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Par : Rezkallah Ines

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THEME

Multifunctional Photonic Crystal Fiber Based on 1x4 Powerful Splitters

Présenté et évalué, le 12/06/2024, par le jury composé de :

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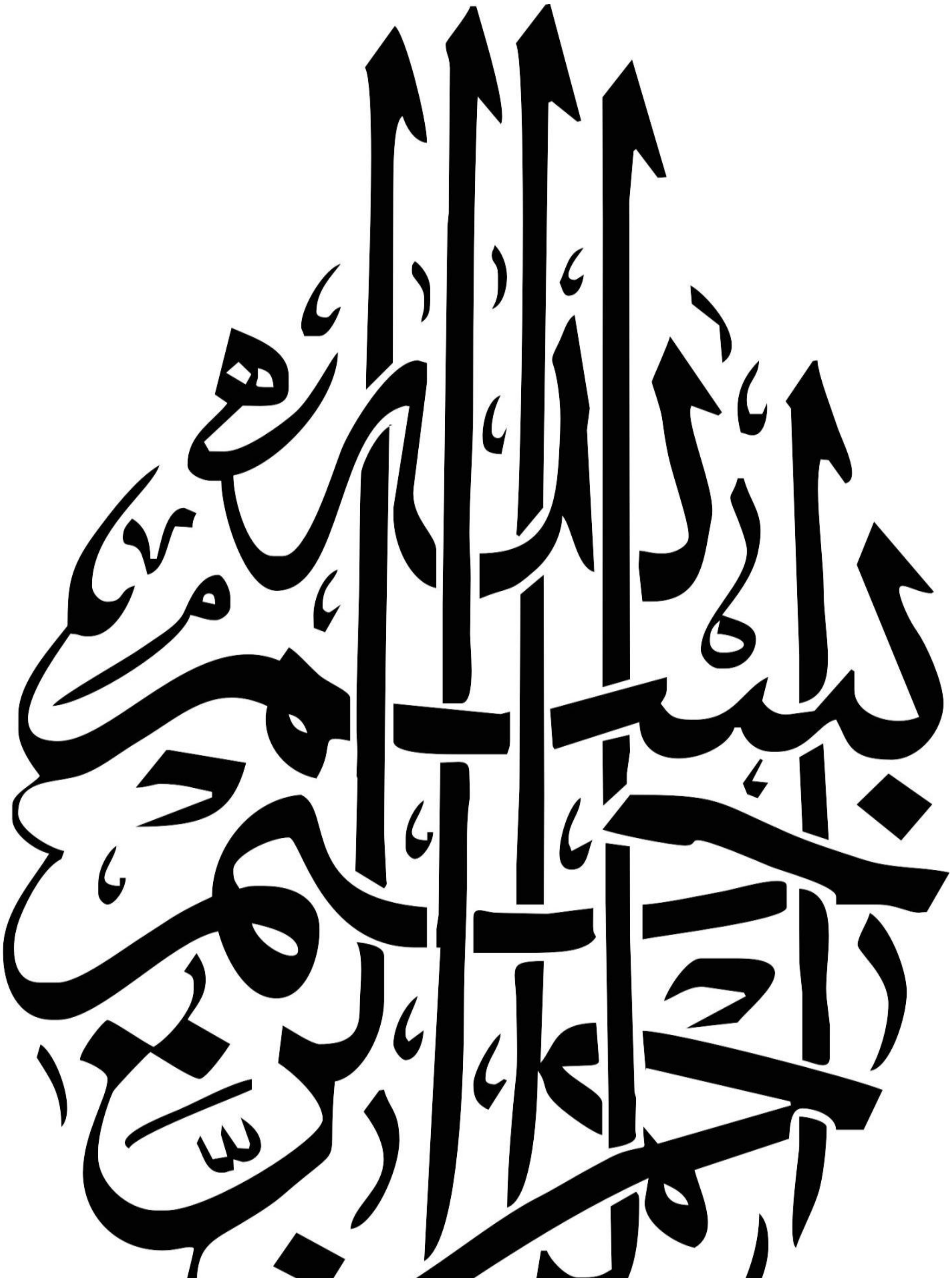
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Thanks

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الى نفسي الطموحة جدا لقد ظننت اني لا استطيع ولكن من قال انا لها نالها وان ابت اتيت بها رغما عنها انا اليوم اقف على عتبة تخرجي و اقطف ثمار تعبي و ارفع قبعتي بكل فخر فااللهم لك الحمد قبل ان ترضى و لك الحمد اذا رضيت و لك الحمد بعد الرضا لأنك وفقتني على إتمام هذا العمل و تحقيق حلمي ....اهدي هذا النجاح

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الى ضلعي الثابت و امان ايامي الى ملهمي نجاحي صناع قوتي صفوة ايامي و سلوة اوقاتي الى الشموع التي تسير لي الطريق الى من شددت عضدي بهم فكانو لي ينابيع ارتوي منها الى خيرة ايامي و صفوتها الى قرة عيني .شيراز و ولدان و عبد الرحيم إلى فلذتي كبدي ابناء اختي مشرق زين ,تولين

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اخرا وليس أخيرا اهدي نجاحي و تعبي الى من كان داعمي و سندي و تاج فوق راسي الى جدي مرحوم 'رزق الله لزهاري 'تمنيت حضوره اهدي له تخرجي و نجاحي

رزق الله ايناس

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بسم الله الرحمان الرحيم الحمد الله الذي ما نجحنا و علونا ما تفوقنا الا برضاه الحمد الله الذي ما اجتزنا دربا و لا تخطينا جهدا الا بفضله واليه ينسب الفضل و الكمال و الاكمال

{ وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِين }

لم تكن رحلة قصيرة ولا طريق محفوف بالتسهيلات لكنني فعلتها فالحمد الله

الذي يسرا البداية و بلغنا النهايات بفضله و كرمه

بكل حب و مشاعر اهدي ثمرة نجاحي و تخرجي الى :

{ وقضى رَبُّكَ أَلَّا تعبدوا إلا إِيَّاهُ وَبِالْوَالِدَيْنِ إحسانا }

ابي رحمه الله 💔

الى من شرفني بحمل اسمه ..والدي العزيز رحمه الله الى نور الذي انار دربي والسراج

الذي لا ينطفه نوره بقلبي ابدا كم من اللحظات التي تمنيت وجودك فيها يا ابي

كنت اتمنى وجودك في تخرجي كي تفتخر بابنتك كنا ننتظر هذي الفرحة سويا

و ها قد تخرجت اليوم يا ابي و انت بجوار ربي...

الى من قيل فيهم : { سَنَشُدُّ عَضُدَكَ بِأَخِيكَ }

الى من كان معي في صغيرة قبل الكبيرة الى من شغل مكان الاب في غيابه الى من

مد يده دون كلل ولا ملل وقت ضعفي اخي ادامك الله ضلع ثابت لي

الى من جعل الله الجنة تحت اقدامها الى انسانة العظيمة التي طالما

تمنت ان تقر عينها برؤيتي في يوم كهذا

الى من ساندني بكل حب عند ضعفي وازاح عن طريقي المتاعب ممهدا لي الطريق

زارعا الثقة والاصرار بداخلي الى عمي عيسى و ابراهيم

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الى اصدقاء اوفياء ورفاق السنين و اصحاب الشدائد و الازمات' حبيبة نور الهدى زهراء سارة

عائشة فاطمة ندى رجاء امال ريان غالية فضيلة غدير اميمة '

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مناصريه ايمان

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General Introduction

General Introduction

Multicore optical fibers play a crucial role in the distribution and consolidation of optical power within fiber networks. This technology enables the division of a single power signal into multiple branches, facilitating its routing to various destinations for diverse applications. Various methods have been developed to manage and direct optical power within these branches. Among these methods, the most prevalent involves fusing multiple optical fibers, whether identical or not, together to create a fused region where power exchange occurs through proximity coupling. It's been noted that constructing splitters with fewer than six surrounding fibers can be challenging, often requiring the incorporation of dummy fibers. However, configurations such as 2*2, 4*4, and 1*7 fiber couplers/splitters can be achieved through the fusion of conventional optical fibers.

Alternatively, the emergence of novel photonic crystal fibers (PCFs), characterized by airholes distributed within a silica matrix along the fiber's length, offers an innovative approach. PCFs allow for the creation of multicore structures within a single fiber without the need for fusion processes. This inherent flexibility makes PCFs highly adaptable for tasks involving optical power division or aggregation. Splitting light into surrounding cores within multicore PCFs is relatively straightforward. Previous research has leveraged PCFs with two or three cores to explore coupling characteristics, wavelength-flattened couplers, narrow bandpass filters, and the creation of multicores for applications such as generating frequency combs through four-wave mixing, phase-locking, and fiber laser arrays.

In this work, we propose and investigate a new design of a multicore PCF that can divide a single optical power equally into four ports. The design consists of four identical cores surrounding an identical central core. Each core is surrounded by small airholes, which are created in order to have a complete power transfer among the cores. To optimize the performance of the proposed device, we use a full-vectorial finite-element method (FEM) with Comsol Multiphysics Software.

The script contains three chapters:

- The first chapter offers a comprehensive introduction to photonic crystals, encompassing their characteristics and applications.
- The second chapter delves into the intricacies of photonic crystal optical fibers and the coupling mechanisms inherent within these fibers.

- The third chapter focuses on simulating the coupling between the central core and external cores utilizing the COMSOL Multiphysics simulation software.

Finally, our work will culminate in a comprehensive conclusion summarizing the findings obtained.

Chapter 1:

Photonic crystals

1.1. Introduction

In recent years, significant research attention has been directed towards the advancement of micro and nanophotonic devices employing photonic crystals (PCs) owing to their adeptness in manipulating light propagation. The first chapter initiates with fundamental insights into photonic crystals. Subsequently, we delve into delineating the diverse types of photonic crystals and their distinctive characteristics. Concluding this initial chapter, we explore several applications within the realms of optics and telecommunications

1.2. History

The term "photonic crystal" was coined over a century ago, with the earliest notions of controlling light propagation through periodic structures dating back to 1887, attributed to Lord Rayleigh.

The formal exploration of photonic crystals began in 1987, when Eli Yabonovitch and Saie John independently introduced the concept of band gap materials, each in their respective contexts. In 1991, A. Genack al [1]. experimentally demonstrated the phenomenon of light localization in periodic structures. Concurrently, Yablonovitch showcased the first three-dimensional photonic band gap in the microwave spectrum. By 1996, Thomas Krauss presented the first optical wavelength demonstration of a two-dimensional photonic crystal [2]. In 2000, a milestone was reached with the fabrication of the first three-dimensional photonic crystal exhibiting a complete photonic band gap in the near-infrared range [3].

In recent years, the field of photonic crystals has undergone remarkable expansion, encompassing a wide array of scientific disciplines and achieving unprecedented progress.

1.2.1. Photonic Crystals

1.2.2. Definition

Photonic crystals are dielectric or metal-dielectric materials with a periodic variation in refractive index at the scale of the wavelength of light. This periodicity causes a prohibition of photon propagation in certain spectral ranges, known as photonic band gaps (PBGs) [4]. These materials can effectively control and manipulate the propagation of light, making them useful in various fields such as integrated optics, photonics, and advanced optical devices.

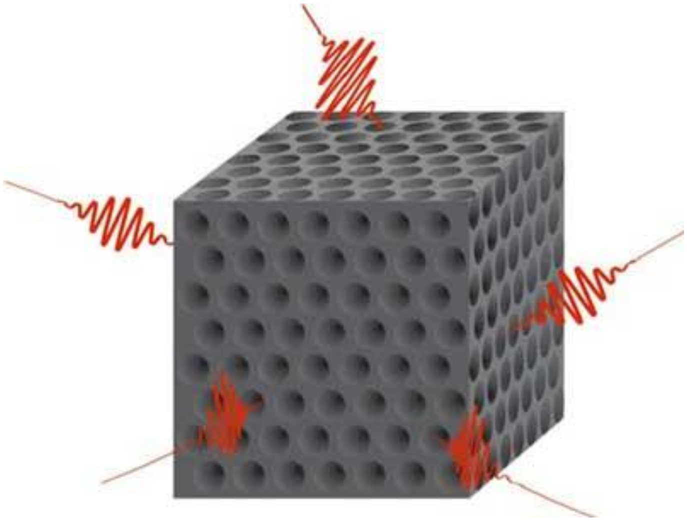


Figure 1.1 : Photonic crystals in a vacuum.

There are different types of photonic crystals classified according to their dimensionality [5]:

1. **One-Dimensional (1D) Photonic Crystals**: These photonic crystals are periodic in one dimension, often formed by a series of flat layers of dielectric materials.
2. **Two-Dimensional (2D) Photonic Crystals**: These photonic crystals are periodic in two dimensions, formed by a lattice of dielectric structures in air or air holes in a dielectric matrix.
3. **Three-Dimensional (3D) Photonic Crystals**: These photonic crystals are periodic in three dimensions, typically consisting of three-dimensional arrays of dielectric microstructures or nanostructures.

