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Design of an optical fiber cable

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Dedication

I dedicate this thesis to my dear parents, the pillars of my life, whose love, prayers, and encouragement have always been my greatest strength. To my brothers and my sister, for their quiet but unwavering support. To all those who, through a word, a gesture, or a look, encouraged me to persevere. To everyone who contributed, directly or indirectly, to the completion of this work. And to those who taught me by example or by heart never to give up. Thank you for being there.

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To my dear parents

I dedicate this work to you with all the love and gratitude I carry in my heart. Thank you for your unconditional support, your silent sacrifices, and your unwavering faith in me. Your presence, your prayers, and your kindness have been my greatest strength throughout this journey.

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abbreviation

- **SMF** : Fibre monomode
- **MMF** : Fibre multimode
- **TIR** : Réflexion interne totale
- **NA** : Ouverture numérique
- **n** : Indice de réfraction
- **$\boldsymbol{\lambda}$** : Longueur d'onde
- **dB** : Décibel
- **nm** : Nanomètre
- **µm** : Micromètre
- **BER** : Taux d'erreur binaire
- **WDM** : Multiplexage en longueur d'onde
- **SiO_2** : Dioxyde de silicium
- **GeO_2** : Dioxyde de germanium
- **B_2O_3** : Trioxyde de bore
- **P_2O_5** : Pentoxyde de phosphore
- **TiO_2** : Dioxyde de titane
- **PMMA** : Polyméthacrylate de méthyle
- **MCVD** : Dépôt chimique en phase vapeur modifié
- **OVD** : Dépôt vapeur externe
- **VAD** : Dépôt axial en phase vapeur
- **PCVD** : Dépôt chimique activé par plasma
- **CVD** : Dépôt chimique en phase vapeur
- **ITU-T** : Union Internationale des Télécoms (secteur normalisation)
- **G.652** : Fibre monomode standard
- **G.652.D** : Version FTTH
- **G.655** : Fibre à dispersion non nulle
- **G.657** : Fibre monomode insensible au pliage
- **LSZH** : Faible fumée, zéro halogène
- **OFNR** : Fibre optique non conductrice pour gaine montante
- **OFNP** : Fibre optique non conductrice pour faux plancher
- **ADSS** : Fibre autoportée diélectrique
- **IOR** : Câble intérieur/extérieur
- **LTC** : Câble à tube libre
- **DTC** : Câble serré pour distribution
- **MOF** : Fibre optique microstructurée
- **MCF** : Fibre à multicœur
- **FTTH** : Fibre jusqu'au domicile
- **FTTx** : Fibre jusqu'au point x
- **LAN** : Réseau local
- **WAN** : Réseau étendu
- **ONU** : Unité de réseau optique
- **ODN** : Réseau de distribution optique
- **OTDR** : Réflectomètre optique temporel
- **EMI** : Interférence électromagnétique
- **COMSOL** : COMSOL Multiphysics
- **IEEE** : Institut des ingénieurs électriciens et électroniciens
- **ISO** : Organisation internationale de normalisation
- **IEC** : Commission électrotechnique internationale

General Introduction

Over the past several decades, optical fiber technology has become a fundamental component in telecommunications, high-speed internet, and optical sensing systems. Its ability to transmit large volumes of data at high speed, with low attenuation and immunity to electromagnetic interference, has made it the backbone of modern communication networks.

However, the continuous and exponential increase in data traffic demands ever greater capacity, reliability, and performance from optical communication systems. To meet these challenges, innovations in fiber design and materials are essential. Multi-Core Fibers (MCFs), which integrate multiple transmission cores within a single cladding, represent a promising solution to increase transmission capacity without enlarging the physical size of cables, making them attractive for next-generation high-density networks.

This thesis aims to study, model, and compare the characteristics of two types of optical fiber structures: conventional single-mode fibers and multi-core fibers. Using both analytical methods—including the calculation of fundamental parameters such as the V-number, effective refractive index, attenuation, and dispersion—and numerical simulations performed with COMSOL Multiphysics, this work seeks to provide a comprehensive understanding of these fiber types.

The thesis is structured into four main chapters as follows:

- Chapter 1: Fundamentals of Optical Fibers This chapter presents the basic principles underlying optical fiber technology, including the physics of light propagation, waveguide theory, modes of transmission, and the main types of fibers used in communication systems. Key parameters such as numerical aperture, cutoff wavelength, and attenuation mechanisms are introduced to provide a solid theoretical framework.

- Chapter 2: Materials and Fabrication Technologies The second chapter focuses on the primary materials employed in fiber manufacturing, such as silica glass and dopants like germanium dioxide and phosphorus pentoxide. It also reviews the principal fabrication methods, including Modified Chemical Vapor Deposition (MCVD), Outside Vapor Deposition (OVD), and Vapor-phase Axial Deposition (VAD). The chapter highlights how material composition and fabrication techniques influence fiber properties and performance.

- Chapter 3: Optical Fiber Cables This chapter explores the design and construction of optical fiber cables, detailing different cable types such as loose tube cables, tight-buffered cables, and armored cables. It discusses considerations related to mechanical protection, environmental resistance, installation environments, and standards compliance. Special attention is given to cable architectures adapted for advanced fibers like multi-core fibers.

- Chapter 4: Modeling and Simulation of Advanced Optical Fiber Structures The final chapter presents the core analytical and numerical work of the thesis. It details the methods used for calculating important fiber parameters such as the normalized frequency (V-number), effective refractive index, attenuation, and dispersion. Using COMSOL Multiphysics, the chapter illustrates the modeling of both conventional single-mode fibers and multi-core fibers, highlighting their modal characteristics and propagation behavior. Comparative analyses are performed to assess their advantages, limitations, and applicability in next-generation optical networks.

By integrating theoretical, material, and practical aspects with advanced simulation techniques, this work aims to contribute to the optimization and deeper understanding of advanced optical fiber technologies for future high-performance communication systems.

Problem Statement

With the ever-growing demand for bandwidth in modern communication systems, conventional single-mode fibers face limitations in terms of capacity and scalability. The challenge lies in developing new fiber designs and technologies that can significantly enhance data transmission without drastically increasing infrastructure complexity or cost. Multi-Core Fibers (MCFs) represent a promising avenue to overcome these challenges by enabling spatial division multiplexing within a single fiber.

However, the design, fabrication, and deployment of MCFs involve complex trade-offs, including core-to-core crosstalk, fabrication tolerances, and compatibility with existing infrastructure. A detailed understanding of their physical behavior, compared to conventional fibers, is essential to evaluate their practical applicability.

This raises the key questions:

- How do the optical properties and performance metrics of multi-core fibers compare with those of traditional single-mode fibers?
- What are the critical parameters affecting the performance of advanced fiber structures?
- How can numerical modeling and simulation tools be effectively employed to analyze and optimize these fibers?

Addressing these questions is crucial for advancing optical fiber technologies and meeting the future demands of high-capacity optical networks.

Research Objectives

This thesis aims to:

- Develop a comprehensive theoretical framework for understanding light propagation in both conventional single-mode fibers and multi-core fibers.
- Analyze the influence of materials and fabrication technologies on fiber properties and performance.
- Investigate different types of optical fiber cables suitable for advanced fiber architectures.
- Perform detailed analytical calculations of key fiber parameters such as normalized frequency (V-number), effective refractive index, attenuation, and dispersion.
- Employ COMSOL Multiphysics software to model and simulate the optical behavior of single-mode and multi-core fibers, validating the analytical results.
- Compare and evaluate the performance, advantages, and limitations of conventional and multi-core fibers to identify their applicability in next-generation optical communication networks.

Methodology

To achieve these objectives, the following approach has been adopted:

- Literature Review: Conduct a thorough review of existing works on optical fiber fundamentals, materials, fabrication methods, cable designs, and recent advances in multi-core fiber technology.
- Analytical Study: Derive and compute key fiber parameters using established theoretical models to characterize modal properties, dispersion, and attenuation.
- Numerical Modeling: Utilize COMSOL Multiphysics to simulate the electromagnetic field distribution, mode profiles, and propagation constants in both single-mode and multi-core fiber geometries.
- Comparative Analysis: Analyze simulation results alongside analytical findings to assess fiber performance. Discuss trade-offs related to crosstalk, fabrication complexity, and suitability for practical deployment.
- Synthesis and Recommendations: Integrate findings to provide insights and recommendations for future fiber design and network implementation.

This structured methodology ensures a comprehensive understanding of the subject and supports the development of optimized fiber optic solutions.

Chapter 1

General Overview of Optical Fiber

1.1 Introduction

Optical fiber is currently the most efficient, reliable, and secure medium for data transmission in the field of telecommunications. With its ability to carry large amounts of data over long distances with minimal loss, it has become the backbone of modern communication networks.

This chapter aims to introduce the fundamental concepts of optical fiber to provide a solid foundation for understanding the subject. It covers the historical evolution, structure, propagation principles, main types, and physical characteristics of optical fibers. This general overview will help highlight their advantages, limitations, and areas of application.

1.1.1 History and Evolution of Optical Fiber

Optical fiber has revolutionized global communications, enabling fast and reliable data transmission. Its development began with early experiments on light guidance, such as John Tyndall's demonstration in 1854.

Narinder Singh Kapany pioneered light transmission through glass fibers in the 1950s. Later, in 1966, Charles Kao and George Hockham proved that purified glass could carry signals over long distances, leading to the first low-loss optical fiber in 1970 by Corning. By the 1980s and 1990s, fiber optics had replaced copper cables in telecommunications, greatly benefiting the internet and mobile networks.

Today, advancements like Dense Wavelength Division Multiplexing (DWDM) and Fiber-to-the-Home (FTTH) continue to enhance fiber technology, while innovations such as hollow-core and photonic crystal fibers promise even greater performance. [1]

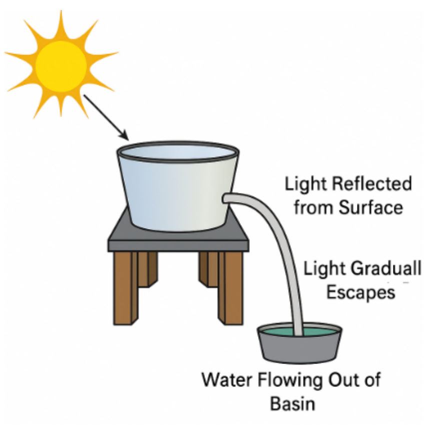


Figure 1.1: Expiremental of john taydall
[2]

1.1.2 Definition of Optical Fiber

Optical fiber is an extremely thin strand made of glass or plastic, designed to transmit light and carry large volumes of digital data at very high speeds over long distances, with extremely low loss. It functions as a waveguide, relying on the principle of total internal reflection to confine light within its core.

1.1.3 Fiber Description

1.1.3.1 Structure of Optical Fiber

An optical fiber cable is structured to protect the fiber and ensure effective light transmission. It consists mainly of a core, which guides the light, and an optical cladding, which surrounds the core to maintain signal confinement through internal reflection.

