 1.55 μm and presented in Figure 4. As the cladding air hole diameter increases, the guiding mode becomes more confined to the core and less prone to leakage to the cladding region, resulting in enhanced coupling and a decrease in CL. The plot in Figure 4 shows that CLR decreases as the value of d increases

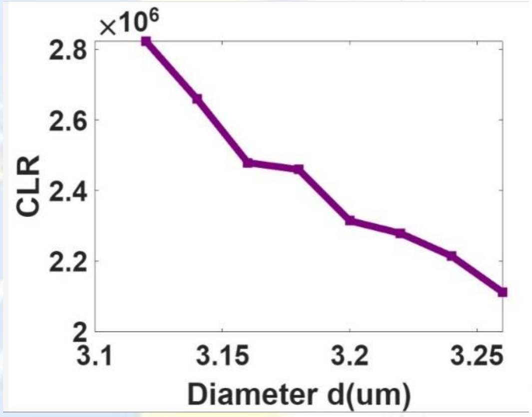


Fig (4) Influence of the diameter of silicon in the core on the CLR.

4.1.3 *Influence of silicon diameter d1*

In the proposed PCF, silicon embedded at the center separates the two cores. The influence of the diameter of the silicon nanowire d1 on the CLR for X- and Y-polarization is analyzed. With the constant values of pitch (Λ ¼ 2.15 μm) and the cladding air hole diameter (d ¼ 1.2 μm), the CLR values are obtained for different values of diameter d1, and the results are shown in Fig.5.As the value of d1 increases, the separation between the two cores increases, which gives rise to an increase in CL and CLR, as seen in Fig. 5. The CLR of 2 is achieved for the diameter of d1 ¼ 0.18 μm and d1 ¼ 0.175 μm for X- and Y-polarization, respectively. The silicon nanowire diameter d1 is chosen as 0.18 μm that accomplishes CLR of 2.004 and 2.112 for X- and Y-polarization.

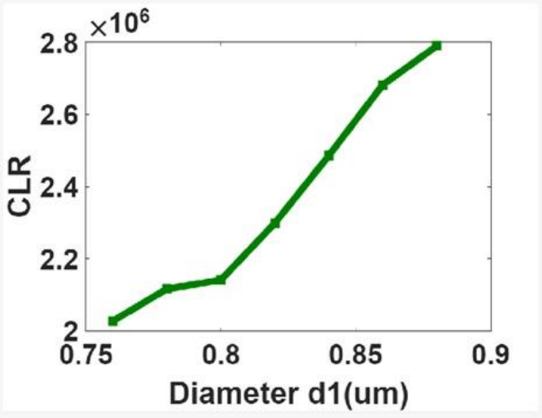
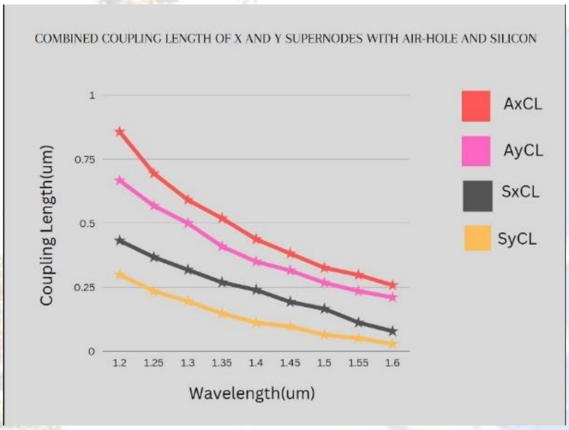


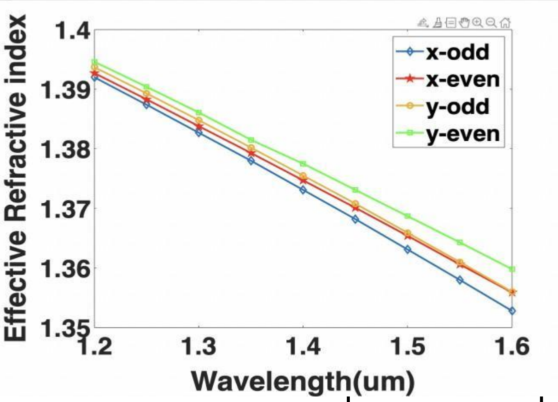
Fig.5 Influence of diameter of silicon in the core on the CLR.