Each type of photonic crystal exhibits unique optical properties and can be used for various applications in the field of optics and photonics.

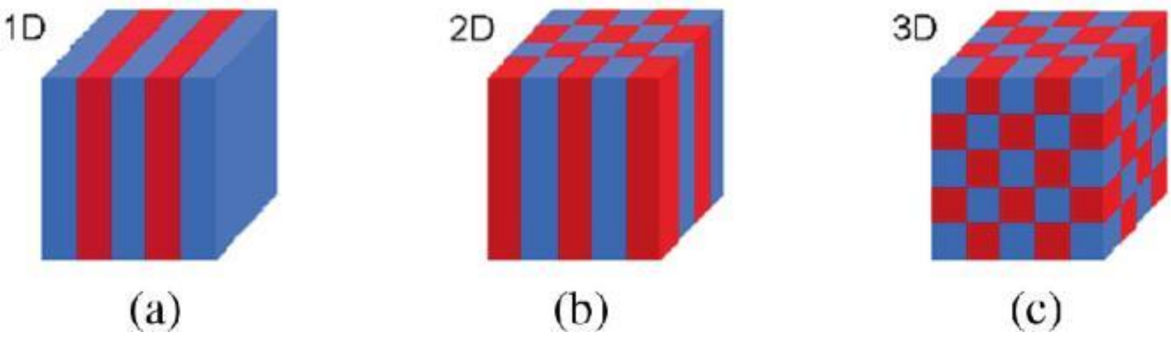


Figure 1.2 : the types of photonic crystals one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D).

1.2.3. Two dimensional photonic crystal

Two-dimensional periodic lattices primarily fall into three main families:

- **Square lattice:** The lattice nodes are located on one side, defined by the length (Figure 1.3). It has been demonstrated that this type of lattice is highly sensitive to the angle of incidence and the polarization of the electromagnetic wave [6]. Therefore, achieving a complete band gap, meaning a band gap that prevents propagation regardless of the angle of incidence or polarization, is challenging.

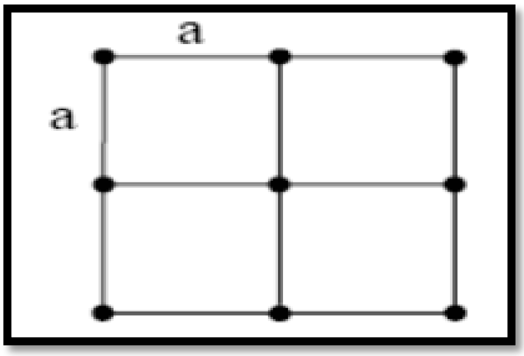


Figure 1.3 : The square network

- **Triangle lattice**: The triangular lattice is the 2D lattice with the highest symmetry when restricted to a single "atom" per unit cell. Each lattice node is spaced from its nearest neighbor at a uniform distance (Figure 1.4). This structure is less sensitive to the angle of incidence than the square lattice, but achieving complete band gap remains challenging [7].

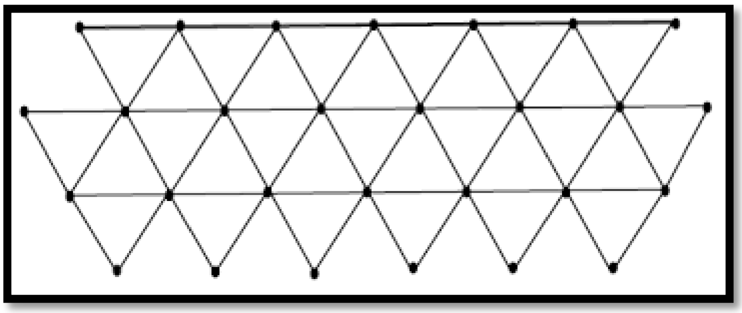


Figure 1.4 : The triangular network.

- **Hexagonal lattice**: In a hexagonal lattice, if all nodes are identical and spaced by a distance "a" (see Figure 1.5), then this structure is called "graphene" because it is similar to the crystalline structure of grapheme [8].

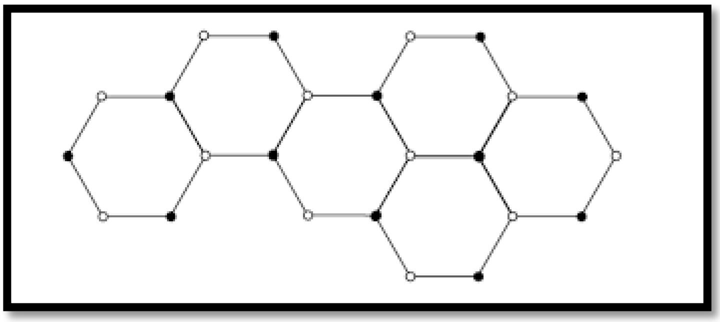


Figure 1.5 : Graphite structure.

1.2.4. Photonic crystal parameters

A photonic crystal is characterized by several parameters:

A. Periodicity: These geometric parameters, chosen according to the frequency domain studied, influence the characteristics of the photonic band gap. The period a is defined as the sum of $a_1$the thickness of the layer with permittivity ε_1, and $a_2$the thickness of the layer with permittivity ε_2.

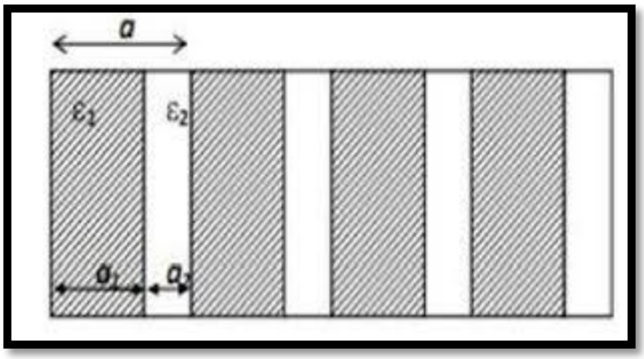


Figure 1.6 : The periods of a one-dimensional photonic crystal.

B. Lattice Parameter: This is the fundamental distance between two constituent bricks. It determines the spectral region where the photonic crystal interacts with the wave.

C. Index Refraction Contrast: In photonic crystals, refractive index contrast refers to the difference in refractive indices between the constituent materials of the crystal. A photonic crystal is typically composed of materials with alternating high and low refractive indices, forming a periodic structure that can manipulate the flow of light in specific ways.

The refractive index constrast is a critical factor in determining the photonic band structure of the crystal, which dictates how light of different wavelengths (frequencies) propagates through it. A higher refractive index constrast generally leads to more pronounced photonic band gaps, which are ranges of frequencies where light propagation is prohibited or strongly inhibited. These band gaps are essential for applications such as controlling the flow of light in optical devices, including waveguides, filters, and sensors.

D. Fill Factor: The fill factor f can be compared to the width of the periodic potential in solid-state physics. When taken for the high-index material, for example, it is defined as the ratio of the volume occupied by this material in the unit cell of the crystal to the total volume of this cell. The influence of these different parameters on the behavior of a photonic structure can be understood by analogy with a periodic potential induced by the arrangement of atoms in a semiconductor.

1.3. Application

1.3.1. Photonic Crystal Waveguide

By introducing a linear defect, such as omitting one or more rows of holes, in the photonic crystal, it is possible to guide light in a chosen direction. A photon remains confined in the guide if its energy lies within the band gap (Figure 1.7). Transmission through these devices can be optimized by modifying the size or shape of the holes at the bend or junction, in order to minimize coupling between the guided mode and radiated modes at the bends [9].

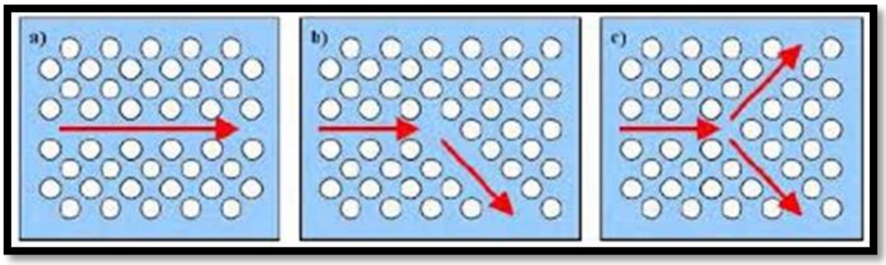


Figure 1.7 : Different components based on linear defects, (a) straight guide, (b) 120◦ bend and (c) Y junction.

1.3.2. CAVITIES

The first cavities using two-dimensional photonic crystals were developed in 1996. These cavities were created by introducing point defects into the photonic crystal lattice. It has been demonstrated that these devices exhibit a high quality factor for resonant modes due to the excellent reflection properties of the crystal, even for large cavities with multiple modes. Cavities on suspended membranes, with very small dimensions, are illustrated in Figure 1.8، showing a triangular-shaped cavity and another with a hexagonal shape, immersed in a triangular photonic crystal.

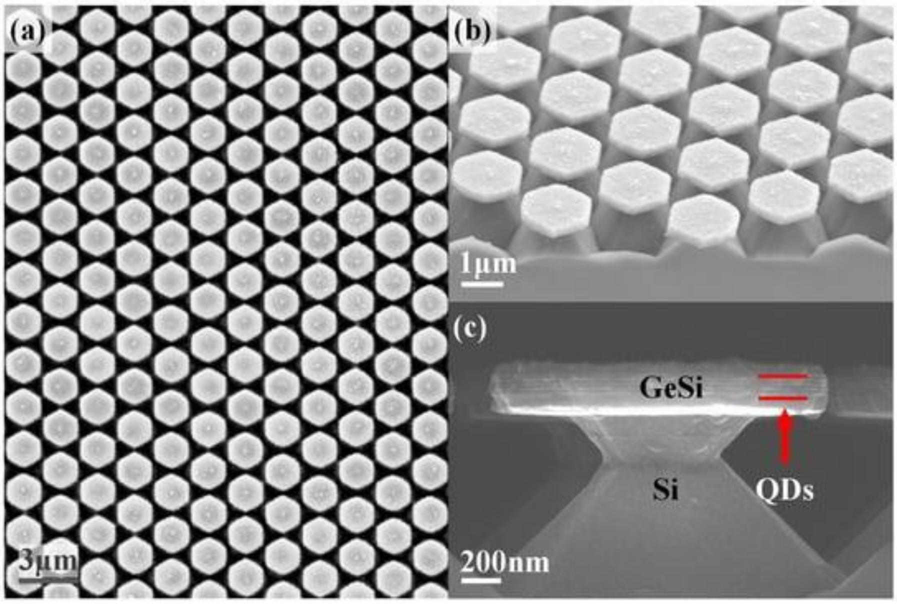


Figure 1.8 : Spectral signatures of hexagonal cavities obtained by photoluminescence.

1.3.3. Wavelength Division Multiplexing (WDM)

A particularly important function in integrated optics that could be achieved with photonic crystals is wavelength division multiplexing (WDM) [10]. The goal is to insert or extract specific wavelengths in a data stream. This device can be realized by exploiting the selectivity of a resonant cavity coupled to waveguides.

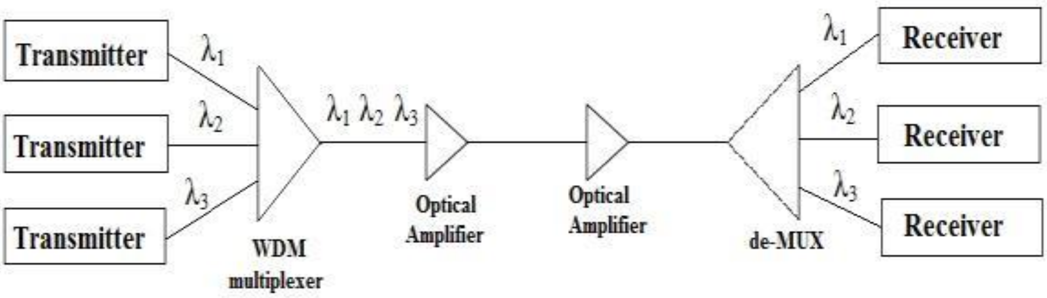


Figure 1.9 : Schematic diagram of a multiplexing device [11].

1.3.4. Add/Drop Filter

The add/drop filter [12] consists of two waveguides coupled by one or two resonators. In an experimental setup, nearly 80% of the power is transferred forward into the drop waveguide. The resonator is a linear cavity composed of ten missing holes (Figure 1.10), whose precise design and utilization of slow optical modes have allowed access to two degenerate modes in the cavity. These modes were compatible for an add/drop functionality.