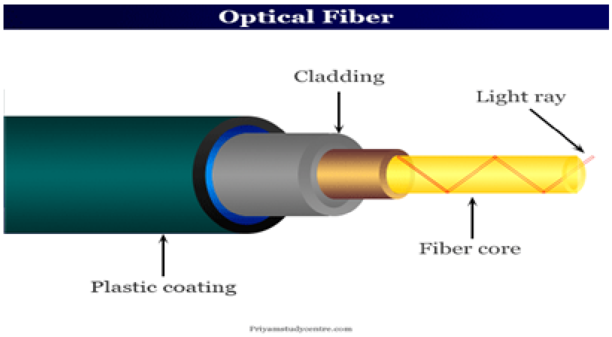


Figure 1.2: structure of an optical fiber
[3]

1.1.3.2 Principe of propagation:

Optical signal guidance in a fiber relies on Snell's law and occurs via total internal reflection between the core and cladding. This requires both materials to be transparent, with the core having a slightly higher refractive index. The signal must also enter at an angle smaller than the numerical aperture to ensure efficient, lossless transmission. [4]

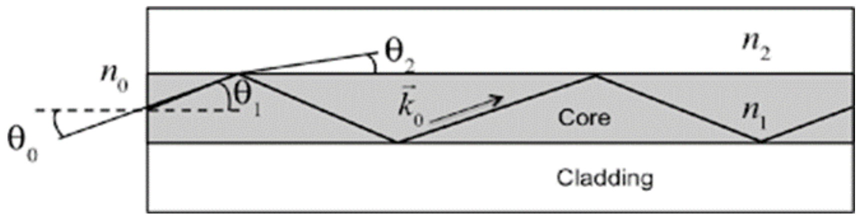


Figure 1.3: Propagation Law of the Optical Signal in a Fiber
[4]

1.1.3.3 Types of optical fiber

1.1.3.3.1 Single Mode Fiber Optic Cable: TIn fiber optics, the term "mode" refers to the path taken by light. Single-mode fibers have a small core diameter (approximately 8.3 microns) and allow only one path and wavelength for light propagation, which greatly reduces reflections and attenuation. Although slightly more expensive than multimode fibers, single-mode fibers are commonly used for long-distance network connections.

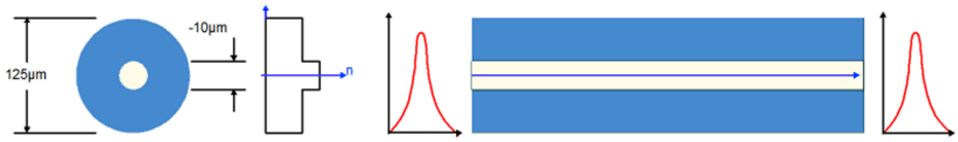


Figure 1.4: Single mode fiber
[5]

1.1.3.3.2 Multimode Fiber Optic Cable Multimode optical fibers have a larger core diameter than single-mode fibers, allowing multiple light paths and wavelengths to be transmitted. They commonly come in two sizes: 50 microns and 62.5 microns. Multimode fibers are typically used for short-distance applications such as patch cables, fiber to the desktop, or connections between patch panels and equipment in LANs. Based on their refractive index profile, multimode fibers are classified into two types: Step-Index and Graded-Index multimode fibers.

1.1.3.3.2.1 The step-index fiber: is characterized by a large core. However, this type of fiber experiences high attenuation, as evidenced by the significant difference between the input and output pulses.

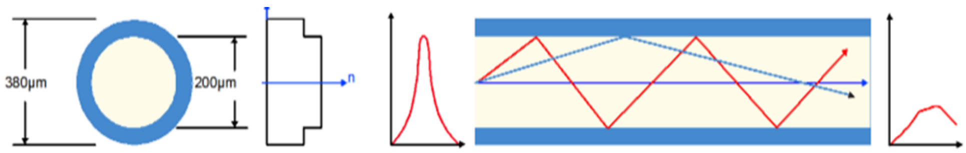


Figure 1.5: The step-index fiber
[5]

1.1.3.3.2.2 graded-index fiber: features a medium-sized core. Its attenuation is lower compared to that of step-index fibers.

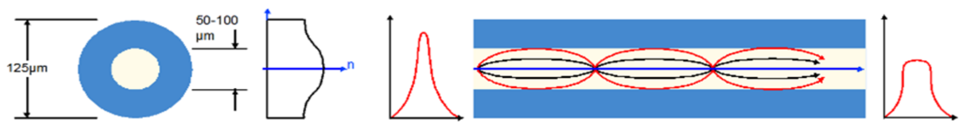


Figure 1.6: The graded-index fiber
[5]

1.1.3.4 Fiber characteristics:

1.1.3.4.1 Attenuation Attenuation refers to the loss of optical signal power as it travels through an optical fiber. It is a key parameter for evaluating fiber performance, directly limiting the maximum transmission distance without amplification. Attenuation is usually measured in decibels per kilometer (dB/km). The experimental curve in Figure I.7 shows that attenuation arises from several physical mechanisms, each dominating specific wavelength ranges. These losses are categorized as intrinsic (due to the fiber material) and extrinsic (caused by defects or impurities). The main mechanisms are described below:

- **Rayleigh Scattering:**

  This type of scattering is predominant in the short-wavelength region, below 1 µm. It is caused by small density fluctuations in the glass structure. The scattering intensity decreases rapidly with increasing wavelength, following a law proportional to 1/ .

- **OH Ion Absorption:** A distinct absorption peak occurs around 1.39 µm due to the presence of hydroxyl (OH) ions in the silica. These ions typically originate from residual moisture introduced during the manufacturing process and cause additional losses in this spectral region.
- **Ultraviolet Absorption:** Ultraviolet absorption involves the absorption of photons at very short wavelengths. It is related to the intrinsic absorption bands of the base material, silica. Although it is not dominant within the telecommunication windows, it defines the lower wavelength limit near 0.8 µm.
- **Infrared Absorption:** Beyond approximately 1.6 µm, attenuation increases significantly due to infrared absorption. This is caused by vibrational absorption in the molecular structure of silica, which sets the upper limit of the useful transmission band.
- **Waveguide Imperfections:** These losses are due to manufacturing defects or small irregularities in the core and cladding geometry. While typically low, they are present across the entire optical spectrum.

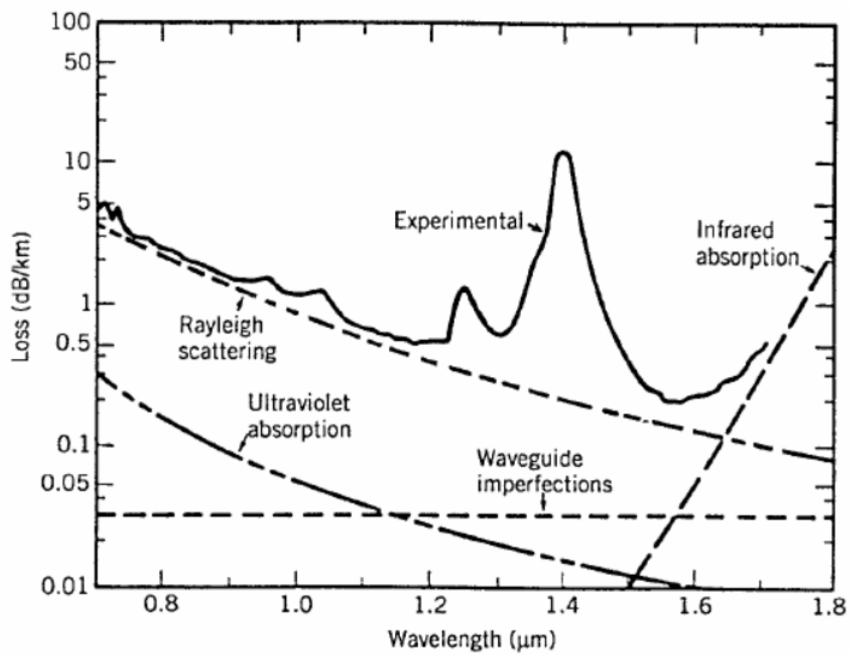


Figure 1.7: Optical fiber attenuation
[6]

1.1.3.4.2 Dispersion Dispersion is a physical phenomenon that causes temporal broadening of light pulses as they propagate through an optical fiber. In other words, a short input pulse becomes stretched in time at the output, potentially causing overlap between transmitted bits and signal degradation. Consequently, dispersion limits both the bandwidth and the transmission distance without compensation..

- **Modal Dispersion:** Modal dispersion in multimode fibers occurs when different light modes travel at varying speeds, causing signal distortion. Higher-order modes experience greater dispersion due to longer paths.

While multimode fibers suffer from significant dispersion, single-mode fibers avoid this issue. Graded-index multimode fibers reduce dispersion by gradually adjusting the refractive index to balance propagation speeds. [7]

- **Chromatic Dispersion**: Chromatic dispersion causes signal spreading due to wavelength-dependent light speeds. It results from material dispersion (refractive index variation) and waveguide dispersion (fiber geometry and refractive index contrast). At certain wavelengths, these effects can cancel out, minimizing dispersion.

  While it can degrade signals, chromatic dispersion can also be optimized for specific fiber applications. [7]

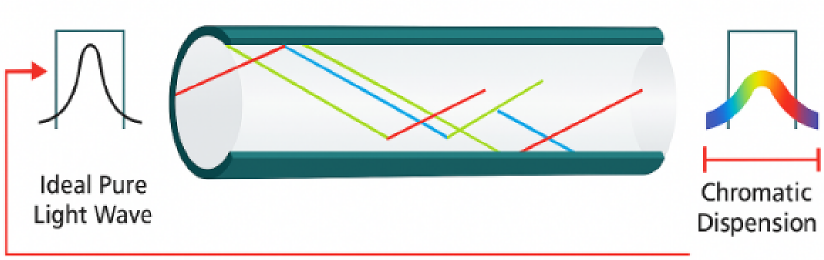


Figure 1.8: Chromatic Dispersion
[8]

1.1.3.4.3 Numerical aperture : Numerical aperture is a characteristic of any optical system. For example, photo detector optical fibre, lenses etc. are all optical system. Numerical aperture is the ability of the optical system to collect the entire light incident on it, in one area. The blue cone is known as the cone of acceptance. As you can see it is dependent on the acceptance angle of the optical fibre. Light wave within the acceptance cone can be collected in a small area which can then we sent into the optical fibre. [4] The numerical aperture (NA) is given by the following equation:

$$NA = \sqrt{n_1^2 - n_2^2} \tag{1.1}$$

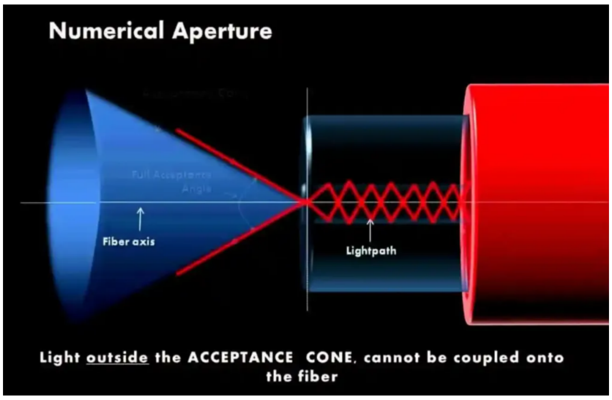


Figure 1.9: Numerical aperture

1.1.3.4.4 Bandwidth: Theoretically, fiber optics offer unlimited bandwidth, capacity, and range, making them ideal for data transmission. However, practical limitations such as material fragility and technical challenges prevent achieving this full potential, despite their revolutionary impact on communications. [9]

1.1.3.4.5 Refractive index: The index of refraction determines the speed of light in a material and causes light to bend when transitioning between media. Beyond a critical angle, light is no longer refracted but fully reflected, a phenomenon known as total internal reflection.

Optical fibers utilize this effect by selecting core and cladding materials with appropriate refractive indices to trap light within the core.

The numerical aperture (NA) defines the maximum angle for total internal reflection, influencing the fiber's ability to guide light efficiently. [10]

1.2 Advantages and limitations of current optical fiber:

1.2.1 Advantages of optical fiber:

- Compact and Durable: With a diameter of only 0.125 mm, optical fibers are much lighter than traditional cables. They are flexible, resistant to corrosion thanks to their silica composition, and can operate in extreme environments like undersea installations.
- High Performance: Optical fibers offer low transmission losses (0.35–0.45 dB/km) and support high bandwidths up to 1.6 Gb/s, with potential for expansion using WDM (Wavelength Division Multiplexing).
- Capacity and Signal Integrity: They can transmit significantly more data—up to 100 times more than twisted pair cables and 10 times more than coaxial cables. They are immune to electromagnetic interference and lightning, with minimal crosstalk between fibers.
- Thermal Resistance and Safety: Optical fibers can withstand temperatures up to 1900 °C and do not generate sparks, making them safe for flammable or hazardous environments.