4.3 Characteristics of the Proposed PCF

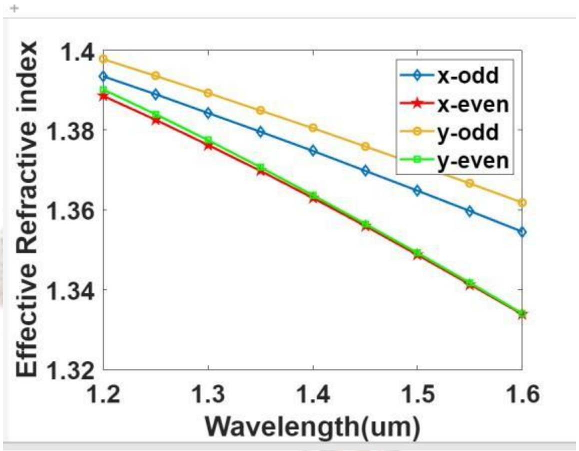
The optimized structural parameters for the proposed PCF-based polarization splitter obtained from the analysis are pitch Λ = 2.15 µm, cladding air hole diameter d = 1.2 µm, and silicon nanowire diameter d1 = 0.18 µm. In the proposed DC PCF four super modes are excited, hence the effective refractive index for x-odd, x-even, y-odd, and y-even are to be considered. The effective refractive index as a function of wavelength is obtained and illustrated in Fig. 6(a) for the DC embedded with the air hole and in air



POLARIZATION	*CL AT 1.55 um*
POL.	
POL.	



(a)



(b)

Fig.6 Effective refractive index characteristics of the proposed PCF with (a) Air-hole core and (b) Si core.

The DC pentagonal PCF structure is known to exhibit asymmetry, which results in mode degeneracy. As the wavelength increases, the effective refractive index difference between the even and odd modes for both X- and Y-polarization modes increases. Figs. 6(a) and 6(b) show that this difference is more significant for the Si core.

The CL is calculated for different wavelengths and shown in Fig. 7 for both the air hole core and silicon core as a function of wavelength. The energy transfer between the two cores requires a longer CL for lower wavelengths as the modes are tightly confined in the core. As the wavelength increases, the modes become less confined, resulting in a decrease in CL. Because the two cores are parallel to the x-axis, the coupling of the X-polarized mode is stronger than that of the Y-polarized mode, resulting in a shorter CL for the X-polarized mode. The CL is inversely proportional to the difference between the refractive indices of the odd mode and even mode. The silicon-embedded PCF exhibits a more significant difference between the odd and even modes, resulting in a shorter CL than the air hole core.

Fig.7 CL characteristics of the proposed PCF as a function of wavelength

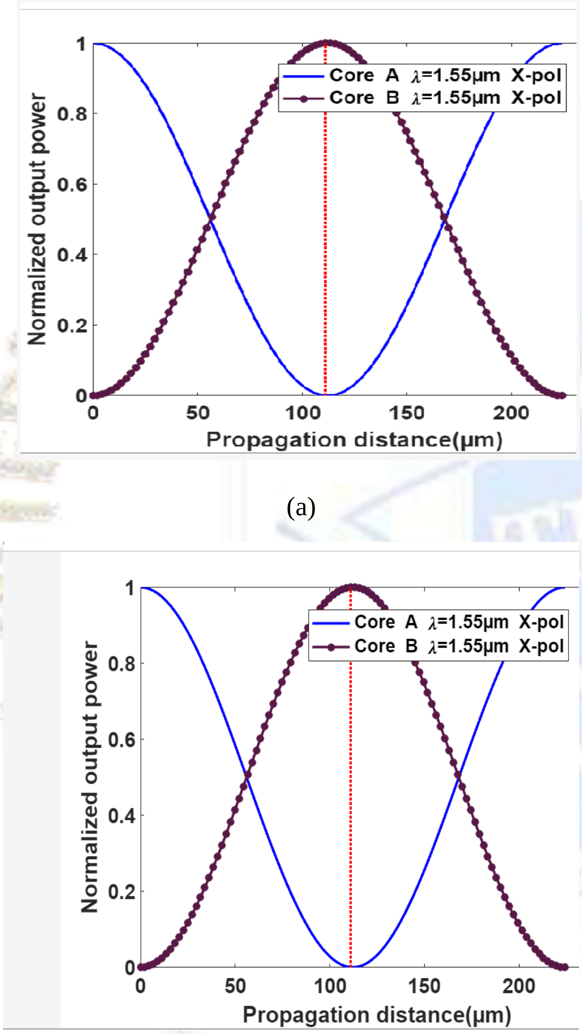
Table (1). CL and CLR obtained for the proposed PCF at 1.55 µm.

The CL obtained at the required wavelength of 1.55 µm for the proposed silicon core PCF is tabulated in Table 1. The aforementioned results obtained for the proposed PCF recommend its application for polarization splitting operation and are validated using CMT.

According to CMT, energy is coupled from one core to the other as the light propagates along the fiber length. When the energy attains a maximum in one of the cores, energy in the *other core will become minimum because the total energy remains constant at any point along the fiber length. When the light is coupled into one of the cores, the energy will be maximum in the same core when the propagation distance is equal to the even multiples of the CL.*

The X-polarized light comprising of the wavelength of 1.55 µm is launched into one of the cores, say core A of the proposed PCF. The CL of X-polarized light at 1.55 µm is112.119565 µm. Thus, at the propagation distance of around 112 µm, the X-polarized light at 1.55 µm is obtained in core A and core B, exhibiting polarization splitting behavior,

as witnessed in Fig. 8(a). Similarly, for Y-polarized light, after propagating through the fiber length of around 51 µm, the wavelength is split at the output of two cores, and the result is shown in Fig. 7(b).