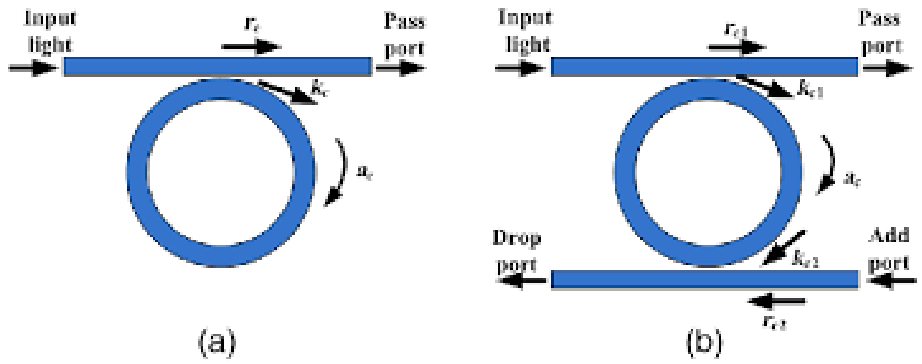


Figure 1.10 : (a) Representation of an Add /drop filtre, (b) operating principle

1.4. Conclusion

Photonic crystals exhibit fascinating properties due to their periodic structure, notably the opening of a photonic band gap that blocks the propagation of light. Although manufacturing three-dimensional structures remains a technical challenge, it is possible to control light in all spatial directions by etching the crystal into a conventional waveguide. Among the geometries used, the triangular hole lattice is particularly effective in opening a wide band gap, making it the preferred approach in the literature. Photonic crystals thus offer promising opportunities for the realization of compact and novel planar optical components, positioning them as an ideal platform for miniature integrated optics.

Chapter 2:

Photonic-crystal fiber

2.1. Introduction

Photonic Crystal Fibers (PCFs) represent a significant advancement in the field of optical fibers. Their internal periodic structure, composed of air-filled capillaries arranged in a hexagonal lattice, enables unique functionalities. Unlike conventional optical fibers, PCFs offer considerable design flexibility, allowing manipulation of several parameters such as lattice pitch, shape and diameter of air holes, glass refractive index, and lattice type. This design freedom overcomes limitations of conventional optical fibers, such as constraints on core diameter for single-mode operation, modal cutoff wavelength, and material limitations. PCFs can be engineered to exhibit desired dispersion properties, such as zero, low, or anomalous dispersion across a wide range of wavelengths. Furthermore, dispersion can be flattened over an extended range. The combination of anomalous dispersion with small mode field areas can result in exceptional nonlinear fibers. Conversely, it's possible to manufacture large-core single-mode fibers, whether solid or with an air core. They (PCFs) offer a wide range of functionalities and design possibilities, paving the way for new applications in various fields, ranging from telecommunications to optical sensors to medical and defense technologies.

2.2. Optical Fiber

An optical fiber is a dielectric waveguide possessing circular symmetry. A conventional optical fiber consists of a core with refractive index n_1 surrounded by an optical cladding with refractive index n_2 lower than n_1 (see Figure 2-1). The index n_2 ensures the condition of total internal reflection for a ray propagating in the core, thereby ensuring efficient light propagation through the fiber.

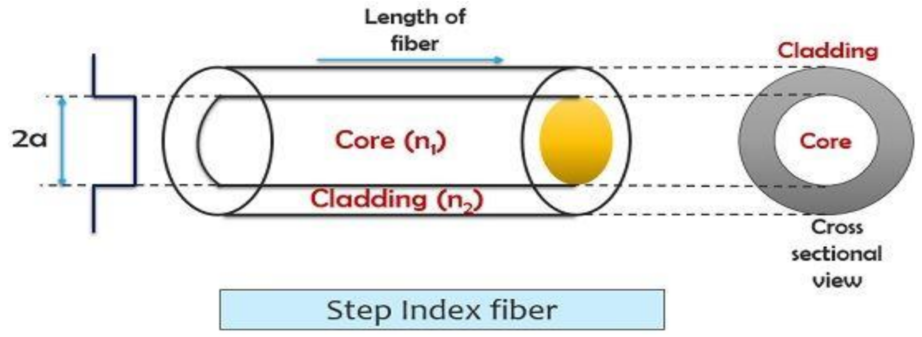


Figure 2.1: Schematic of a step-index optical fiber

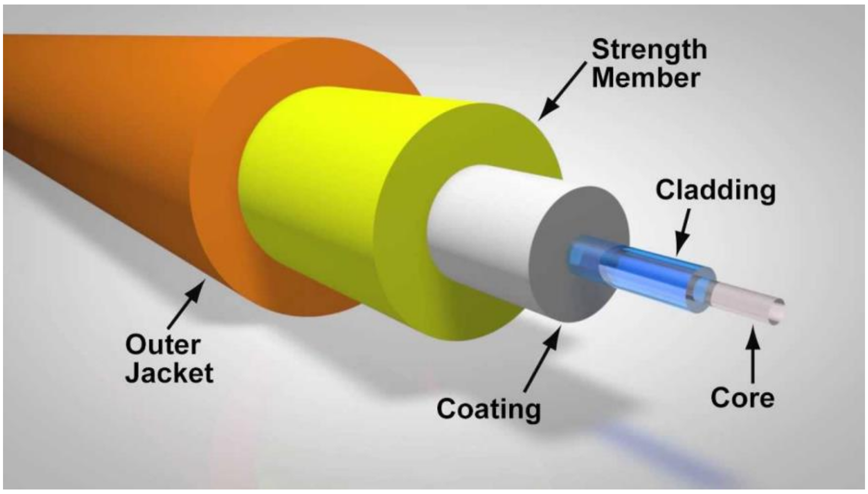


Figure 2.2: optical fiber

Traditionally used fibers in the telecommunications domain guide light through total internal reflection. Air-silica microstructure fibers (ASMFs), which are experiencing considerable development today, either utilize this guiding principle when the core is made of pure silica, or utilize photonic bandgap guidance, especially in the case of hollow-core fibers [13].

The operating principle of an optical fiber is as follows: When a ray of light enters an optical fiber through one of its ends at an appropriate angle, it undergoes multiple total internal reflections. This phenomenon allows the ray to propagate to the other end of the optical fiber without experiencing significant losses, following a zigzag path inside the fiber. Thus, light propagation in the fiber can occur with very low losses, even when the fiber is bent.

2.3. Photonic-crystal fiber

Photonics crystal fibers, also referred to as microstructured fibers or cavity fibers consist of a regular or irregular arrangement of air channels with micrometer-scale dimensions arranged along the axis of propagation. The parameters defining this arrangement and adjusting the optical properties of the fibers include the distance between the centers of two adjacent holes, denoted by Λ (pitch), and the diameter of the holes, denoted by d [14]. These opto-geometric parameters define the d/Λ ratio corresponding to the proportion of air present in the fiber. The hole arrangement can take the form of a triangular, hexagonal, or random matrix. The central region of the fiber, which allows light guiding, is considered the fiber core. Typically, in the case of solid-core fibers, the core is made of pure silica.

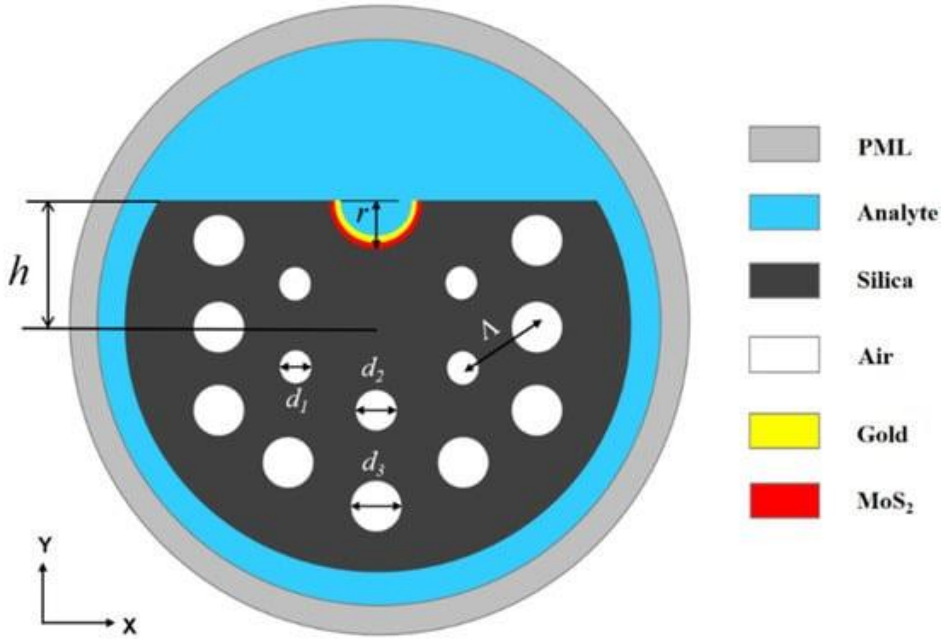


Figure 2.3: Cross section of a PCF with its parameters.

The guiding of light in a photonic crystal fiber relies on two main mechanisms:

A. Total Internal Reflection (TIR) Guiding: Similar to conventional optical fibers, light is guided along the fiber by undergoing total internal reflections at the interfaces between the core material (typically silica) and the air channels. This mechanism allows light to propagate through the fiber by following a zigzag path.

B. Photonic Bandgap (PBG) Guiding: In some photonic crystal fibers, especially those with a hollow core, guiding can also be achieved by creating a photonic bandgap, where certain wavelengths of light are forbidden from propagation. This can be achieved by adjusting the geometry of the fiber to create a periodic structure that interferes with the propagation of light at certain frequencies.

These two guiding mechanisms enable light to propagate efficiently through the photonic crystal fiber, offering unique optical performance and flexible design possibilities.

2.3.2. Classification of photonic crystal fibers

In photonic crystal fibers, light guidance can occur in two different ways depending on the specific geometry of the fiber: either the core index is higher than that of the cladding, or it is lower [15].

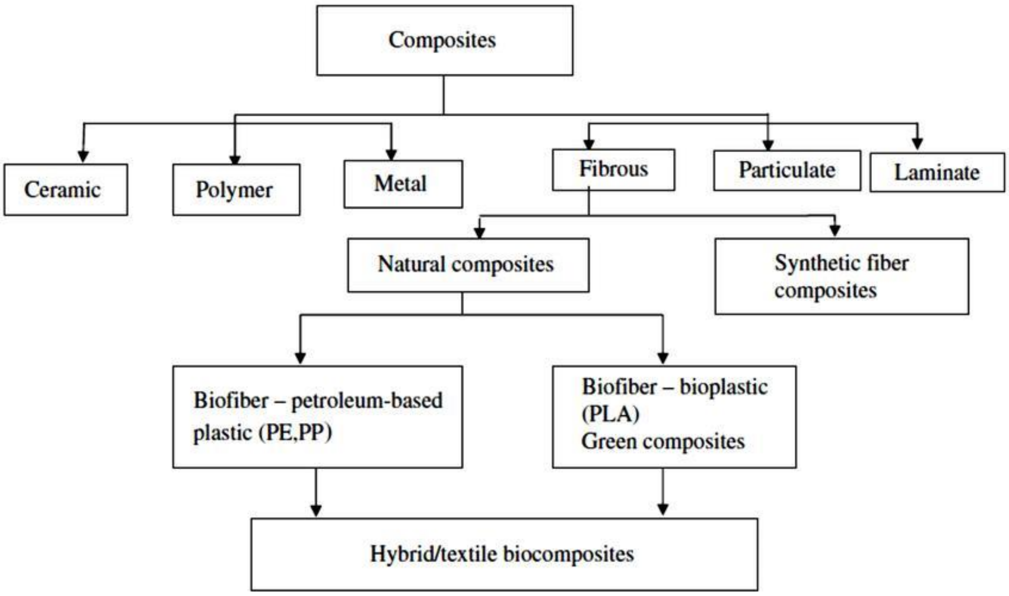


Figure 2.4: Classification of FMAS according to their guidance mechanisms [16].

The wide range of possibilities offered by photonic crystal fibers (PCFs) in terms of degrees of freedom allows for the creation of fibers with specific dispersion characteristics, such as zero dispersion at a given wavelength or constant dispersion in a desired band. Moreover, it is feasible to manufacture polarization-maintaining fibers with birefringence up to two orders of magnitude higher than conventional fibers. The significant nonlinear properties of these fibers can also be exploited to generate a continuum of light. It is possible to design single-mode PCFs with a core size considerably larger than conventional fibers, even exceeding fifty times the wavelength of operation, using suitable photonic structures [17].

These fibers are of considerable interest for transmitting high optical powers in various domains such as telecommunications, high-power lasers used for cutting or marking, as well as for doped fiber lasers or amplifiers [18] .In the remainder of our study, we will focus on this type of solid-core fibers, which we will refer to as photonic crystal fibers or PCFs.

2.4. Advantages and applications of Asmfs:

Air-Silica Microstructure Fibers (ASMFs) offer several advantages over conventional optical fibers, leading to various applications [19]:

2.4.1. Advantages

a. **Low Nonlinearities**: ASMFs can have lower nonlinearities compared to conventional fibers due to the air holes' presence, allowing for higher power handling capabilities without nonlinear effects becoming dominant.

b. **Tailored Dispersion**: ASMFs allow for precise control over dispersion characteristics, enabling customized dispersion profiles for specific applications such as dispersion-compensating fibers in optical communications.

c. **High Birefringence**: ASMFs can achieve higher levels of birefringence compared to conventional fibers, making them suitable for polarization-maintaining applications like sensing and polarization-based signal processing.

d. **Large Mode Area**: ASMFs can be designed with a larger mode area, reducing nonlinear effects such as stimulated Brillouin scattering and enabling high-power laser delivery for applications like material processing and medical treatments.