1.2.2 Limitation of optical fiber:

- High initial cost: The installation cost of fiber optic networks is often higher than copper networks due to specialized equipment and the need for skilled labor.
- Complex installation: Installing and splicing fibers requires specific expertise, precise tools, and a controlled environment to prevent contamination or damage.
- Mechanical sensitivity: Besides being fragile, optical fiber can be affected by excessive tension, crushing, or vibrations, which can degrade its performance.
- Difficult repair: Repairing broken or damaged fiber is more delicate and costly compared to copper cables, requiring specialized tools and experienced technicians.

1.3 Application and fields of use

Application / Field of Use	Description
Medical Industry	Used in various instruments to examine internal body parts due to its thin and flexible nature. Essential in endoscopy, surgical lasers, microscope lasers, and biomedical lasers.
Communication	Plays a vital role in optical fiber communication systems for transmission and reception. Enhances speed and accuracy in networking applications.
Defense and Aerospace	Ensures high-level data security in military and aerospace sectors. Used in SONAR hydrophones, seismic applications, and aviation wiring.
Broadcasting	Delivers high-speed, high-bandwidth HDTV signals. More cost-effective than copper cables for HDTV, CATV, VOD, and other broadcasting services.
Decorations and Lighting	Widely used in Christmas decorations and fiber-optic lighting due to its affordability.

Table 1.1: Applications and fields of use of optical fibers

[11]

1.4 Opticonnect project:

The Opti-Connect Project is a research initiative aimed at enhancing optical fiber performance for next-generation communication systems. The project explores new fiber designs, improved signal processing techniques, and enhanced durability.

1.5 Conclusion:

This first chapter provided an overview of optical fibers, highlighting their structure, fundamental properties, and operating principles. We examined the different types of fibers and the key factors affecting their performance, such as attenuation and dispersion.

This introduction lays the essential foundation for understanding the role of optical fibers in modern technologies while identifying current challenges and limitations.

The next chapter, titled Raw Materials and Manufacturing Technologies of Optical Fibers, will focus on the materials used in fiber production and the main manufacturing techniques, including the MCVD process. This study will offer deeper insight into technological choices and innovations for next-generation optical fibers.

Chapter 2

Raw Materials and Manufacturing Technologies of Optical Fibers

2.1 Introduction:

Optical fibers are central to modern communication networks, enabling fast and reliable data transmission worldwide. Their performance depends not only on advanced manufacturing technologies—from preform creation to fiber drawing and coating—but also on the careful selection of raw materials. This chapter provides an overview of both the materials and processes involved in optical fiber production, highlighting how each contributes to the quality, efficiency, and future potential of these essential components.

2.1.1 Main Categories of Raw Materials

2.1.1.1 Silica-Based Glass (SiO_2)

Silica (SiO_2), or silicon dioxide, is the most commonly used raw material in the production of modern optical fibers. It is a natural compound, mainly found in the form of quartz sand.

However, the silica used in fiber optics is not directly extracted from sand. Instead, it must be of extremely high purity, with impurity levels lower than one part per billion (ppb), to meet the stringent requirements of optical communication systems. [12]

Figure 2.1: Silica
[13]

Silica possesses several key properties that make it an ideal material for light transmission:

- High optical transparency across a wide range of wavelengths, especially around 1.3 µm and 1.55 µm, which are critical for telecommunications.

- Low attenuation, with losses of less than 0.2 dB/km in modern optical fibers
- Chemical stability and corrosion resistance.
- High thermal resistance (∼1713°C melting point).
- Excellent mechanical and chemical strength.

2.1.1.2 Purification and Processing of Silica

The $SiCl_4$ precursor undergoes multiple purification steps, including distillations and gas-phase treatment with chlorine and hydrogen, to remove organic, metallic, and moisture contaminants. Purified material is then deposited in a controlled environment to minimize contamination, with the elimination of water being critical to prevent light absorption by hydroxyl groups that impair signal transmission. [14]

2.1.1.3 Preform Manufacturing

The optical fiber's core and cladding are formed by depositing the silica in layers after it has been purified, dopants like fluorine or germanium dioxide (GeO2) are added to localize adjust the refractive index. The subsequent steps are as follows on the finished preform:

- Sintering, a partial fusion procedure that makes the material that was deposited dense enough to form a solid glass rod.
- Consolidation at high temperatures to produce a uniform glass structure and eliminate any remaining porosity.

In a fiber drawing tower, this consolidated preform is finally drawn into fiber, producing the final optical fiber that is ready for use. [15]

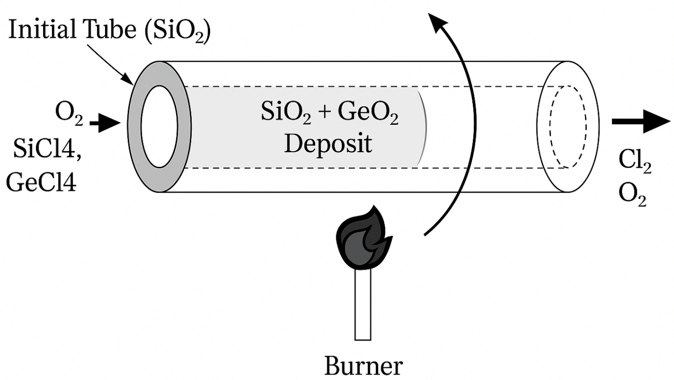


Figure 2.2: Preform Fabrication
[5]

2.1.1.4 Fluoride Glasses (ZrF_4, BaF_2, LaF_3, AlF_3)

Fluoride glasses are a class of non-oxide glasses, primarily composed of metal fluorides, such as zirconium fluoride (ZrF_4), barium fluoride (BaF_2), sodium fluoride (NaF), aluminum fluoride (AlF_3), and lanthanum fluoride (LaF_3).

Unlike traditional silica-based glasses, fluoride glasses are known for their:

· High transparency in the mid-infrared (IR) range,
· Low refractive index (typically between 1.45 and 1.5),
· Ability to transmit light up to 7 µm or more, depending on the specific compositi. [16]

2.1.1.5 Optical Properties and Advantages

- Extended infrared transmission, up to 7 µm far beyond silica's transmission limit (2.5 µm).
- Low chromatic dispersion, which increases the quality of the IR application signal.
- Specialized communication systems benefit from low absorption losses at specific IR wavelengths.

However, they also have several limitations:A lower level of chemical and thermal stability than silica,

- More mechanical brittleness,
- Sensitivity to humidity many fluoride glasses are hygroscopic.

2.1.1.6 Typical Composition – ZBLAN Example

ZBLAN is one of the most widely used fluoride glasses for optical fiber manufacturing. Its composition includes:

- ZrF_4 (Zirconium fluoride): main network former
- BaF_2, NaF, AlF_3, LaF_3: modifiers that fine-tune refractive index, viscosity, and mechanical strength.

ZBLAN-based fibers are flexible, lightweight, and highly efficient in the infrared domain, making them suitable for advanced photonic applications. [17]

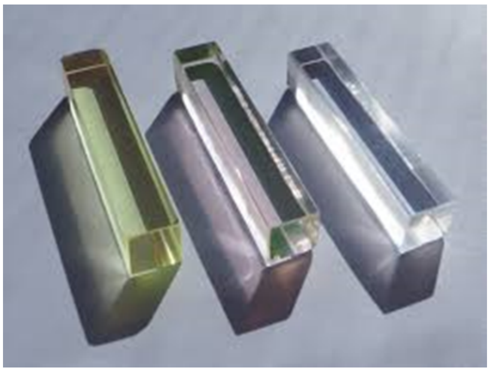


Figure 2.3: ZBLAN Example
[17]

2.1.1.7 Chalcogenide Glasses (As_2S_3, As_2Se_3, GeS_2, $GeSe_2$)

Chalcogenide glasses are optical materials mainly composed of chalcogen elements (S, Se, Te) combined with metals like Ge, As, and Sb. They are transparent in the mid- to far-infrared range (2–12 µm) and are used in applications where silica glasses are ineffective, such as infrared imaging, long-range IR telecommunications, IR lasers, and specialized sensors.

Their key optical properties include:

- Extended infrared transmission (2 µm to over 10 µm)
- Low absorption in the IR range, enabling low transmission losses
- Good chromatic dispersion control, important for multimode fiber systems

Drawbacks are:

- Mechanical fragility compared to silica or fluoride fibers
- Sensitivity to humidity, requiring careful fabrication and handling
- Higher production costs than silica materials

2.1.1.8 Typical Composition of Chalcogenide Glasses

A typical optical chalcogenide glass composition is based on germanium telluride (GeTe), usually combined with other chalcogens such as sulfur or selenium. The composition generally includes 50 to 60% of GeTe, 10 to 20% arsenic (As), 10 to 30% selenium (Se), and 5 to 10% sulfur (S).

This combination of elements allows for the fabrication of high-performance optical fibers specifically designed for infrared applications. [16]

2.1.2 Polymers (Plastic Optical Fibers - POFs)

Polymers are materials made of long chains of monomers bonded through chemical reactions. They are widely used in various fields, including the production of plastic optical fibers. These fibers, with a polymer core instead of glass, are more flexible and cost-effective, though less efficient for long-distance transmission. They are especially suitable for short-distance communication, optical sensors, and lighting applications. [18]

The most commonly used polymers in the production of plastic optical fibers are:

- Polymethyl methacrylate (PMMA)
- Polystyrene (PS)
- Polyethylene (PE)
- Fluoropolymers (such as PTFE)

These materials are chosen for their optical properties, ease of manufacturing, and relatively low cost. [18]

2.1.2.1 Types of Polymers Used in Optical Fibers

Several polymers are specifically employed in the production of optical fibers, each selected for its unique properties and suitability to certain applications.

2.1.3 Materials properties Comparaison

This table summarizes the key characteristics and typical applications of different optical fiber materials:

Polymer	**Main Properties**	**Limitations / Applications**
Polymethyl Methacrylate (PMMA)	Good transparency, high refractive index, low cost	Sensitive to shock and heat
Polystyrene (PS)	Shock resistant alternative to PMMA	Lower optical transparency, reduces transmission efficiency
Polyethylene (PE)	Flexible, moisture resistant	Limited light transmission efficiency, suitable for short distances
Fluoropolymers (PTFE, FEP)	Exceptional chemical and thermal resistance	High cost, complex manufacturing process

Table 2.1: Types of Polymers Used in Optical Fibers

Property	**Silica (Silica)**	**Fluoride Glass**	**Chalcogenide Glass**	**Polymer**
Transparency Range	0.2 – 2.5 μm	0.3 – 7 μm	1 – 12/15 μm	~0.5 – 0.7 μm (visible)
Refractive Index	~1.44	~1.5	>2.0	~1.49
Thermal Resistance	Very high	Medium	Low to medium	Low (~80–100 °C)
Chemical Stability	Excellent	Low	Medium	Low to medium
Mechanical Robustness	Excellent	Medium	Low	Good (flexible)
Manufacturing Cost	High (extreme purity required)	High	High	Low
Typical Applications	Telecom, laser, sensors	Medical IR, laser, special sensors	IR sensors, non-linear optics	Domestic networks, automotive, short distance

Table 2.2: Comparison of Optical Fiber Materials

2.2 Raw materials of the Coating:

The coating of optical fibers is crucial to protect the fiber from moisture, mechanical damage, and abrasion while preserving its optical properties. It also enhances the flexibility and durability of the fiber. The coating is applied once the fiber has been drawn and cooled. Common materials used for these coatings include:

- **Polyurethane (PU):** Known for its abrasion resistance, flexibility, and protection against moisture. It is commonly used in demanding industrial and military environments.
- **Acrylate:** Used in primary and secondary coatings, it offers good moisture protection and is easy to apply at a low cost. It is a common choice in optical fiber manufacturing.