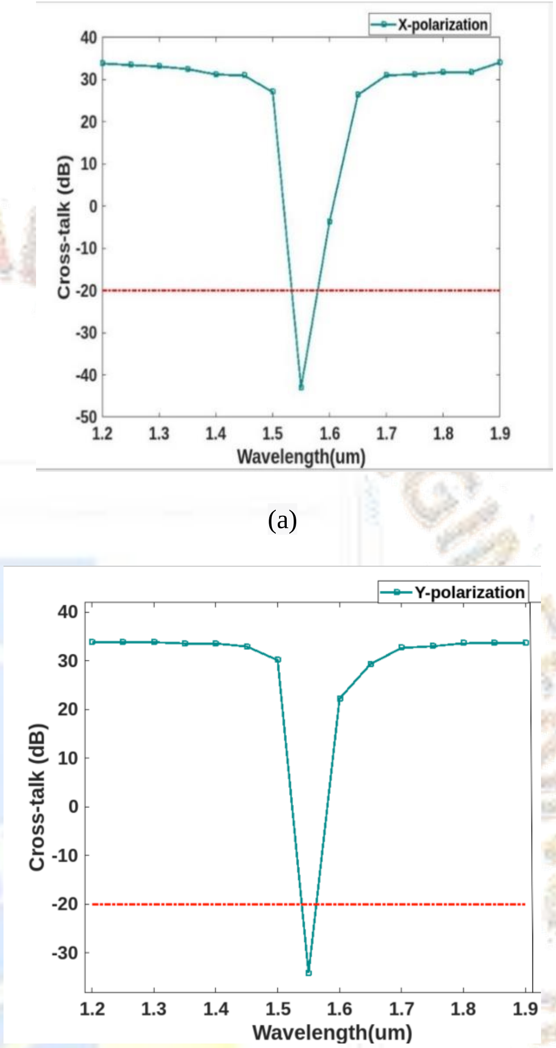
(a)

(b)

Fig. (8) Propagation of light through the two cores of the proposed PCF at 1.55 µm, when the light is launched into core A (a) X-polarization and (b) Y-polarization.

4.4 <u>Cross Talk performance of the proposed PCF</u>

The CT is a parameter that quantifies the level of unwanted wavelengths present in addition to the desired wavelength. In the case of the proposed PCF-based polarization splitter, when light containing a specific wavelength is introduced into core A, the maximum power output is obtained from both core A and core B at 1.55 µm for both polarization modes. However, it is important to take into account the CT that may arise from other spectral components around the undesired wavelength due to fabrication tolerances. The CT performance of the proposed polarization splitter at the output of core A and core B for X-polarization and Y-polarization at 1.55 µm is shown in Figs. 9(a) and 9(b), respectively.



(a)

(b)

Fig.9 CT performance of the polarization splitter at (a) core A (X- polarization) and (b) core B (Y- polarization).

The maximum CT values for the X and Y polarization modes occur at 1.55 µm due to the undesired wavelength at core A and core B, as indicated in Table 2. In order to ensure the best performance of the polarization splitter, a CT of -20 dB is considered, and the range of wavelengths over which the CT is less than -20 dB is referred to as the CT Bandwidth. Table 2 lists the CT value and the CT bandwidth of the wavelength splitter.

It is apparent from Table 2 that when the X-polarized mode is propagated through the proposed PCF length of 112.119565 µm, it attains a CT bandwidth of -43.0261 dB centered at 1.55 µm. On the other hand, when the Y-polarized mode is propagated through the device length of 51.124498 µm, a CT bandwidth of -34.1291 dB centered at 1.55 µm is achieved.

Based on the analysis, it is clear that the proposed PCF requires different lengths to function as a polarization-splitting device for the X and Y polarization modes.

Table. 2 Cross Talk of the proposed PCF at core A and B

Polarization Mode	***Device Length(um)***	***CT (dB) due to 1.55um***
X-Polarization	*112.11um*	*-43.0261 (CORE-A)*
Y-Polarization	*112.11um*	*-34.1291 (CORE-B)*

V. CONCLUSION

The proposed silicon embedded DC hexagonal PCF-based polarization splitter can effectively separate the desired 1.55 μm for both X- and Y-polarized modes. The structural parameters such as pitch, the diameter of the cladding air hole, and the diameter of silicon are optimized to achieve the CLR of 2. With the proposed PCF of length 112 μm, the X-polarized mode achieved CT of -43.0261 dB at 1.55 μm.. With a length of 112 μm, the Y-polarized mode attained a CT of -34.1291 at 1.55 μm . The proposed polarization splitter achieves a better CT performance and shorter device size compared to the reported works in the literature.

Table.3 Comparison of the performance of the proposed PCF with that of the literature listed in the following references.

Literature referred	*Pol.mode*	PCF length(μm)	CT (dB) at 1.55(μm)
[1]	x	3120	-48
[3]	x	420	-69.09
[6]	x	890.5	>-45
[7]	x	300	-23
[10]	x	53880	-114.5
	y		-73.3
Proposed PCF	x	112.11	-43.0261
	y		-34.1291

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