2.4.2. Applications

i **Telecommunications**: ASMFs are used in optical communication systems for dispersion compensation, wavelength division multiplexing (WDM), and high-speed data transmission.

ii **Sensing**: ASMFs are employed in various sensing applications, including distributed sensing, biomedical sensing, and environmental monitoring, due to their tailored dispersion properties and high birefringence.

iii **High-Power Laser Delivery**: ASMFs are used to deliver high-power laser beams in material processing, laser surgery, and defense applications, where precise control over dispersion and large mode area are critical.

iv **Nonlinear Optics**: ASMFs are utilized in nonlinear optics research and applications such as supercontinuum generation, frequency conversion, and optical parametric amplification due to their low nonlinearities and tailored dispersion characteristics. Overall, the unique properties of ASMFs make them valuable tools in various fields, ranging from telecommunications to sensing to high-power laser delivery and nonlinear optics.

2.5. Multicore Fiber (MCF)

Multicore fibers (MCFs) are a type of optical fiber that contains multiple cores, each capable of carrying independent optical signals. These cores are typically arranged in a regular pattern within the fiber structure. MCFs offer several advantages over single-core fibers [20]:

A. **Increased Capacity**: By utilizing multiple cores within a single fiber, MCFs can significantly increase the transmission capacity compared to single-core fibers. This is particularly useful in applications where high data rates or multiple channels of communication are required.

B. **Space Efficiency**: Instead of laying multiple single-core fibers, MCFs allow for multiple channels of communication to be transmitted within a single physical fiber, saving space and simplifying installation.

C. **Fault Tolerance**: MCFs can provide redundancy and fault tolerance by allowing signals to be rerouted through different cores in the event of a core failure or damage, improving the reliability of the communication network.

D. **Flexible Network Design**: MCFs offer flexibility in network design, allowing for the implementation of various transmission schemes such as wavelength division multiplexing (WDM) or spatial division multiplexing (SDM), which can further increase the transmission capacity and adapt to changing network demands.

MCFs find applications in various fields such as telecommunications, data centers, and high performance computing, where high-capacity and reliable communication links are essential. They are also being explored for emerging technologies such as quantum communication and sensing.

Figure 2.5: Multicore fiber

2.6. Coupling in optical fiber

In the context of optical fiber, coupling refers to the transfer of light between different components or sections of the fiber optic system. This transfer can occur at various interfaces within the system [20]:

A. Input Coupling: This refers to the process of launching light into the optical fiber from an external source, such as a laser or LED. Proper input coupling is essential to efficiently couple light into the fiber core without excessive loss.

B. Coupling between Fibers: In situations where multiple fibers are connected, such as in patch panels or splices, coupling refers to the transfer of light from one fiber to another. This coupling can occur through physical contact, as in the case of connectors, or through evanescent field coupling in fused or tapered fibers.

C. Component Coupling: Optical fibers are often used to connect various optical components, such as lasers, modulators, detectors, and amplifiers. Coupling in this context refers to the transfer of light between the fiber and the component, ensuring efficient interaction between them.

D. Mode Coupling: In multimode fibers, coupling can occur between different modes of light propagating through the fiber. This can lead to mode dispersion and modal noise in the fiber system.

Efficient coupling is crucial for achieving high-performance optical fiber systems with minimal losses. Techniques such as lensed fibers, graded-index fibers, and mode conditioning cables are often used to optimize coupling efficiency in optical fiber systems.

There are mathematical equations and models used to describe and control coupling in optical fiber systems. Some of the key equations and concepts include:

1. **Fresnel Equations**: These equations describe the reflection and transmission coefficients at an interface between two media with different refractive indices. They are used to calculate the amount of light reflected and transmitted at various interfaces within the optical fiber system.
2. **Coupling Efficiency**: Coupling efficiency is a measure of how effectively light is transferred between components in the optical fiber system. It can be calculated using equations that take into account factors such as the numerical aperture of the fiber, mode matching between components, and alignment losses.
3. **Overlap Integral**: The overlap integral quantifies the degree of spatial overlap between the optical mode of the input source and the mode of the optical fiber. It is used to calculate the coupling efficiency between the source and the fiber.
4. **Mode Coupling Equations**: In multimode fibers, mode coupling can be described using coupled mode theory, which involves a set of coupled differential equations governing the evolution of the modal amplitudes along the fiber length. These equations can be solved numerically to predict the modal behavior and coupling effects in the fiber.
5. **Graded-Index Profile**: In fibers with a graded-index profile, such as graded-index multimode fibers or tapered fibers, the coupling efficiency can be optimized by designing the refractive index profile to match the mode profiles of the input and output components.

These equations and models are used in the design and optimization of optical fiber systems to maximize coupling efficiency and minimize losses.

2.7. Conclusion

Photonic crystal fibers combine the properties of 2D photonic crystals and conventional fibers. Research on photonic crystal fibers is still in its early stages, and we can expect numerous new developments, as well as more precise and efficient modeling and characterization methods. Guiding mechanisms based on the photonic bandgap have been implemented and tested. Several new interesting properties such as hollow-core guidance and endless single-mode fibers, as well as tuning properties with liquid crystals, have been studied. Dispersion engineering is possible in PCFs in a range inaccessible to conventional fibers (flat dispersion over a wide range, zero dispersion, and anomalous dispersion in the visible domain).

It is still difficult to estimate the impact of PCFs on the development of photonics, but we can expect a series of new applications in the fields of telecommunications, sensing, beam delivery, surgery, spectroscopy, and fiber lasers in the coming years.

Chapter 3: Results and discussion

3.1. Introduction

Simulation is an essential step in realizing a structure, as it guides and directs us toward selecting the correct static parameters and operating conditions according to predefined objectives. Therefore, the objective of simulation is to elucidate the specific characteristics of the objects under study to facilitate their design. When aiming to optimize structure parameters, it is crucial to focus on the design phase and utilize appropriate software. This chapter presents a series of simulation results obtained using COMSOL software (finite difference method). Where we explore the properties of Photonic Crystal Fibers (PFCs), including chromatic dispersion, effective index, and coupling coefficient for a multicore fiber.

3.2. Simulation method

COMSOL Multiphysics is a powerful finite element analysis (FEA) and simulation software used for modeling and simulating physics-based systems. It allows engineers, scientists, and researchers to simulate and analyse various physical phenomena across multiple disciplines, such as electromagnetics, structural mechanics, fluid dynamics, heat transfer, acoustics, and chemical reactions.

COMSOL provides a user-friendly interface where users can create, simulate, and analyze complex multiphysics models. It offers a wide range of built-in physics modules and predefined material properties, making it suitable for simulating a diverse array of problems. Additionally, COMSOL allows for customization and scripting, enabling users to implement specific modelling techniques or algorithms tailored to their needs.

Overall, COMSOL is a versatile and comprehensive simulation tool used in academia, research, and industry for solving challenging engineering and scientific problems involving coupled physical phenomena (for more details see Appendix 1).

3.3. Proposed fiber design

The proposed multicore Photonic Crystal Fiber (PCF) design [21], illustrated in Figure 3.1, features a cladding comprised of air holes with constant diameter and pitch, with multiple cores created by single missing air holes at various locations. Our design includes five cores, labeled 1 through 5, with core 1 positioned centrally, serving as the launch point for optical power. Cores 2 and 4 are horizontally placed, while cores 3 and 5 are aligned vertically. Careful selection of core positions maintains structural symmetry, allowing us to simplify analysis by considering only one quarter section of the multicore PCF.

The spacing between cores 1 and 2, and cores 1 and 3, varies, leading to different coupling coefficients for cores 1–2 and cores 1–3. Achieving equal power transfer between neighboring cores requires equal horizontal and vertical coupling coefficients. To ensure this balance, we adjust the vertical coupling coefficient by reducing the diameter of air holes (denoted by d') located above and below each core, as indicated by red circles in Figure 3.1 .The size of these small airholes is optimized to equalize horizontal and vertical coupling coefficients.

In our numerical calculations, the background material silica has a refractive index of 1.45, and we neglect material dispersion due to the short length of the proposed fiber splitter (a few millimeters) and its operation within the C-band. However, for operations at shorter wavelengths (e.g., 800 nm), consideration of silica's wavelength dependency is necessary.

(a)

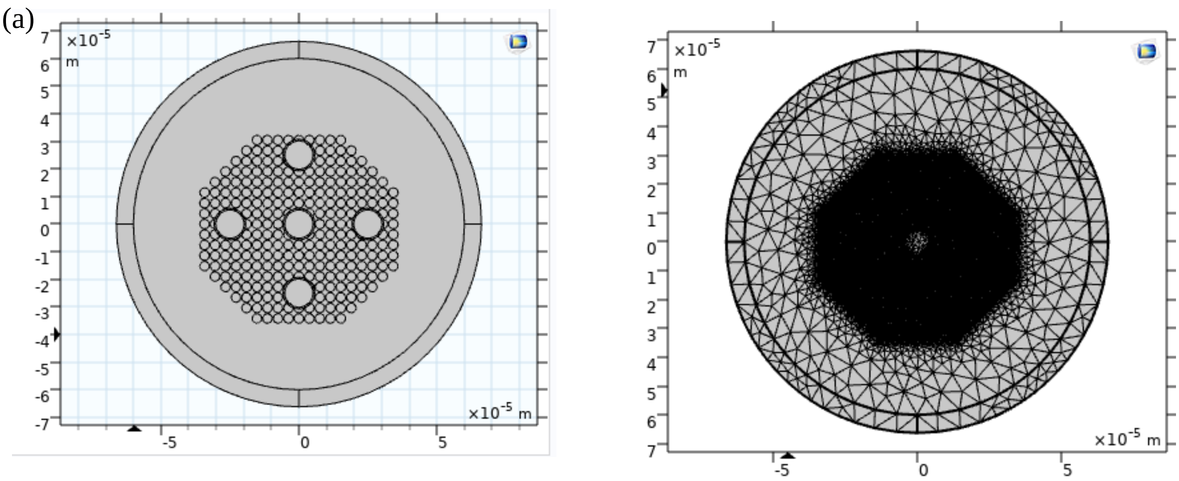


Figure 3.1: (a) Schematic view of multicore PCF-based 1x4, (b) The mesh of the one core fiber

The mesh of the structure (one core) is depicted in Figure 3.1 (b), showing the division of the structure into small finite elements connected together to form a continuous network. Each finite element is characterized by a set of nodes or interpolation points, and the physical properties of the structure are assigned to these elements. This mesh is used to represent the design parameters and enable the search for optimal configurations by adjusting the shape, size, or position of the elements.

The parameters of our structure are summarized in the table above:

Name	Value	Expression
DCL (Cladding outer diameter)	120[um]	/
Λ	1550[nm]	/
Pitch	3.8 [um]	Λ
T (The thickness of the air core)	0.6 [um]	/
N (The number of repeated cladding air hole)	15	/
Dhol (The cladding air holes diameter)	/	0.9*P
PML (The perfectly match layer)	/	4*λ

Table 3 .1: The parameters of proposed fiber design.

3.4. Coupled mode theory

In our analysis of the proposed multicore PCF power splitter, we utilize standard coupled-mode equations [22]. The mode coupling between the cores can be described by a simple set of equations. We define the coupling coefficients k_h and k_v, which represent the coupling between horizontally placed cores (core 1-core 2 or core 1-core 4) and vertically aligned cores (core 1-core 3 or core 1-core 5), where core 1 is the central core. Figure 3.2 illustrates the conceptual coupling between the isolated cores. It's important to note that we neglect the coupling between the adjacent outer cores (core 2 and core 3), because the coupling coefficient k_d between the adjacent outer cores is sufficiently small compared with the horizontal and vertical coupling Coefficients. The coupling characteristics are succinctly captured by the coupled-mode equations.

$$\frac{da_1}{dz}+j\beta a_1=-j\{\ (a_2+a_4\ )K_h+(a_3+a_5\ )K_v+k_1\ \} \qquad (3.1)$$

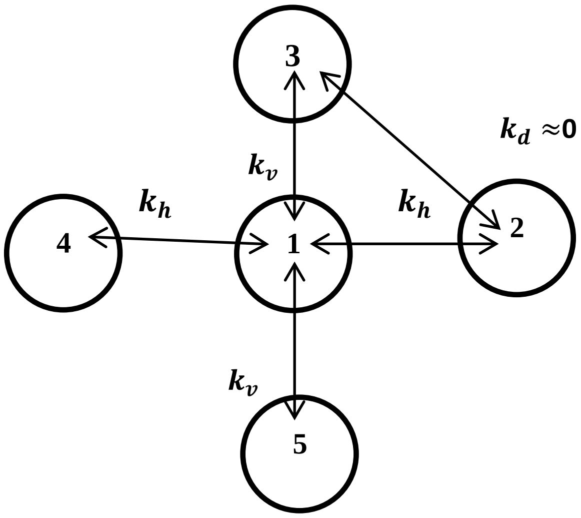


Figure 3 . 2: Schematic picture of coupling between the cores.

$$\frac{da_2}{dz}+j\beta a_2=-ja_1(k_h+k_2) \qquad (3.2)$$

$$\frac{da_3}{dz}+j\beta a_3=-ja_1(k_v+k_3) \qquad (3.3)$$

$$\frac{da_4}{dz}+j\beta a_4=-ja_1(k_h+k_4) \qquad (3.4)$$

$$\frac{da_5}{dz}+j\beta a_5=-ja_1(k_v+k_5) \qquad (3.5)$$

Where a_k (k= 1, 2, 3, 4, 5) are the amplitude of the fundamental mode in core k, is the propagation constant of the fundamental mode,

k_h And k_v are the coupling coefficients between the horizontally placed cores and The vertically aligned cores, respectively.