- **Silicone:** Used in high-temperature and extreme environments, silicone provides resistance to oxidation and significant flexibility, making it ideal for aerospace or military applications.
- **Fluoropolymers (PTFE):** Offering exceptional resistance to chemicals and heat, this material is used for optical fibers in extreme or chemical environments.
- **Polyethylene (PE) and Polypropylene (PP):** Used for secondary coatings, they are more flexible and cost-effective, making them suitable for domestic or non-critical applications.
- **Epoxy:** Resistant to heat and moisture, epoxy is used in applications where mechanical protection and high resistance are required. [19]

2.3 Criteria for materials selection in fiber design:

Choosing the right material depends on several factors:

Factor	**Details**
Transmission Wavelength	Silica is best for visible and near-IR; fluoride and chalcogenide for mid-IR; polymers for visible light.
Mechanical Strength	Silica is strong but brittle; polymers are more durable.
Attenuation	Lower attenuation is preferred for long-distance communication.
Manufacturing Complexity	Silica and polymers have mature manufacturing processes; fluoride and chalcogenide fibers are harder to process.
Application-Specific Needs	Silica is best for telecom; fluorides and chalcogenides are better suited for infrared sensing.

Table 2.3: Criteria for Choosing Optical Fiber Materials

2.4 Environmental Constraints and Recyclability

2.4.1 Ecological Impact of Fiber Manufacturing

The production of optical fibers raises several environmental concerns. Silica fiber manufacturing consumes large amounts of energy due to its high-temperature processes. Additionally, fluoride and chalcogenide glasses may contain toxic elements such as arsenic and selenium. Plastic optical fibers (POFs), although more recyclable, still contribute to plastic pollution.

2.4.2 Recycling and Sustainability

Recycling capabilities vary by material. Silica fibers are difficult to recycle but can sometimes be reused in new preforms. Polymers are easier to recycle, though they tend to degrade over time. Fluoride and chalcogenide fibers are challenging to recycle due to their chemical sensitivity and instability.

2.4.3 Future Trends

Efforts are being made to develop eco-friendly materials and to implement lower-energy manufacturing techniques. There is also increasing interest in biodegradable polymers, especially for short-term or disposable fiber applications, to reduce the environmental footprint of optical technologies.

2.5 Optical fiber manufacturing technologies

2.5.1 Manufacturing processes:

The fabrication of optical fibers involves two main stages: preform production and fiber drawing. The preform is a solid silica rod that defines the optical and geometric properties of the final fiber, including its refractive index profile. Once drawn, the fiber maintains the same core-to-cladding ratio and optical characteristics as the preform.

2.5.2 Preform Fabrication:

Preform fabrication is a critical step, as it determines the optical performance of the final fiber. Several industrial methods are used to manufacture preforms, which can be grouped into two main categories:

- Inside Vapor Deposition techniques:
  - MCVD (Modified Chemical Vapor Deposition)
  - PCVD (Plasma Chemical Vapor Deposition)
- Outside Vapor Deposition techniques:
  - OVD (Outside Vapor Deposition)
  - VAD (Vapor Axial Deposition)

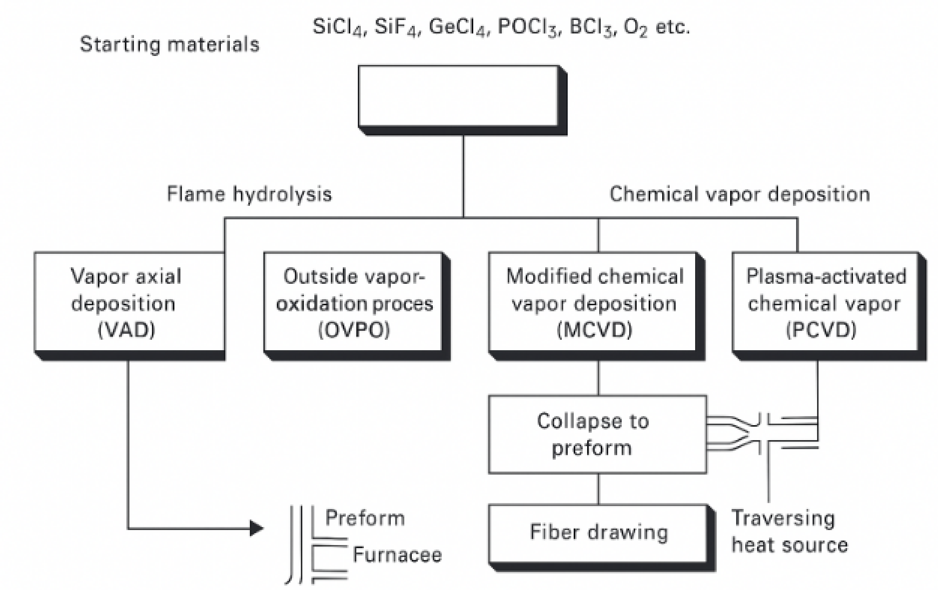


Figure 2.4: Schematic illustration of the vapor-phase deposition techniques used [20]

Vapor-phase deposition techniques are widely used to produce silica-rich glasses with exceptional transparency and optimal optical performance. These processes employ volatile precursors such as $SiCl_4$, $GeCl_4$, SiF_4, BCl_3, BBr_3, $POCl_3$, and O_2 These compounds can be distilled to reduce the concentration of transition metal impurities to extremely low level typically below one part per billion (10^{-9}) thus minimizing absorption losses associated with these contaminants

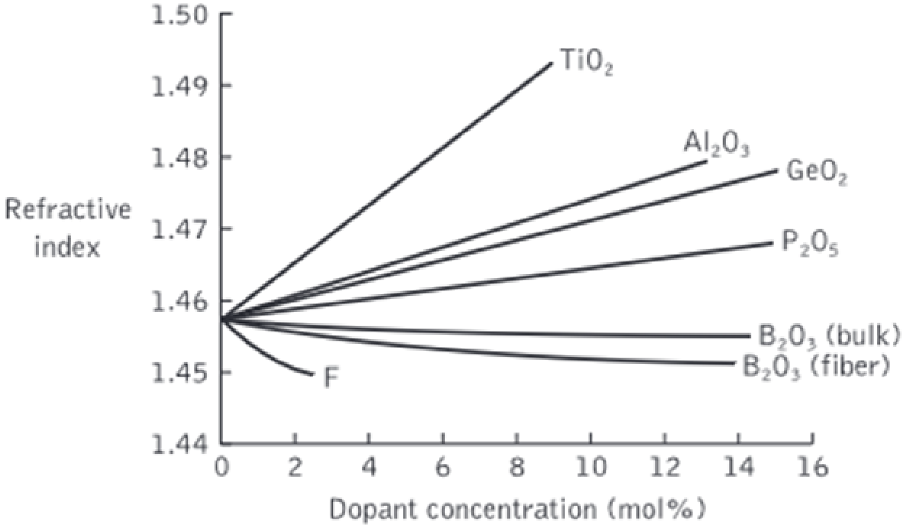


Figure 2.5: The variation in the refractive index of silica using various dopants. [20]

The refractive index of the glass is precisely controlled by introducing dopants derived from non-silica starting materials. Commonly used dopants includeGeO$_2$, TiO_2, P_2O_5, Al_2 , and fluorine. These oxides significantly alter the refractive index of silica, allowing the design of custom optical profiles suited for different fiber types [20]

2.5.3 MCVD (Modified Chemical Vapor Deposition):

The MCVD (Modified Chemical Vapor Deposition) process is a common technique for producing optical fiber preforms essential for high-performance fibers. It involves rotating a silica tube at high speed while externally heated to approximately 1500 °C. Reactive gases such as silicon tetrachloride ($SiCl_4$), germanium tetrachloride ($GeCl_4$), and oxygen are introduced inside the tube, where they chemically react at high temperatures to form fine silica particles that deposit on the tube's inner surface. The key reactions involved are:

$$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$$

$$GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2$$

These reactions produce silica (SiO_2) and germanium dioxide (GeO_2), which are critical for controlling the refractive index of the optical fiber.

As the silica tube rotates, thin layers are deposited on its inner surface with precise dopant adjustments to create the desired refractive index profile. After multiple deposition cycles, the tube is heated to collapse inward, forming a solid preform that incorporates the designed refractive index profile necessary for fiber fabrication. [21]

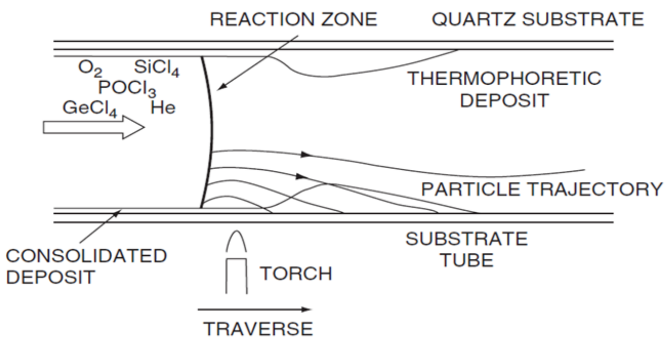


Figure 2.6: Particle formation and thermophoretic deposition in modified chemical vapor deposition (MCVD)
[22]

The preform is subsequently heated in a drawing tower and drawn into a continuous optical fiber, often extending for several kilometers. The fiber retains the optical properties defined by the preform, enabling the production of fibers with tailored characteristics such as single-mode or multi-mode operation.

The MCVD process provides precise control over the refractive index profile, making it a vital method for manufacturing high-quality optical fibers used in telecommunications and other applications. [21]

2.5.4 PCVD:

The PCVD (Plasma Chemical Vapor Deposition) method resembles MCVD but uses high-frequency plasma, typically microwaves, to activate chemical reactions at lower temperatures (700–900 °C).

This allows better doping control, especially for specialized fibers. In PCVD, plasma is generated inside a silica tube with precursor gases, depositing fine glass layers on the tube's inner walls.

Unlike MCVD, which relies on high temperatures, PCVD uses a non-isothermal plasma at low pressure within a 2.45 GHz microwave cavity, enabling volatile reactants to react without particle formation in the vapor phase. [21]

The chemical reactions involved are similar to those in MCVD and occur inside the plasma:

$$SiCl_4 + O_2 \text{ (plasma)} \rightarrow SiO_2 + 2Cl_2$$

$$GeCl_4 + O_2 \text{ (plasma)} \rightarrow GeO_2 + 2Cl_2$$

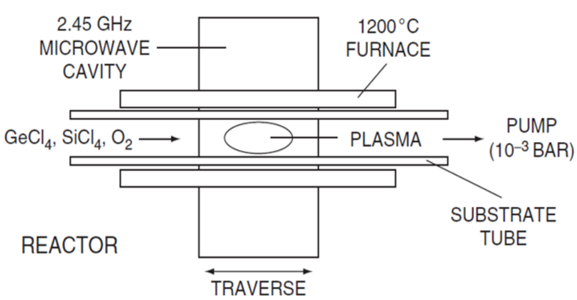


Figure 2.7: Schematic representation of PCVD process
[21]

The process moves the reaction zone along the tube without rotation, producing highly uniform layers with nearly 100% efficiency at low temperatures (around 500 °C). It allows precise control of up to 2000 layers with graded index profiles, resulting in fibers with optimal optical properties.

This technique supports large-scale production, creating preforms capable of yielding hundreds of kilometers of fiber with excellent homogeneity and low dispersion. Additional heating is used to prevent cracking from high chlorine content. [23]

2.5.5 OVD (Outside Vapor Deposition):

The Outside Vapor Deposition (OVD) process involves the deposition of materials on the outside of a rotating glass target rod, typically made of ceramic or quartz, within a controlled chamber.