Since the cores 2 and 4 and cores 3 and 5 are identical, the mode amplitude shall be equal. Therefore, coupled-mode equations can be reduced to (3.6)-(3.8) as below:

$$\frac{da_1}{dz}+j\beta a_1=-J\ \{2a_2\ k_h+2a_3k_v+\ k_1\} \qquad (3.6)$$

$$\frac{da_2}{dz}+j\beta a_2=-ja_1k_h+k_2 \qquad (3.7)$$

$$\frac{da_3}{dz}+j\beta a_3=-ja_1k_v+k_3 \qquad (3.8)$$

With boundary conditions $a_1(0)$ =1, $a_2(0)$ = $a_3(0)$ =0.

For simplicity, the coupling coefficients are assumed to be polarization independent.

By making the substitution

a_k=A_n expo (-j $(\beta + \sigma)z$) into (3.6)-(3.8), the characteristic equation can be written as

$$\begin{vmatrix} \sigma & -2K_h & -2K_v \\ -K_h & \sigma & 0 \\ -K_v & 0 & \sigma \end{vmatrix} = 0 \qquad (3.9)$$

Where σ in (3.8) is an eigenvalue calculated by solving (3.8), resulting into three eigenvalues and corresponding three eigenvectors. The eigenvalues are 0,

$\sqrt{2({K_h}^2 + {K_v}^2)},\ et\ -\sqrt{2({K_h}^2 + {K_v}^2)}$.

The field at a position can be represented by the linear combination of the eigenvectors. Each eigenvector represents a mode.

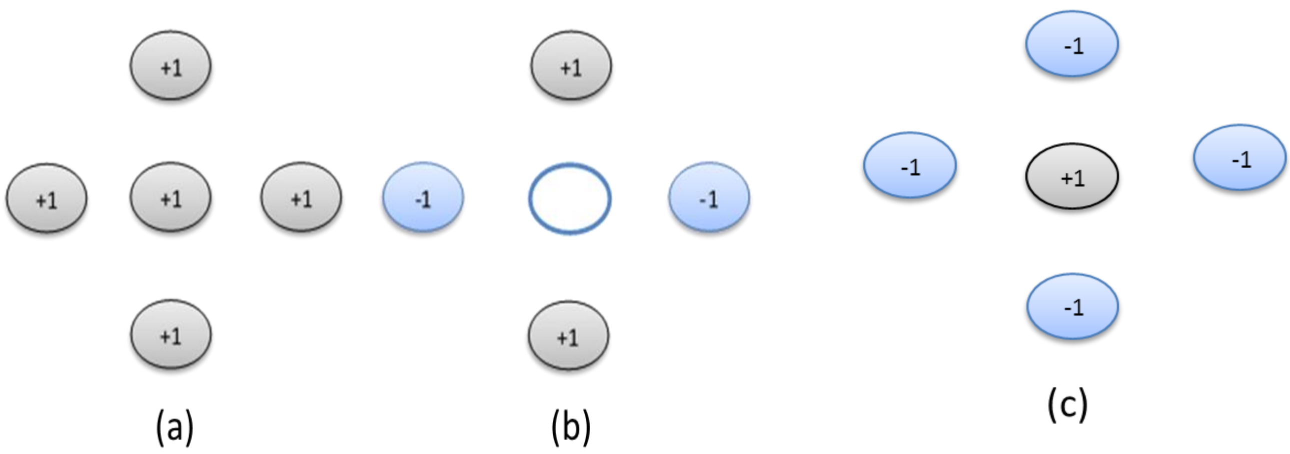


Figure 3. 3: Relative amplitude and phases of supermodes in the proposed multicore PCF splitter, (a) denotes all modes of isolated cores are in phase, (b) modes in outer cores are out of phase to each other, and (c) all modes in outer cores are in anti-phase.

3.4.1. Coupling coefficient

To compute the coupling coefficients of the proposed multi core PCF coupler, we use Finite Element Method (FEM) [23].

The geometrical parameters of the multicore PCF are d/Λ =0.45, d'/Λ,

Where d is the hole diameter of large air holes in the cladding,

d' is the hole diameter of small air holes,

And Λ is the separation between two consecutive air holes.

The size of small air hole d' is obtained by the coupling characteristics.

- → As a first step of our numerical simulations, we evaluate the horizontal and vertical coupling coefficients using the FEM solver by varying the diameter of small air holes and maintaining the pitch Λ constant .
- → The cross-coupling between the adjacent outer cores, namely, core 2-core 3, core 3-core 4, core 4-core 5, and core 5-core 2 is neglected, because the cross-coupling coefficient K_d is sufficiently small in comparison to K_h And K_v .

The variation of the coupling coefficients at a 1550 nm wave length is shown in Figure 3.4 as a function of normalized pitch constant (Λ/λ) for different d'/Λ values, namely, d'/Λ = 0 .20, d'/Λ =0 .30 and d'/Λ =0 ,40

The dashed black curves correspond to the horizontal coupling coefficient K_h and the dashed red curves stand for vertical coupling coefficient K_v .

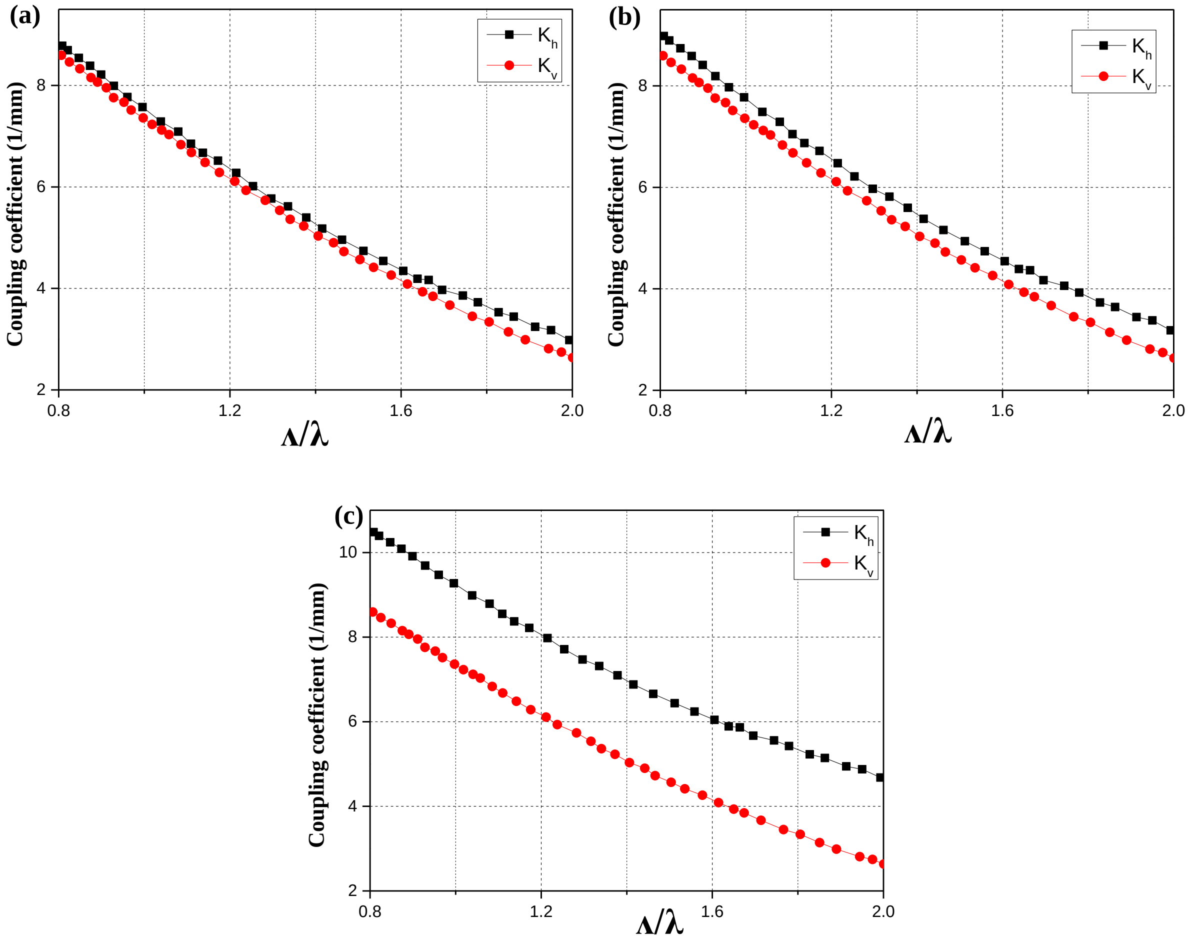


Figure 3.4: Coupling coefficient variation as a function of normalized pitch for different values of small hole diameter, namely, (a) d'/Λ = 0.20, (b) d'/Λ=0.30 and (c) d'/Λ =0.40

The vertical coupling coefficient is smaller than the horizontal coupling coefficient when d'/Λ is 0.40, 0.30 and 0.20 and decreases exponentially as normalized pitch increases Through numerical simulations, we arrive at d'/Λ =0.23, where K_h and K_v become equal at a normalized pitch value of 1.7, suggesting the complete power transfer in surrounding cores with equal coupling ratio. As the operating wavelength is set to 1550 nm, the pitch value can be computed as 2.64 m, where K_h=K_v . The variation of coupling coefficient as a function of pitch for d'/Λ =0.23 is plotted in Figure 3.5, the coupling length is computed as~5.8 mm with Λ =2.64 μm at 1550 nm with length.

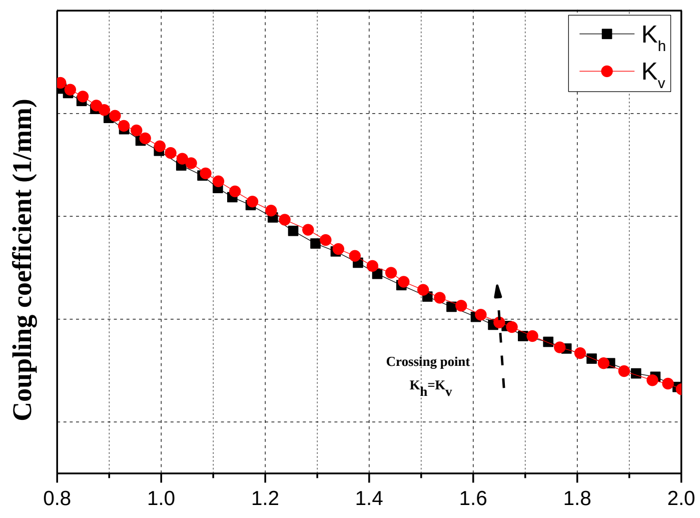


Figure 3.5: Coupling coefficient variation as a function of normalized pitch.

At The crossing point, $k_h = k_v$ indicating the complete power transfer to surrounding cores. The computed pitch value is 2, 64 µm at 1550 nm wavelength.

3.4.2. Effective index

The change in the effective index with wavelength is shown in Figure 3.6.

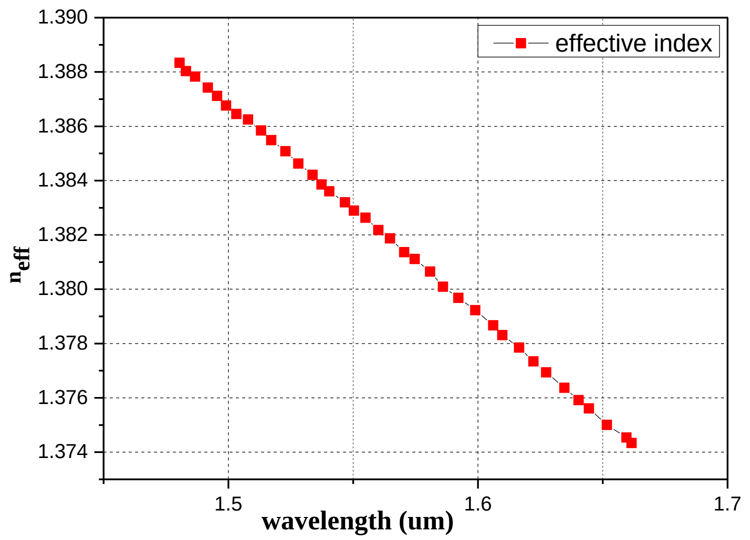


Figure 3.6: Variation of effective index with wavelength

We observe that the change in the effective index, experienced by light propagating within the fiber, is particularly rapid in multicore PCFs. This phenomenon is primarily attributed to various factors inherent in the structure of these fibers, with core-to-core coupling being a key contributor. In multicore PCFs, light can couple between adjacent cores due to evanescent field interactions. As the wavelength changes, the coupling between cores undergoes variation, thereby influencing the effective index of the guided modes. Notably, when the wavelength aligns with specific coupling conditions, such as phase matching, significant and rapid changes in the effective index can manifest.

3.4.3. Chromatic dispersion

We note that the proposed device offers high negative dispersion of -3500ps/nm.km, as shown in Figure 3.7

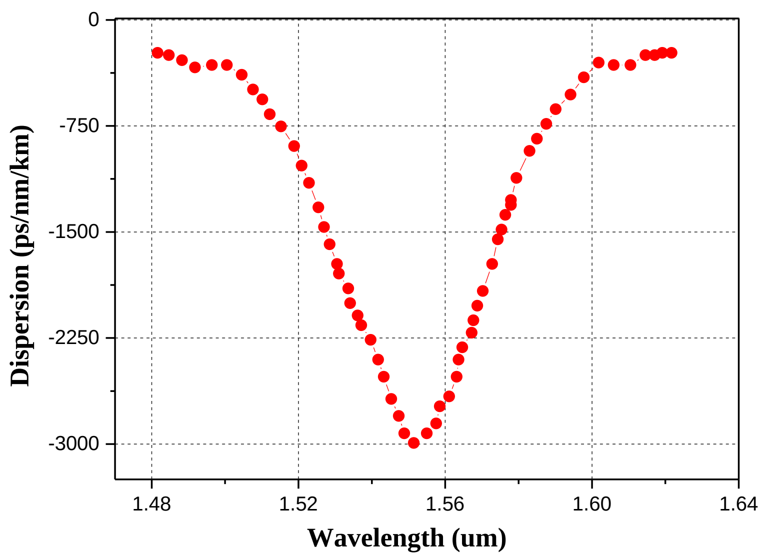


Figure 3.7: Variation of dispersion with λ for Multicore PCF

3.5. Conclusion

In this chapter we have presented the 1x4 power splitter based on multicore PCFs. Coupled mode equations are derived to show the power transfer to the neighbouring cores with 25% coupling ratio, the proposed multicore PCF divides the power equally into the neighbouring cores.

General Conclusion

In recent years, photonic crystal fibers (PCFs) have emerged as a promising platform for various optical applications due to their unique properties and versatile functionalities. Among these, the development of powerful splitters within PCFs has garnered significant interest, enabling efficient splitting of optical signals for diverse applications ranging from telecommunications to sensing and beyond.

In this work, we present a novel multifunctional photonic crystal fiber incorporating 1x4 powerful splitters. These splitters, integrated within the PCF structure, offer unprecedented capabilities for splitting optical signals with high efficiency and minimal loss.

The integration of powerful splitters within the PCF platform opens up new avenues for advanced optical functionalities, including wavelength division multiplexing, polarization-sensitive imaging, optical coherence tomography, and beyond. Additionally, the compact and versatile nature of PCFs makes them well-suited for integration into various optical systems and devices, paving the way for next-generation optical communication networks and photonic applications.

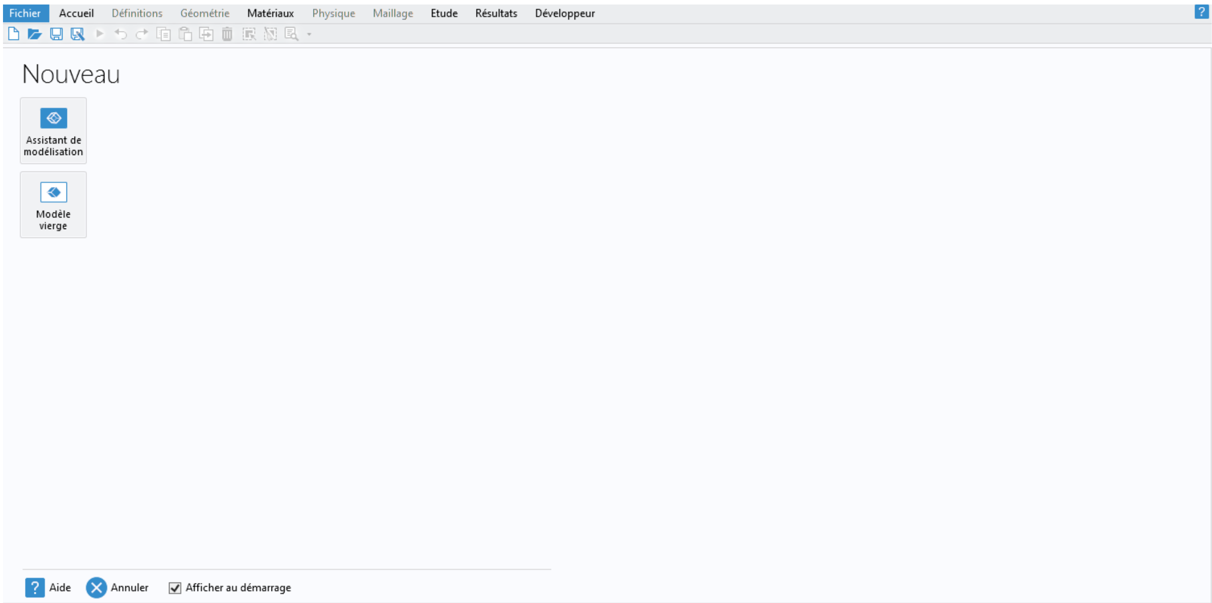
The power coupling characteristics of this newly designed multicore PCFs were demonstrated numerically by employing accurate FEM (with Comsol software). The coupled-mode equations have also derived to compare the power transfer among the neigh- boring cores with 25% of coupling ratio. The proposed multicore PCF can split a single input power into four ports with equal power in each four cores, showing the capability to acts as 1x4 power splitter. Through numerical simulations, it has been revealed that the power can be divided into four cores in the multicore PCF having, $d/\Lambda=0.45$ at 1550 nm wavelength.

Appendix

COMSOL Multiphysic is a numerical simulation software based on the finite element method and which encompasses all stages of the modelling process: from the definition of geometries, material properties and physics, describing specific phenomena, to the resolution and post-processing of models while ensuring precise and reliable results.

Creating a new model

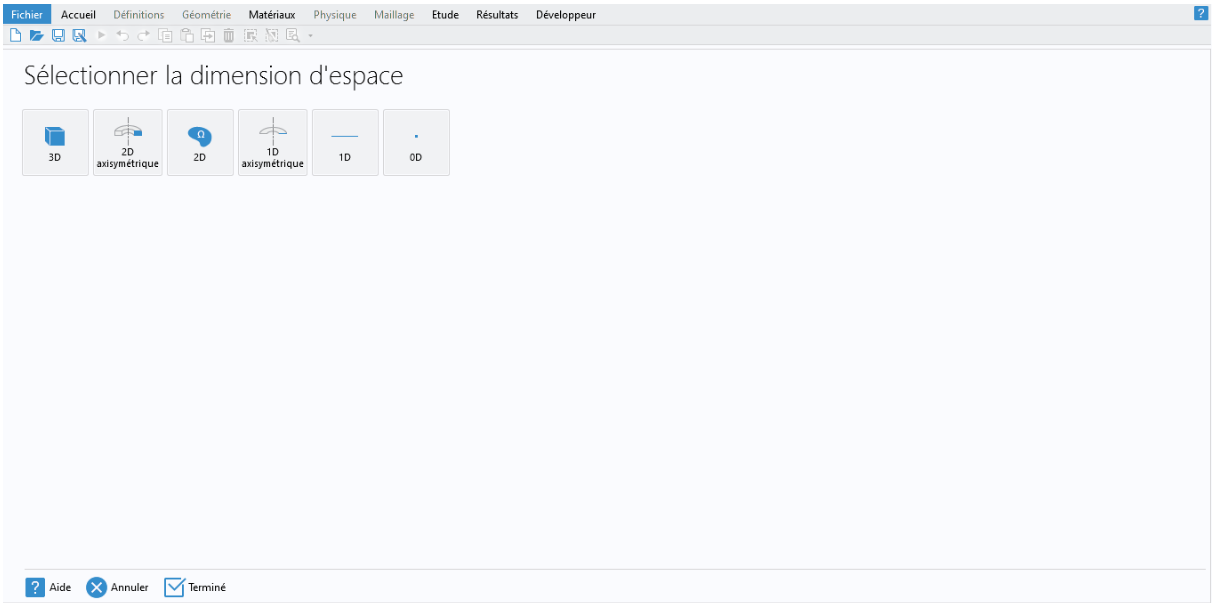
You can configure a template guided by the template wizard or start from a blank template as shown in the figure below.



CREATE A TEMPLATE GUIDED BY THE TEMPLATE WIZARD

The model wizard will guide you in configuring the spatial dimension, physics and study type in a few steps:

- Start by selecting the space dimension for your model component:
  3D, 2D Axisymmetric, 2D, 1D Axisymmetric or 0D
- add one or more physical interfaces. These are organized into several branches of physics in order to facilitate their location.
- These branches do not correspond directly to the products. When products are added to your COMSOL Multiphasic Installation, one or more branches will be populated with additional physical interfaces.



Select the study type that represents the solver or set of solvers that will be used for the calculation.

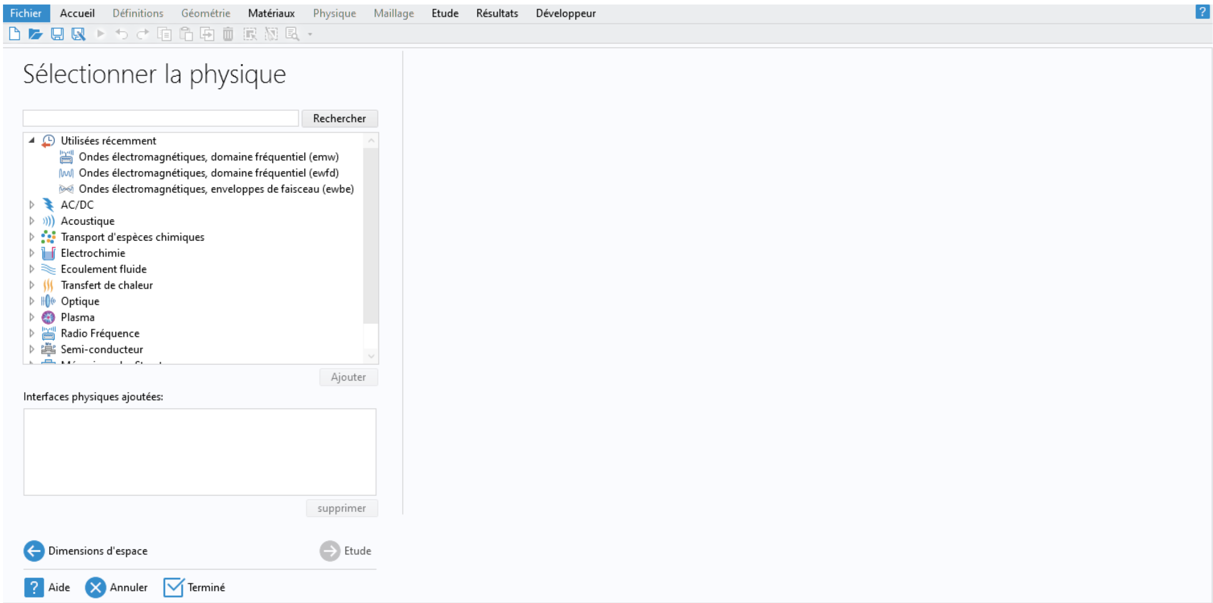
Finally, click done. The desktop is now displayed with the template tree configured according to the choices you made in the template wizard.