In this method, a computer-regulated mixture of precursor gases is directed into the space between the rotating rod and a moving heat source, such as a torch. As the heat source moves along the length of the rod, a chemical reaction occurs, generating fine particles of silica and dopants that deposit onto the rod, forming a white soot.

This soot is then consolidated (sintered) in a high-temperature furnace to create a solid preform. The chemical reactions involved are:

$$SiCl_4 + O_2 \rightarrow SiO_2 \text{ (soot)} + 2Cl_2$$

$$GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2$$

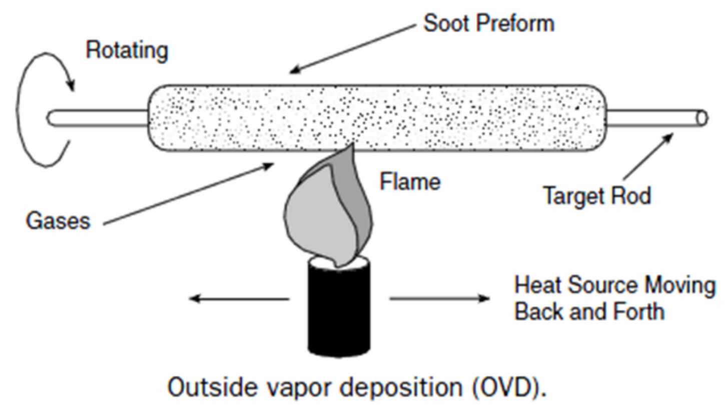


Figure 2.8: OVD
[22]

The deposition process builds up multiple layers of glass soot, which is then heated to collapse into a solid preform. This preform is drawn into optical fiber, maintaining its internal structure.

OVD is widely used industrially for producing large preforms efficiently and cost-effectively with tailored fiber properties.[22]

2.5.6 VAD (The Vapor Axial Deposition):

The Vapor Axial Deposition (VAD) method, similar to OVD, forms the preform vertically by depositing silica soot on a downward-growing rod. A heat source triggers reactions in a gas mixture to produce the soot. As deposition progresses, the heat source moves downward. After achieving the desired size, the porous soot is sintered into a solid glass preform. The chemical reactions involved in the soot formation are as follows:

$$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$$

$$GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2$$

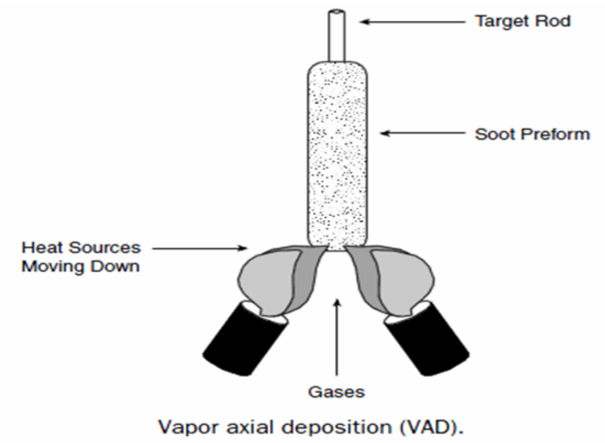


Figure 2.9: VAD
[11]

The VAD method is particularly well-suited for the production of very large fibers, providing excellent axial homogeneity. The solidified preform is then transferred to a drawing tower, where it is heated and drawn into an optical fiber of the required diameter and length, preserving the structural and optical properties established during deposition. [11]

2.5.7 Comparative table of preform fabrication techniques

Our contribution is based on the following table which provide a comparative overview of the main preform fabrication methods, highlighting their deposition types, preform geometries, activation sources, and key benefits

Method	**Deposition**	**Preform Shape**	**Activation**	**Advantages**
MCVD	*Internal*	Horizontal tube	External heating torch (∼1500 °C)	- Good dopant control - High purity - Well-established process
PCVD	*Internal*	Horizontal tube	Microwave plasma (700–900 °C)	- Lower temperatures - Precise dopant control - Suitable for specialized fibers
OVD	*External*	Rotating mandrel	Oxy-hydrogen flame	- High-volume production - Large preforms - Good industrial throughput
VAD	*External axial*	Vertical growth	Oxy-hydrogen flame	- Fast vertical growth - Long preforms - Minimal mechanical handling

Table 2.4: Comparison of fiber preform fabrication methods

2.6 Optical Fiber Drawing Process:

The fiber drawing stage transforms a heated glass preform into a fine fiber with a standard diameter of 125 μm. The preform is placed vertically in a drawing tower and heated above 2000 °C. A droplet initiates the fiber, which is pulled under constant tension to ensure uniformity. This step is essential for achieving low attenuation, high strength, and precise geometry in modern fibers.

A typical drawing tower includes a preform feed system, a high-temperature furnace, a diameter monitor, a coating application unit, a UV curing system, a traction capstan, and a take-up drum.[21]

2.7 Protective Coating Application on Optical Fiber

To protect optical fibers from mechanical damage, a polymer coating is applied immediately after drawing. This coating shields the fiber from shocks and moisture, preserves flexibility, and prevents microcrack propagation. Applied inline by extrusion or dip-coating and cured with UV light, the coated fiber is then wound onto reels for further processing.[24]

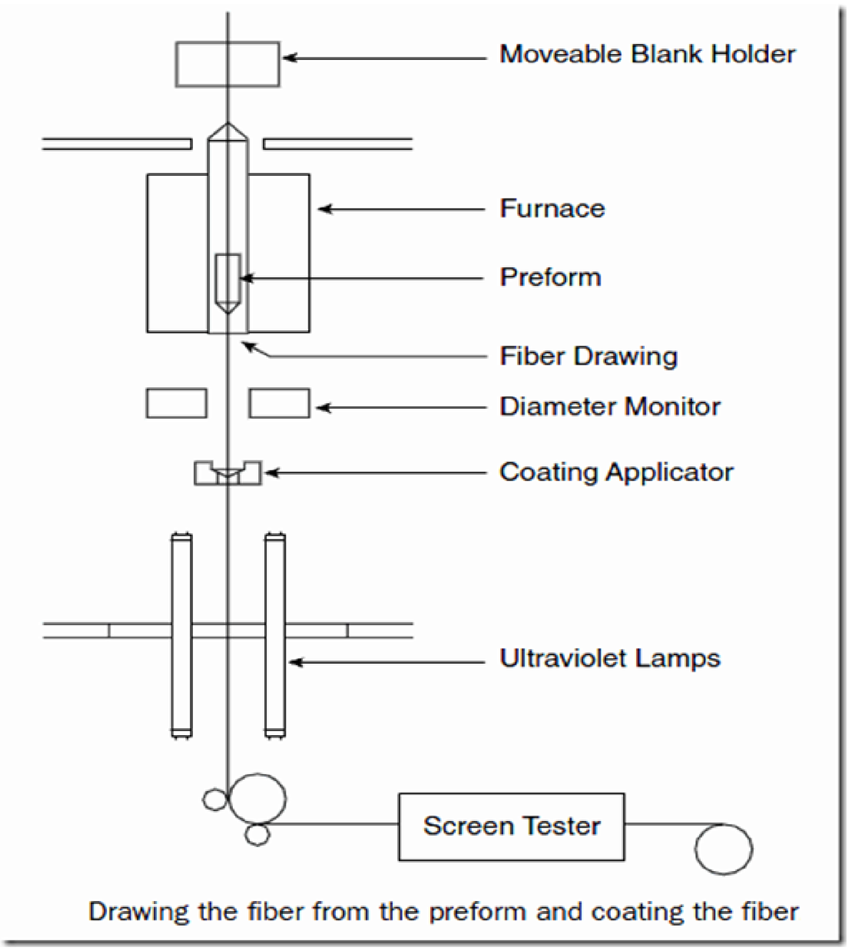


Figure 2.10: Drawing and Coating the fiber
[24]

2.8 Fiber testing and characterization:

After production, optical fibers undergo a series of rigorous tests to ensure their quality and compliance with industry standards. These tests are generally grouped into four categories:

Category	**Description**
Geometrical Characterization	Measurement of **fiber diameter** with a laser micrometer, **core-to-cladding concentricity**, and **protective coating thickness** to ensure performance and durability.
Optical Characterization	**Attenuation**: Measured with cut-back method or OTDR. **Chromatic dispersion**: Evaluates high-speed transmission capacity. **Polarization Mode Dispersion (PMD)**: Monitored for long-distance and high-bandwidth applications.
Mechanical Testing	**Tensile strength**: Tests resistance to breakage. **Bend resistance**: Ensures performance under curved or constrained conditions.
Standards Compliance	Fibers validated against **international standards** (ITU-T G.652, IEC norms). Must meet specifications for specific uses (telecommunications, sensing, FTTH).

Table 2.5: Optical Fiber Characterization and Testing Category

2.9 Challenges and solutions in the production:

The production of optical fibers involves various complex challenges that can affect quality, performance, and cost. Key challenges include:

Challenge	**Solution**
Material Purity and Contamination	Use ultra-pure silica and maintain cleanroom environments to avoid impurities that degrade performance.
Dimensional Accuracy and Uniformity	Real-time monitoring and automatic feedback control maintain consistent fiber diameter.
Mechanical Strength and Fiber Breakage	Apply protective coatings and perform proof testing to ensure durability and reliability.
Signal Attenuation and Loss	Use doping, optimized fiber designs, and proper installation techniques to minimize losses.
Production Scalability and Cost Efficiency	Employ high-throughput methods like OVD and VAD, and integrate automation to increase efficiency.
Energy and Environmental Constraints	Use energy-efficient furnaces and heat recovery systems to reduce environmental impact.

Table 2.6: Challenges and solutions

2.10 Conclusion:

This chapter covered the fundamental materials used in optical fiber production, highlighting the key role of silica, fluoride glasses, chalcogenide glasses, and polymers for coatings.

These materials are essential for ensuring the performance and durability of fibers in various environments. The evolution of manufacturing technologies, such as MCVD and PCVD, is crucial to meet the growing demands of telecommunication networks. These advancements support ongoing innovation needed for the expansion of networks and future connectivity.

The next chapter will delve into the next step: the design and integration of optical cables into communication networks.

Chapter 3

Optical fiber cables

3.1 Introduction

The outstanding transmission performance of optical fibers cannot be fully utilized without appropriate protection. On their own, fibers are vulnerable to mechanical stress, moisture, extreme temperatures, and various external hazards. To address these challenges, fibers are integrated into specially designed structures known as optical fiber cables, which ensure their protection, stability, and long-term durability.

These cables come in different forms depending on installation requirements whether indoors, outdoors, underground, aerial, or submarine. As such, cabling represents a strategic step in the deployment of reliable and high-performance optical communication networks.

3.2 General structure of an optical fiber cable:

The structure of a fiber optic cable is designed to protect the optical fibers and ensure reliable performance. Each layer buffer, strength member, and outer jacket contributes to mechanical protection, flexibility, and environmental resistance.

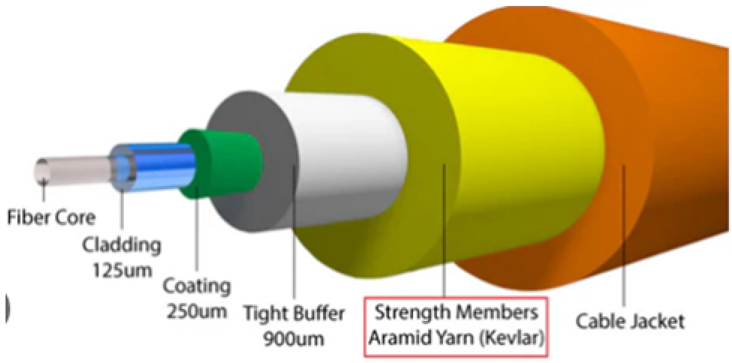


Figure 3.1: structure of an optical fiber cable
[25]

- **Optical fiber:** The core transmission medium.
- **Primary coating:** Protects the fiber from microbends and external stress.
- **Buffer layer (tight or loose):** Provides additional protection and flexibility.
- **Strength members:** Often made of aramid yarn (e.g., Kevlar), steel, or fiberglass, they reinforce the cable against pulling forces.