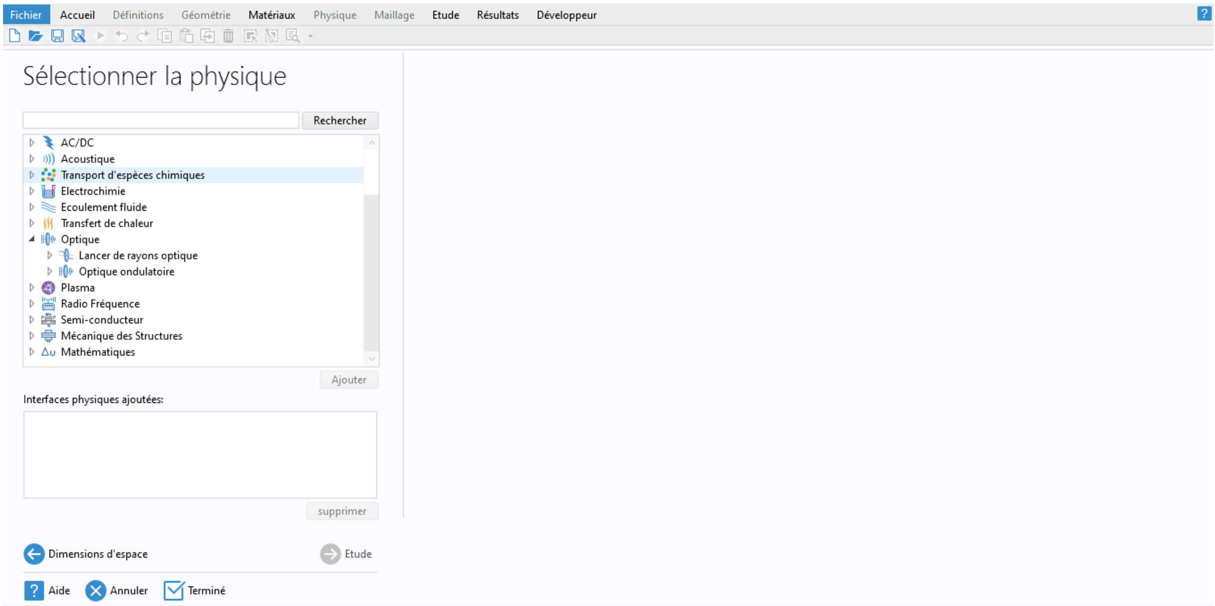
CREATING A BLANK TEMPLATE

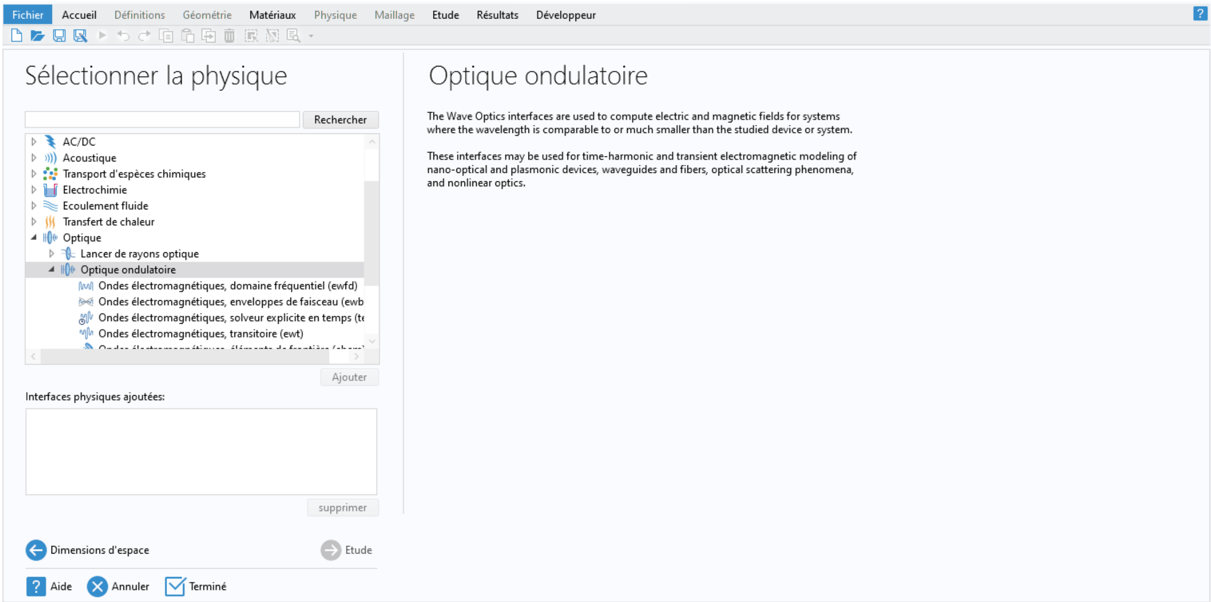
The Blank Model option will open the COMSOL Desktop interface without any

Component or study. You can right-click the model tree to add a component of a certain spatial dimension, physical interface, or study.

The following images show the method used to construct and simulate the photonic crystals .




Fichier
Accueil
Définitions
Géométrie
Matériaux
Physique
Maillage
Etude
Résultats
Développeur
Sélectionner la physique
Rechercher
AC/DC
Acoustique
Transport d'espèces chimiques
Electrochimie
Ecoulement fluide
Transfert de chaleur
Optique
Lancer de rayons optique
Optique ondulatoire
Plasma
Radio Fréquence
Semi-conducteur
Mécanique des Structures
Mathématiques
Ajouter
Interfaces physiques ajoutées:
supprimer
Dimensions d'espace
Etude
Aide
Annuler
Terminé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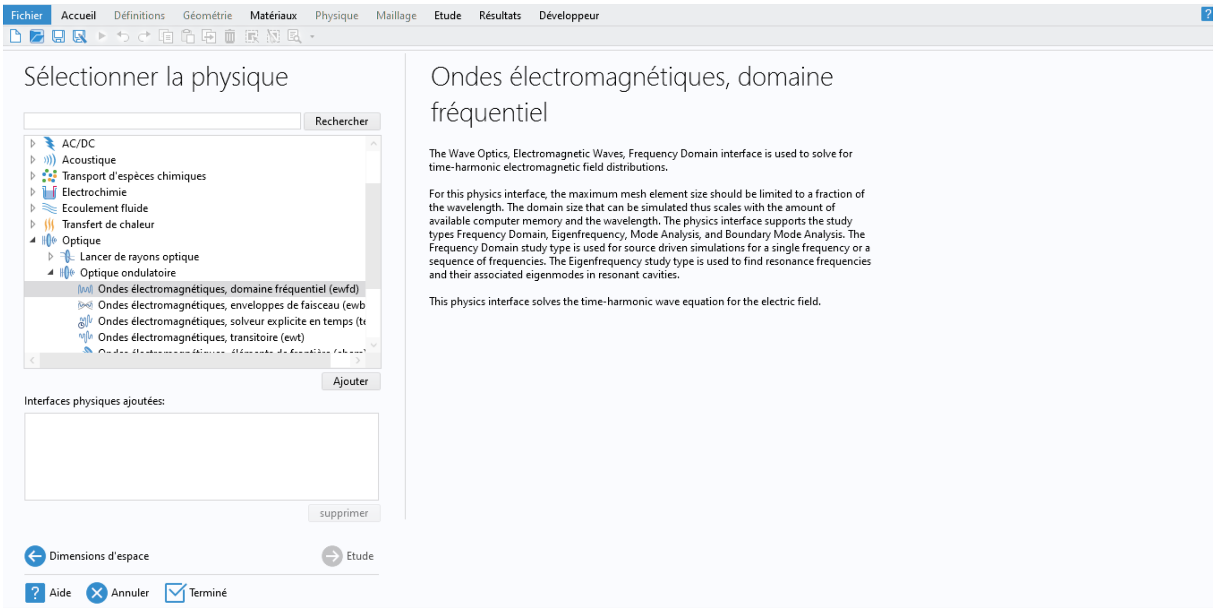
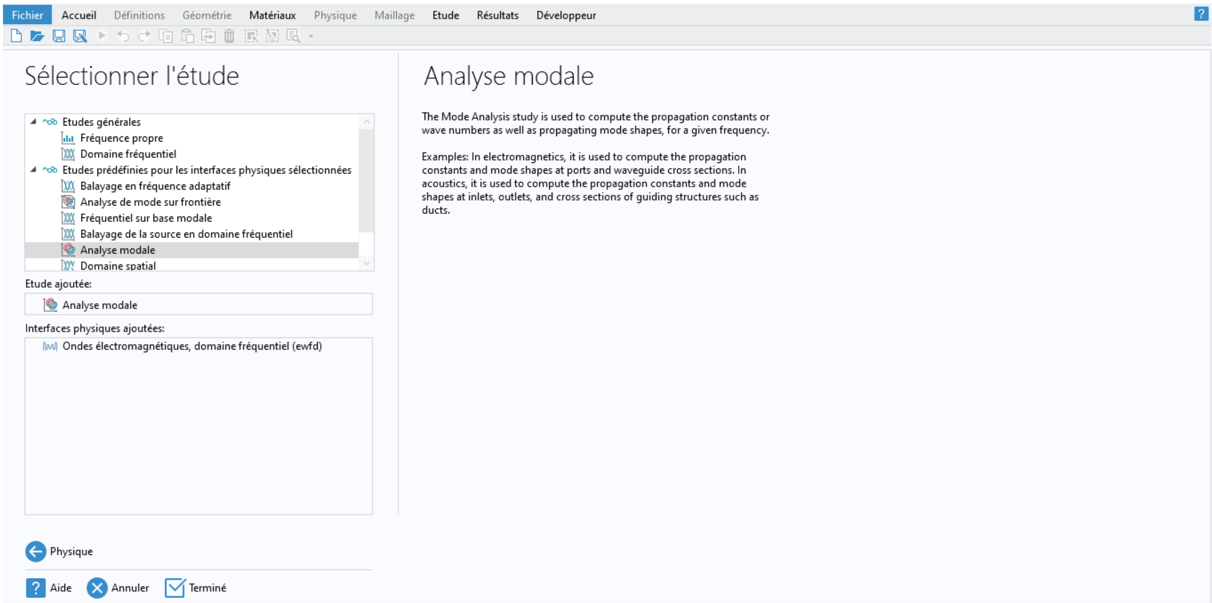
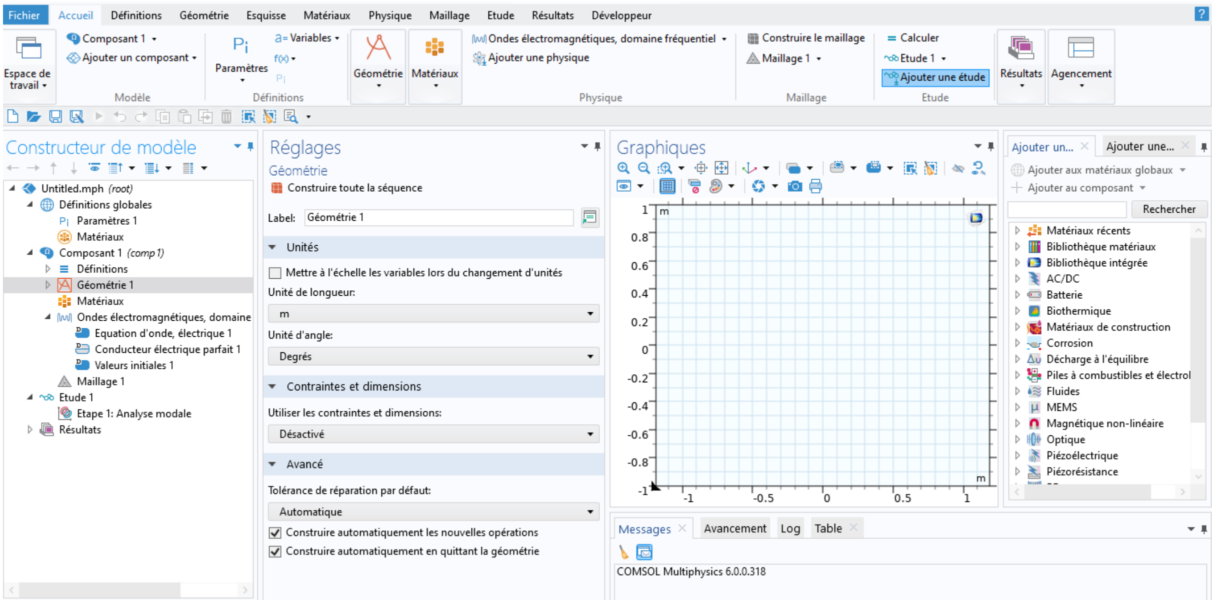
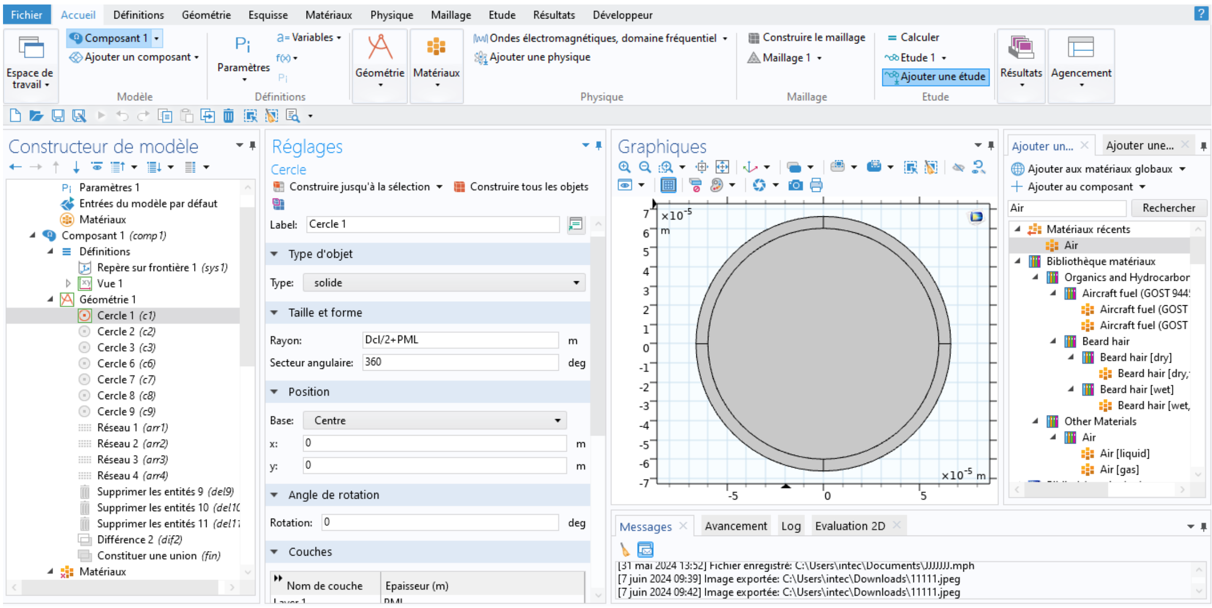
Résultats
Développeur
Sélectionner la physique
Rechercher
AC/DC
Acoustique
Transport d'espèces chimiques
Electrochimie
Ecoulement fluide
Transfert de chaleur
Optique
Lancer de rayons optique
Optique ondulatoire
Ondes électromagnétiques, domaine fréquentiel (ewfd)
Ondes électromagnétiques, enveloppes de faisceau (ewb
Ondes électromagnétiques, solveur explicite en temps (te
Ondes électromagnétiques, transitoire (ewt)
Ajouter
Interfaces physiques ajoutées:
supprimer
Dimensions d'espace
Etude
Aide
Annuler
Terminé
Optique ondulatoire
The Wave Optics interfaces are used to compute electric and magnetic fields for systems where the wavelength is comparable to or much smaller than the studied device or system.
These interfaces may be used for time-harmonic and transient electromagnetic modeling of nano-optical and plasmonic devices, waveguides and fibers, optical scattering phenomena, and nonlinear optics.