- **Outer jacket (sheath):** Provides overall protection from environmental damage (e.g., water, UV, chemicals).[25]

3.3 Types of Fiber Optic Cables:

3.3.1 Indoor cables:

Indoor fiber optic cables are lightweight, flexible, and designed for use in buildings. They feature fire-resistant, low-smoke, halogen-free (LSZH) jackets and typically use a tight-buffered structure for easy handling and termination. Ideal for LANs, data centers, and FTTH, they are suited for tight spaces like ceilings, risers, and conduits

3.3.1.1 simplex and duplex cables:

Simplex and duplex fiber optic cables differ primarily in the direction of communication. A simplex cable allows unidirectional data transfer, with a single fiber strand and an outer jacket. It is used in applications requiring data transfer in one direction, such as sensors and monitoring systems. On the other hand, a duplex cable enables bidirectional communication, featuring two fiber strands, which allows data to be sent and received simultaneously.[26]

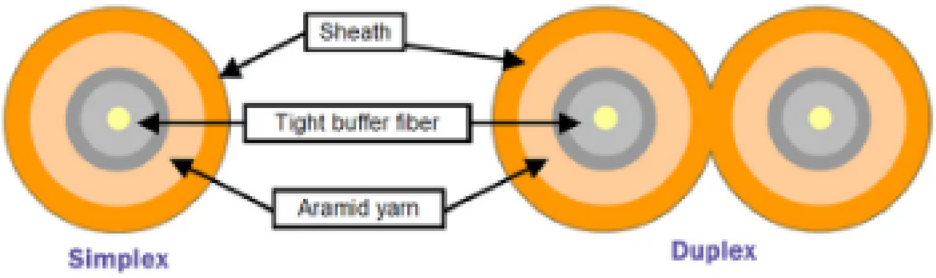


Figure 3.2: Simplex and Duplex cables
[26]

3.3.1.2 Distribution cables:

Distribution fiber optic cables are used indoors to connect multiple fibers within buildings or data centers. They are compact and flexible, containing tight-buffered fibers and strength members, without gel or rigid rods. These cables are suitable for vertical installations, ceiling spaces, and environments requiring low smoke emission in case of fire.[27]

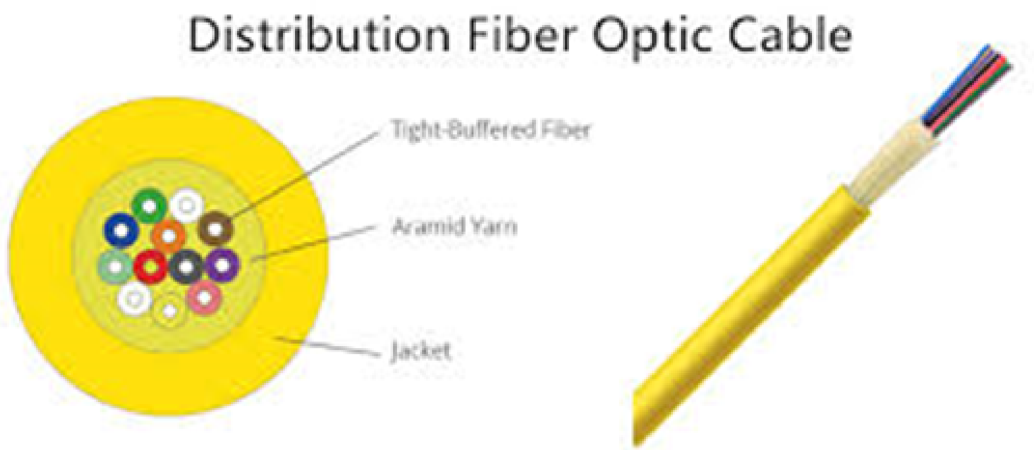


Figure 3.3: Distribution cables
[27]

3.3.1.3 Breakout cables:

Breakout fiber optic cables are used for indoor or short-distance applications where individual fibers need direct connection. Each fiber has its own tight buffer and protective subunit jacket, providing durability and easy termination. Though bulkier than distribution cables, they offer greater mechanical strength, making them ideal for data centers, patch panels, and rugged environments.[27]

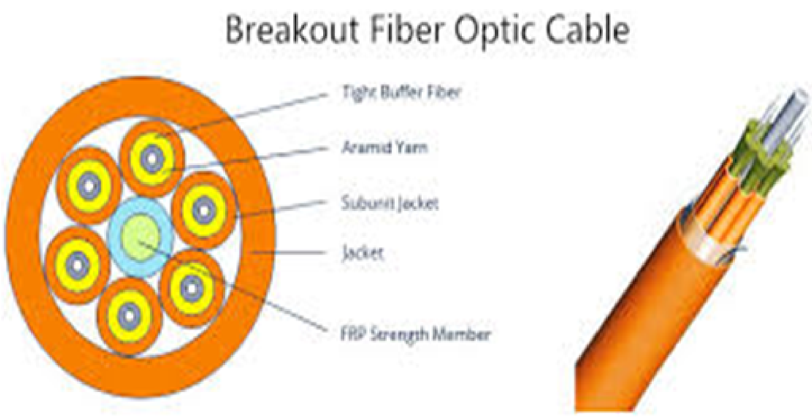


Figure 3.4: Breakout cables
[27]

3.3.1.4 Riser-rated (OFNR) and Plenum-rated (OFNP):

Riser-rated (OFNR) and Plenum-rated (OFNP) cables are types of fiber optic cables classified based on their fire-resistance and suitable installation environments.[30]

3.3.1.4.1 Riser-rated cables (OFNR) are designed for vertical runs between floors in a building (e.g., in riser shafts). They have fire-resistant jackets that prevent flames from traveling between floors but are not suitable for air-handling spaces.

3.3.1.4.2 Plenum-rated cables (OFNP) have the highest fire-resistance rating and are intended for installation in air-handling spaces like drop ceilings or raised floors. They produce very low smoke and toxic fumes in case of fire.[28] OFNP cables can be used in place of OFNR cables, but not the other way around

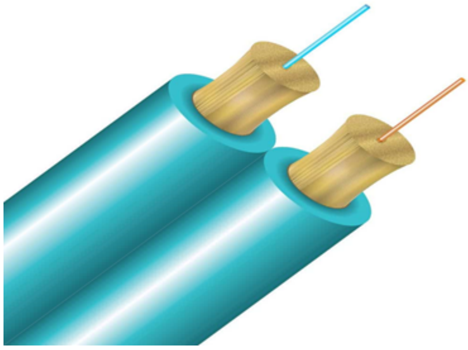


Figure 3.5: Riser-rated (OFNR) and Plenum-rated (OFNP)
[28]

3.3.2 Outdoor cables:

Outdoor fiber optic cables are built to resist harsh conditions, with UV-resistant jackets, water-blocking materials, and optional metal armoring for added protection. Using a loose-tube design, they handle thermal and mechanical stress well over long distances. They are ideal for underground, aerial, or conduit installations in long-distance networks, inter-building links, metropolitan areas, and telecom backbones.[29]

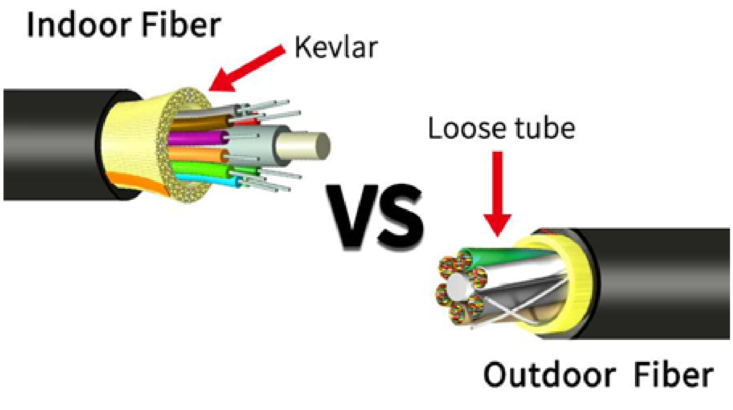


Figure 3.6: Indoor and Outdoor Fiber
[30]

3.3.2.1 Loose-tube cables:

Loose tube cables are designed for long-distance outdoor use. They contain multiple fiber-filled tubes arranged around a central strength member, with filling elements for structural integrity and water-blocking components to prevent moisture. A durable black outer sheath protects the cable, making it suitable for burial, conduit, or aerial installation.[31]

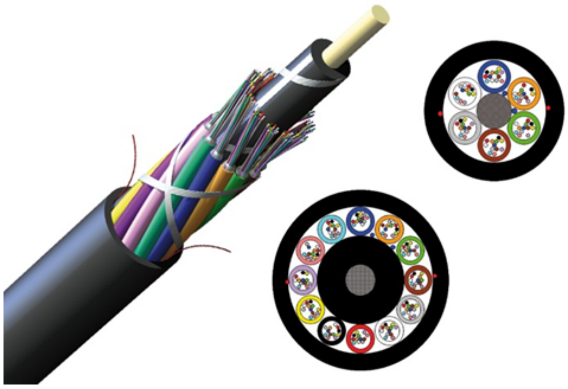


Figure 3.7: Loose-tube cables
[32]

3.3.2.2 Armored/unarmored cables:

Armored cables provide additional protection with a layer of steel or aluminum, making them suitable for environments with a high risk of physical damage, such as underground or industrial installations.

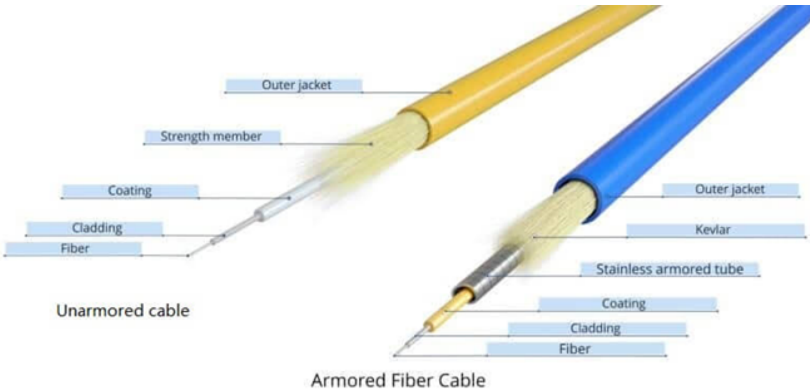


Figure 3.8: Armored/unarmored cable
[29]

Non-armored cables, on the other hand, are lighter and more flexible, making them suitable for environments less exposed to mechanical stress, such as aerial installations or conduit applications. [29]

3.3.2.3 Direct-burial cables:

Direct-burial cables are designed specifically for underground installation without the need for additional protective conduit. These cables have an outer sheath that is rugged and resistant to environmental factors such as moisture, chemicals, and physical wear. They are typically used in applications where the cable will be buried directly in the ground, offering a durable solution for outdoor or underground communication networks. [33]

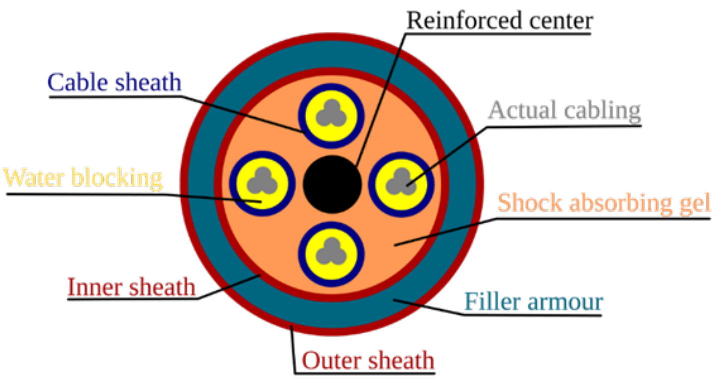


Figure 3.9: Direct-burial cables
[33]

3.3.2.4 Aerial self-supporting cables (ADSS):

Aerial Self-Supporting Cables (ADSS) are designed for overhead installations without the need for additional support structures like messenger wires. These cables are equipped with a specialized construction that allows them to be suspended in the air between utility poles or other support structures.[34]

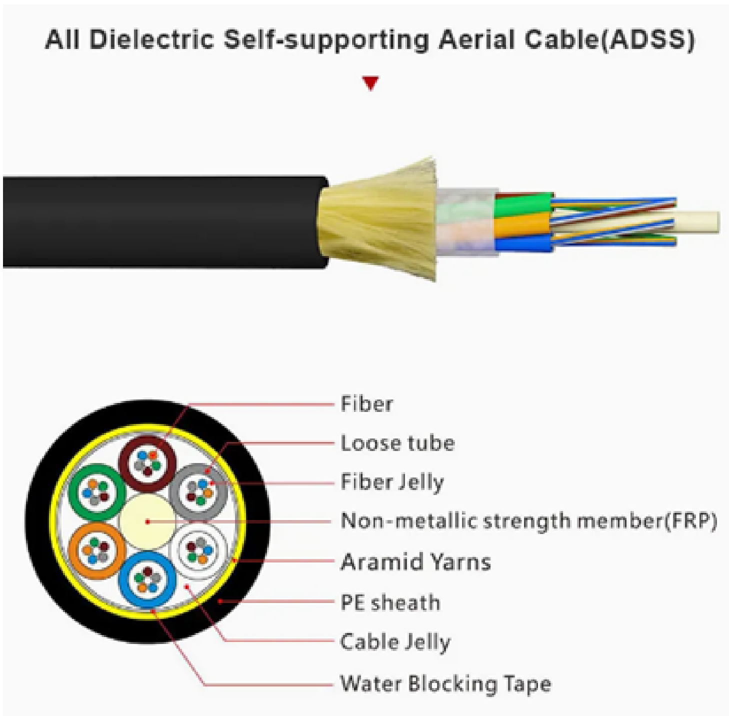


Figure 3.10: Aerial self-supporting cables (ADSS)
[34]

3.3.3 Aerial cables:

Aerial cables are suspended optical fiber cables used where underground installation is impractical or expensive, such as in urban or rural areas. They are designed to resist mechanical stresses (wind, snow, gravity) with reinforcements like steel wires or fiberglass rods. Easy to access and cost-effective to deploy, they feature a protective sheath, suspension wire, steel reinforcements, and a water-blocking system to ensure durability and reliability.

Figure 3.11: Aerial cables
[35]

transmission.[35]

3.3.4 Submarine cables:

Submarine cables connect distant landmasses across oceans and are built to withstand harsh marine conditions. They feature multiple protective layers—outer sheath, metallic armor, and hydrophobic gel for waterproofing and durability. Designed to resist deep-sea pressure and external threats, they can last over 25 years with minimal maintenance.[36]

Figure 3.12: Submarine cables
[36]

3.4 Technical Characteristics and Performance:

The technical characteristics and performance of optical fiber cables are critical to ensure their efficiency, durability, and functionality in various installation environments.

Characteristic	**Description and Solutions**
Mechanical Resistance	Reinforcements (aramid, steel) protect against pulling, bending, and crushing.
Moisture Protection	Waterproof coatings and water-blocking gels avoid fiber degradation.
Rodent Protection	Steel armor and special sheaths prevent animal-induced damage.
Fire Resistance	Jackets with fire-retardant, low-smoke materials reduce fire hazards.
Thermal Behavior	Operates between $-40\,^{\circ}\mathrm{C}$ and $+70\,^{\circ}\mathrm{C}$; resists thermal variation.
Cabling Attenuation	Minimized via optimized materials, connectors, and reduced bending.

3.5 Standards and Regulations:

The performance, design, and installation of optical fiber cables are regulated by international standards and classifications to ensure quality, safety, and interoperability between manufacturers and across countries.

- International Standards: Global organizations such as ITU-T, IEC, ISO/IEC, and ANSI/TIA define standards that cover fiber optic cable performance, testing procedures, and installation guidelines. These ensure that products from different sources are compatible and meet consistent quality expectations.[40]
- Fiber and Cable Classifications: Fibers and cables are categorized based on their physical properties and usage context:

Type	**Description**
G.652	Standard single-mode fiber, ideal for long-distance transmission.
G.657	Bend-insensitive single-mode fiber, suitable for tight bends and confined installations.
OFNR	Non-conductive riser cables, used for vertical shafts in buildings.
OFNP	Non-conductive plenum cables, designed for use in air-handling spaces where fire safety is critical.

- Cable Labeling and Coding:Fiber optic cables are color-coded and labeled to indicate important characteristics like fiber type, fire resistance rating (e.g., OFNR, OFNP), and compliance with safety regulations, ensuring proper selection and safe installation.

3.6 Applications and Cable Selection:

Optical fiber cables are versatile and used in a wide range of applications. Selecting the appropriate type of cable depends on the specific requirements of the environment and the intended use. Here's a breakdown of key applications and criteria for cable selection.

3.6.1 Telecommunications and FTTH Networks:

- Telecommunications: Optical fibers are widely used in telecommunications networks to enable high-speed, long-distance data transmission. They are used for backbone networks, data centers, and local exchange equipment.
- FTTH (Fiber to the Home): FTTH networks use optical fiber to deliver internet, television, and telephone services directly to residential homes. Fiber cables in these networks are often characterized by their low attenuation, high bandwidth, and ability to support high-speed connections over long distances.

3.6.1.1 Cable Selection for Telecommunications and FTTH:

- Single-mode fibers like G.652 are commonly used for long-distance transmission in telecom networks.
- G.657 is often chosen for FTTH due to its bend-insensitive properties, which allow easier installation in tight spaces.

Figure 3.13: FTTH
[36]

3.6.2 Industrial Networks and Optical Sensing:

- Industrial Networks: Optical fibers are used in industrial settings for data communication, offering immunity to electromagnetic interference (EMI), which is essential in environments with high electrical noise, like factories or plants.
- Optical Sensing: Optical fibers are used in a variety of sensing applications, such as temperature, pressure, and chemical sensing. Fiber optic sensors are often used for real-time monitoring of industrial processes, providing high accuracy and resistance to harsh environmental conditions.

3.6.2.1 Cable Selection for Industrial Networks and Optical Sensing

- Armored cables are typically chosen for industrial environments to protect against mechanical damage.
- Multi-mode fibers are widely used for short-distance data transmission, such as within factory settings.

3.6.3 Extreme Environments (Military, Offshore, Underwater)

- **Military:** Fiber optic cables for military use must endure harsh conditions including extreme temperatures, moisture, and mechanical stress, while ensuring high data rates and secure communication.
- **Offshore and Underwater:** Cables for submarine and offshore applications need to resist underwater pressure, saltwater corrosion, and physical damage. They are essential for deep-sea communication, offshore oil platforms, and other marine environments.

3.7 Criteria for Choosing the Appropriate Cable

When selecting the appropriate optical fiber cable for a specific application, the following criteria should be considered:

Criterion	**Description**
Environment	Requires protection from moisture, mechanical stress, and temperature extremes. Industrial/offshore settings need armored and water-resistant cables.
Distance	Single-mode fibers are best for long distances (e.g., FTTH, telecom) due to low attenuation.
Bandwidth and Speed	Multi-mode fibers suit short distances with high bandwidth; single-mode for long-range, high-speed data.
Flexibility and Bend Radius	Bend-insensitive fibers (e.g., G.657) prevent signal loss in tight or curved spaces.
Fire Safety	Indoor/high-risk areas require OFNR or OFNP cables for compliance with fire safety standards.
Durability and Protection	Outdoor or harsh environments need rugged sheathing, armor, and water-blocking features.

Table 3.3: Main factors influencing the choice of optical fiber cable.

3.8 Conclusion:

Fiber optic cables are not merely protective coverings; they are carefully designed systems optimized for performance, longevity, and scalability. The design and quality of these cables have a direct impact on the reliability and capacity of optical communication networks. A deep understanding of cable technologies is crucial for the advancement of next-generation networks and the development of innovations

Chapter 4

Modeling and Simulation of Advanced Optical Fiber Structures

4.1 Introduction

Optical fibers are key to modern communications, enabling long-distance light transmission with minimal loss. To meet rising data demands, innovations like multi-core fibers (MCFs) offer higher transmission capacity within a compact design.

This chapter presents a comparative study between conventional single-core and multi-core optical fibers using advanced modeling and simulation. It focuses on how geometry and refractive index variations affect electromagnetic field propagation and evaluates their respective performances.

Simulations are performed with COMSOL Multiphysics, using the Wave Optics Module to model electromagnetic behavior under different conditions.

4.2 Presentation of the Multi-Core Optical Fiber

Multi-core optical fibers (MCFs) are an advanced type of optical fiber that contain multiple cores within a single cladding structure. Each core can independently guide light, allowing multiple optical signals to be transmitted simultaneously through a single fiber. This architecture significantly enhances the data transmission capacity without increasing the physical size of the fiber, making it a promising solution for overcoming the capacity limitations of conventional single-core fibers.

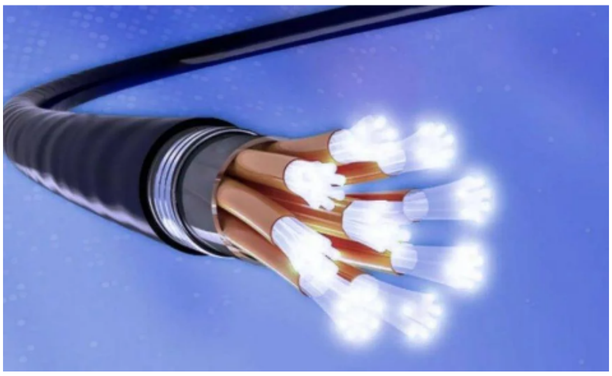


Figure 4.1: multi-core optical fiber
[37]

4.2.1 Structural Design

An MCF typically consists of:

- **Multiple cores**, which may be identical or slightly different in geometry or refractive index.
- **A common cladding**, usually made of silica, that surrounds all the cores and provides confinement of the optical modes.
- **Core arrangement**, which can vary — the most common configurations include linear arrays, square grids, or hexagonal lattices [25].

The spacing between the cores, known as core pitch, is a critical design parameter. If the cores are placed too closely, inter-core crosstalk can occur, which may degrade signal quality. On the other hand, increasing the spacing reduces the risk of crosstalk but also decreases the integration density.

4.2.2 Applications and Advantages

MCFs offer several advantages:

- Increased bandwidth density: Multiple data channels can be transmitted in parallel.
- Space efficiency: Reduces the number of individual fibers needed in communication systems.
- Lower cost per bit in high-capacity systems due to shared cladding and packaging.
- Potential for spatial-division multiplexing (SDM), a key technology in future ultra-high-capacity networks.

These properties make MCFs highly attractive for next-generation optical networks, data centers, and long-haul transmission systems.

4.3 Simulation Methodology

To analyze the optical behavior of the studied fibers, a series of numerical simulations were conducted using COMSOL Multiphysics, a finite element method (FEM) software that allows for accurate modeling of complex physical phenomena, particularly in guided-wave optics.

4.3.1 Overview of COMSOL Multiphysics

COMSOL Multiphysics is a simulation platform designed for solving multiphysics problems in a unified environment. For this study, the Wave Optics Module was used, as it is specifically developed for modeling electromagnetic wave propagation in dielectric media such as optical fibers.