Fichier Accueil Définitions Géométrie Matériaux Physique Maillage Etude Résultats Développeur
Sélectionner la physique
Rechercher
AC/DC
Acoustique
Transport d'espèces chimiques
Electrochimie
Ecoulement fluide
Transfert de chaleur
Optique
Lancer de rayons optique
Optique ondulatoire
Ondes électromagnétiques, domaine fréquentiel (ewfd)
Ondes électromagnétiques, enveloppes de faisceau (ewb
Ondes électromagnétiques, solveur explicite en temps (te
Ondes électromagnétiques, transitoire (ewt)
Ajouter
Interfaces physiques ajoutées:
supprimer
Dimensions d'espace
Etude
Aide
Annuler
Terminé
Ondes électromagnétiques, domaine fréquentiel
The Wave Optics, Electromagnetic Waves, Frequency Domain interface is used to solve for time-harmonic electromagnetic field distributions.
For this physics interface, the maximum mesh element size should be limited to a fraction of the wavelength. The domain size that can be simulated thus scales with the amount of available computer memory and the wavelength. The physics interface supports the study types Frequency Domain, Eigenfrequency, Mode Analysis, and Boundary Mode Analysis. The Frequency Domain study type is used for source driven simulations for a single frequency or a sequence of frequencies. The Eigenfrequency study type is used to find resonance frequencies and their associated eigenmodes in resonant cavities.
This physics interface solves the time-harmonic wave equation for the electric field.


Fichier Accueil Définitions Géométrie Matériaux Physique Maillage Etude Résultats Développeur
Sélectionner l'étude
Etudes générales
Fréquence propre
Domaine fréquentiel
Etudes prédéfinies pour les interfaces physiques sélectionnées
Balayage en fréquence adaptatif
Analyse de mode sur frontière
Fréquentiel sur base modale
Balayage de la source en domaine fréquentiel
Analyse modale
Domaine spatial
Etude ajoutée:
Analyse modale
Interfaces physiques ajoutées:
Ondes électromagnétiques, domaine fréquentiel (ewfd)
Physique
Aide
Annuler
Terminé
Analyse modale
The Mode Analysis study is used to compute the propagation constants or wave numbers as well as propagating mode shapes, for a given frequency.
Examples: In electromagnetics, it is used to compute the propagation constants and mode shapes at ports and waveguide cross sections. In acoustics, it is used to compute the propagation constants and mode shapes at inlets, outlets, and cross sections of guiding structures such as ducts.


Fichier
Accueil
Définitions
Géométrie
Esquisse
Matériaux
Physique
Maillage
Etude
Résultats
Développeur
Composant 1
Ajouter un composant
Espace de travail
Modèle
Paramètres
Variables
Définitions
Géométrie
Matériaux
Ondes électromagnétiques, domaine fréquentiel
Ajouter une physique
Physique
Construire le maillage
Maillage 1
Maillage
Calculer
Etude 1
Ajouter une étude
Etude
Résultats
Agencement
Constructeur de modèle
Untitled.mph (root)
Définitions globales
Paramètres 1
Matériaux
Composant 1 (comp1)
Définitions
Géométrie 1
Matériaux
Ondes électromagnétiques, domaine
Equation d'onde, électrique 1
Conducteur électrique parfait 1
Valeurs initiales 1
Maillage 1
Etude 1
Etape 1: Analyse modale
Résultats
Réglages
Géométrie
Construire toute la séquence
Label: Géométrie 1
Unités
Mettre à l'échelle les variables lors du changement d'unités
Unité de longueur:
m
Unité d'angle:
Degrés
Contraintes et dimensions
Utiliser les contraintes et dimensions:
Désactivé
Avancé
Tolérance de réparation par défaut:
Automatique
Construire automatiquement les nouvelles opérations
Construire automatiquement en quittant la géométrie
Graphiques
Ajouter un...
Ajouter une...
Ajouter aux matériaux globaux
Ajouter au composant
Rechercher
Matériaux récents
Bibliothèque matériaux
Bibliothèque intégrée
AC/DC
Batterie
Biothermique
Matériaux de construction
Corrosion
Décharge à l'équilibre
Piles à combustibles et électrol
Fluides
MEMS
Magnétique non-linéaire
Optique
Piézoélectrique
Piézorésistance
Messages
Avancement
Log
Table
COMSOL Multiphysics 6.0.0.318


Fichier
Accueil
Définitions
Géométrie
Esquisse
Matériaux
Physique
Maillage
Etude
Résultats
Développeur
Composant 1
Ajouter un composant
Constructeur de modèle
Paramètres 1
Entrées du modèle par défaut
Matériaux
Composant 1 (comp1)
Définitions
Repère sur frontière 1 (sys1)
Vue 1
Géométrie 1
Cercle 1 (c1)
Cercle 2 (c2)
Cercle 3 (c3)
Cercle 6 (c6)
Cercle 7 (c7)
Cercle 8 (c8)
Cercle 9 (c9)
Réseau 1 (arr1)
Réseau 2 (arr2)
Réseau 3 (arr3)
Réseau 4 (arr4)
Supprimer les entités 9 (del9)
Supprimer les entités 10 (del10)
Supprimer les entités 11 (del11)
Différence 2 (dif2)
Constituer une union (fin)
Matériaux
Réglages
Cercle
Construire jusqu'à la sélection
Construire tous les objets
Label: Cercle 1
Type d'objet
Type: solide
Taille et forme
Rayon: Dcl/2+PML m
Secteur angulaire: 360 deg
Position
Base: Centre
x: 0 m
y: 0 m
Angle de rotation
Rotation: 0 deg
Couches
Nom de couche
Epaisseur (m)
Graphiques
Ajouter aux matériaux globaux
Ajouter au composant
Air
Rechercher
Matériaux récents
Air
Bibliothèque matériaux
Organics and Hydrocarbon
Aircraft fuel (GOST 944
Beard hair
Beard hair [dry]
Beard hair [wet]
Other Materials
Air
Air [liquid]
Air [gas]
Messages
Avancement
Log
Evaluation 2D
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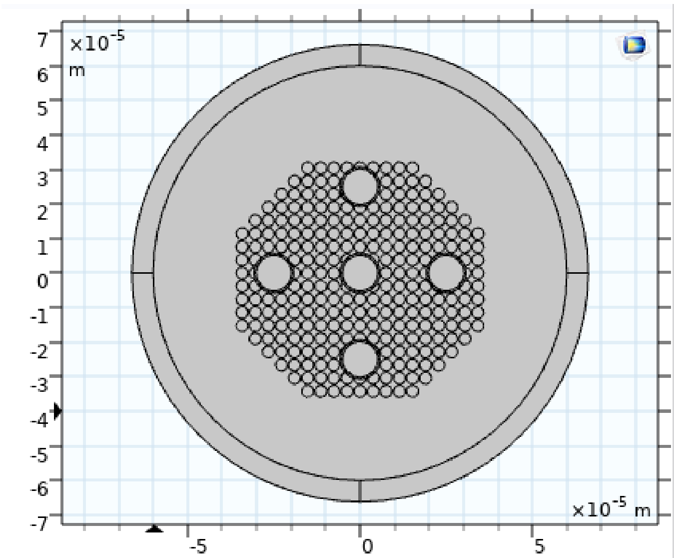
[7 juin 2024 09:39] Image exportée: C:\Users\intec\Downloads\11111.jpeg
[7 juin 2024 09:42] Image exportée: C:\Users\intec\Downloads\11111.jpeg


×10^-5
m
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-5
0
5
×10^-5 m

Reference

Reference

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Abstract

Optical fiber is the preferred medium for transmitting information in modern times. However, to keep up with the growing demands spurred by the internet's expansion, continuous enhancement of fiber propagation properties is imperative. A new generation of fibers aims at reducing losses and enhancing overall performance compared to traditional counterparts. This study introduces a hexagonal photonic crystal fiber (PCF) design for analyzing various optical properties across different wavelengths. The geometry is utilized to examine parameters such as effective refractive index, dispersion, effective mode area, nonlinearity coefficient, and birefringence. Silica glass is selected as the base material, with the cladding area composed of layers of air holes. The research focuses on modeling and analyzing wave propagation characteristics in optical crystal fibers.

Keywords: finite-element methods (FEMs), microstructured fibers, optical fiber devices, photonic crystal fiber, power splitter

Résumé

La fibre optique est un guide de lumière qui constitue aujourd'hui le support privilégié pour le transport de l'information. Cependant, afin de répondre aux besoins croissants générés par le développement d'Internet notamment, il était nécessaire d'améliorer toujours les caractéristiques de propagation dans les fibres. Une nouvelle génération de fibres a été conçue dans le but d'obtenir des pertes moindres et de meilleures performances que les fibres classiques. Ce travail présente une conception de la géométrie de la fibre à cristal photonique hexagonale (PCF) pour l'analyse différentes propriétés optiques en ce qui concerne la plage de longueurs d'onde. Cette géométrie a été utilisée pour analyser l'indice de réfraction effectif, la dispersion, la zone de mode effectif, le coefficient non linéaire et la biréfringence. Le verre de silice est choisi comme matériau de base et la région de revêtement est constituée de couches de trous d'air. Ce travail s'appuie sur la modélisation et l'analyse des caractéristiques de propagation des ondes dans une fibre à cristal photonique

Mots clés : méthodes d'éléments finis (FEM), fibres microstructures, dispositifs à fibres optiques, fibre à cristaux photoniques, répartiteur de puissance.

ملخص

الألياف الضوئية هي دليل بصري اليوم هو الوسيلة المفضلة لنقل المعلومات. ومع ذلك ، من أجل تلبية الاحتياجات المتزايدة الناجمة عن تطوير الإنترنت على وجه الخصوص ، كان من الضروري دائما تحسين خصائص انتشار الألياف. تم تصميم جيل جديد من الألياف للحصول على خسائر أقل وأداء أفضل من الألياف التقليدية. يقدم هذا العمل تصميما هندسيا سداسي من الألياف البلورية الضوئية (PCF) للتحليل خصائص بصرية مختلفة فيما يتعلق بنطاق الطول الموجي. تم استخدام هذه الهندسة لتحليل معامل الانكسار الفعال ، والتشتت ، ومنطقة الوضع الفعال ، ومعامل اللاخطية ، والانكسار. يتم اختيار زجاج السيليكا كمادة خلفية وتتكون منطقة الكسوة من طبقات من فتحات الهواء. يعتمد هذا العمل على نمذجة وتحليل خصائص انتشار الموجات في الألياف البلورية البصرية.

مصطلحات الفهرس - قارنات الألياف ، طرق العناصر المحدودة (FEMs) ، الألياف ذات البنية الدقيقة ، أجهزة الألياف الضوئية ، الألياف البلورية الضوئية ، مقسم الطاقة.