This module allows us to

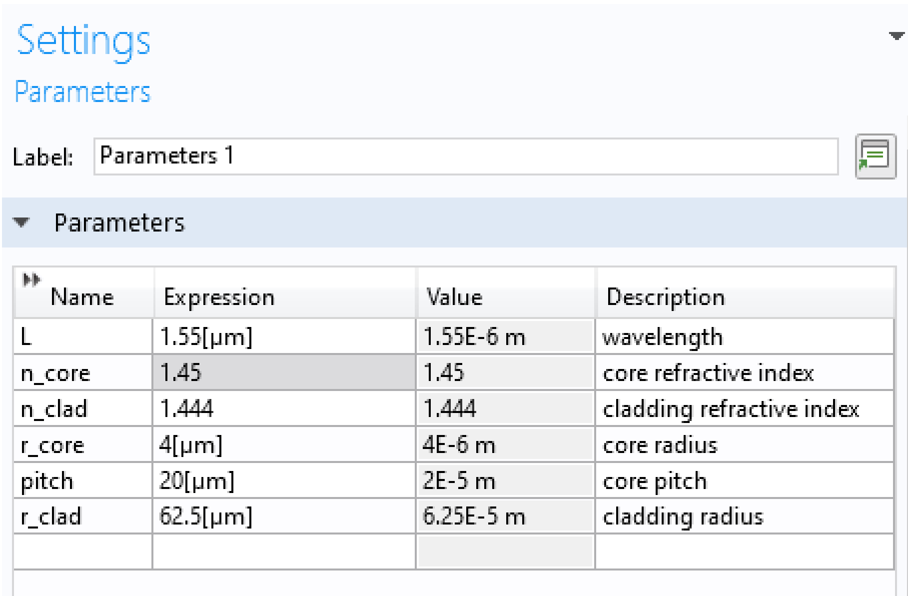
- Simulate wave propagation in 2D, 2D axisymmetric, or 3D structures;
- Analyze guided modes (eigenmodes);
- Study loss, dispersion, and inter-core coupling in multi-core fibers.

4.4 Simulation Methodology with COMSOL Multiphysics

The modeling of the multicore optical fiber was carried out using COMSOL Multiphysics, employing the ”Electromagnetic Waves – Frequency Domain” module, which is well-suited for analyzing optical modes at a fixed wavelength. The objective of this simulation is to study the guiding behavior of fundamental modes in a fiber with four identical cores, and to evaluate the impact of refractive index variations of the core materials on the overall optical performance.

4.4.1 Design Parameters and Model Setup

The following figure shows the parameters defined in COMSOL for the optical fiber model ?were selected based on standard single-mode fiber design principles and realistic values used in industry.



Settings
Parameters
Label: Parameters 1
Parameters

Name	Expression	Value	Description
L	1.55[µm]	1.55E-6 m	wavelength
n_core	1.45	1.45	core refractive index
n_clad	1.444	1.444	cladding refractive index
r_core	4[µm]	4E-6 m	core radius
pitch	20[µm]	2E-5 m	core pitch
r_clad	62.5[µm]	6.25E-5 m	cladding radius

Figure 4.2: Parameters defined for the optical fiber simulation

4.4.2 Geometry Creation

A 2D model was defined , representing an optical fiber composed of four identical single-mode circular cores, each with a diameter of 8 µm, arranged symmetrically with a center-to-center spacing of 20 µm. All cores are embedded in a common pure silica cladding.

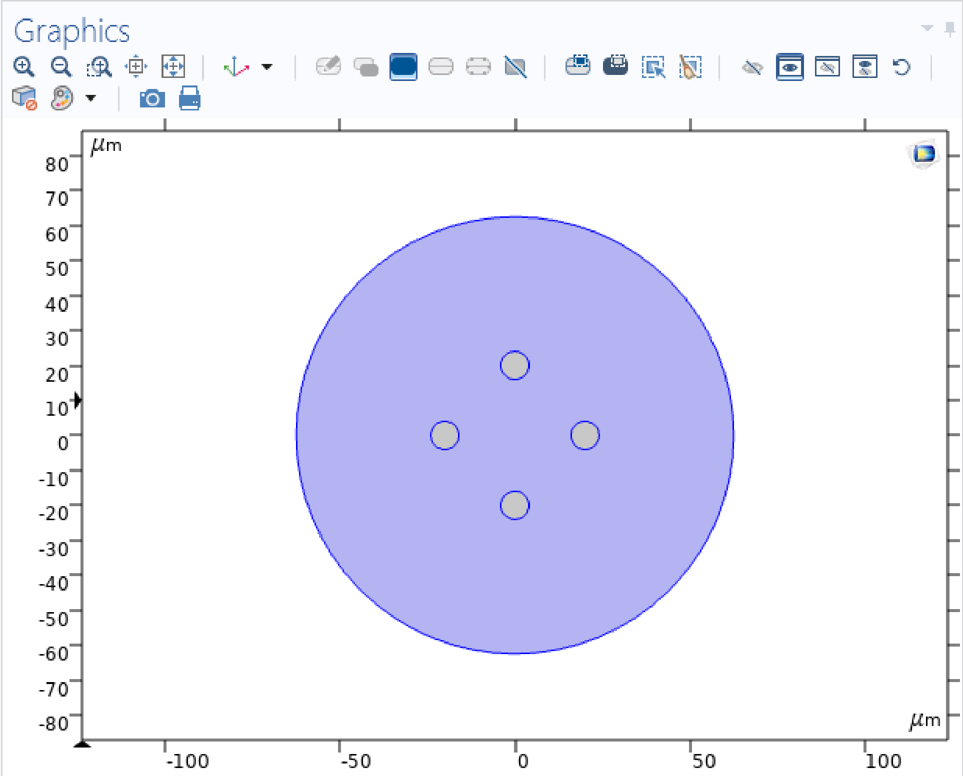


Figure 4.3: Geometry of the multicore optical fiberr

2D is enough for modal analysis because it focuses on the cross-section of the fiber. It gives accurate results while being much faster and less resource-intensive than 3D

4.4.3 Material Definition

two materials were defined to model the optical fiber:

- Core: A custom material was created using the Add Blank Material option, with a refractive index set to n = 1.45, representing a doped glass.
- Cladding: The built-in Fused Silica material from COMSOL's library was used, with a refractive index of n = 1.444.

4.4.4 Scattering Boundary Conditions

In order to replicate an open and realistic environment within the simulation, scattering boundary conditions were applied along the outer boundaries of the computational domain. These conditions absorb outgoing waves, preventing them from reflecting back into the structure and distorting the field distribution. By doing so, they allow for the accurate modeling of wave propagation, as if the surrounding space extended infinitely, which is essential for reliable mode analysis in optical fibers.

4.4.5 Domain Meshing

To ensure accurate resolution of the optical modes, a non-uniform mesh was applied:

- Core region:An Extremely Fine mesh was used in the core region to accurately capture the rapid variations of the electromagnetic field. Since the optical modes are mainly confined within the core, high numerical precision is required to correctly compute the field distribution and the effective refractive index. This fine meshing ensures the reliability and accuracy of the simulation results.
- A Normal mesh size was applied in the cladding region, as the electromagnetic field in this area exhibits smoother and less significant variations. This choice reduces computational load while maintaining sufficient accuracy, since the field is primarily confined within the core and decays gradually in the cladding.

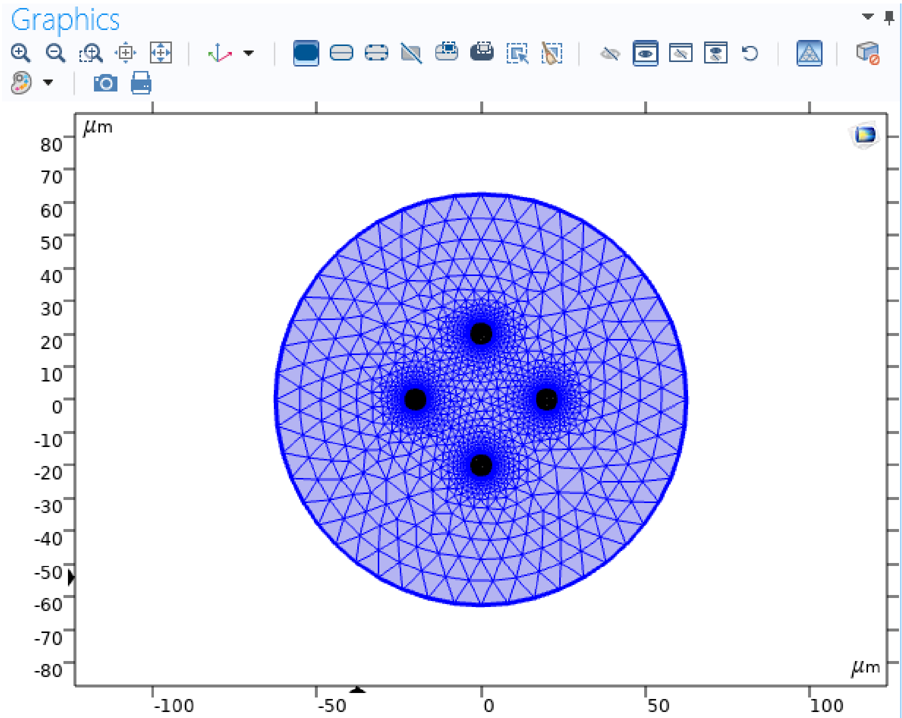


Figure 4.4: Meshed geometry of the modeled optical fiber

4.5 Simulation Results

The main results from the COMSOL simulation are presented here, including guided mode analysis, effective indices, and field confinement in the fiber.

4.5.1 Electromagnetic Field Distribution

The eigenmodes of the fiber were computed using the Mode Analysis study in COMSOL. The figure below shows the transverse electric field distribution (Ex) of the fundamental mode.

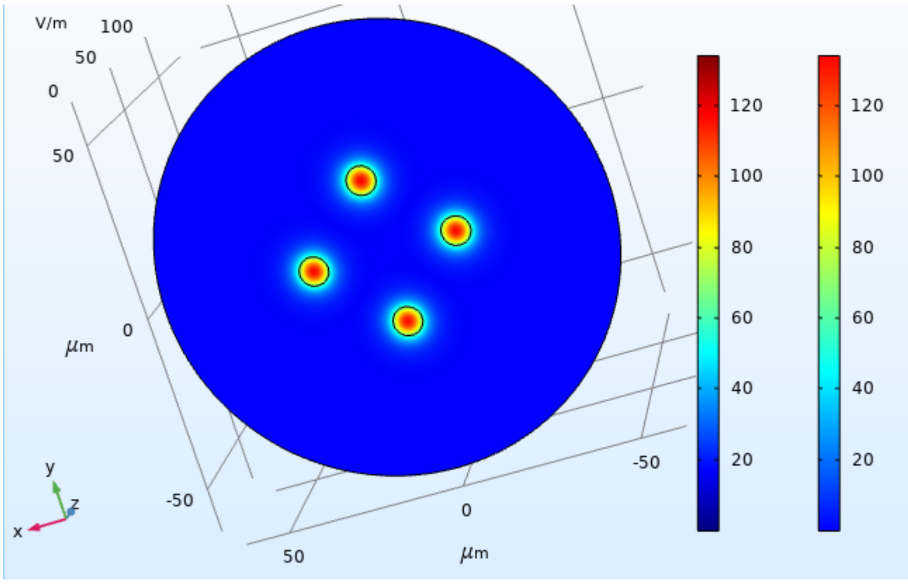


Figure 4.5: Transverse electric field distribution (Ex) of the fundamental mod

- The field is well confined within the core region.
- The field symmetry reflects the circular geometry of the core
- independence between the cores observed depending on the core spacing.

4.5.2 Effective Index n_{eff}

The COMSOL software was used to calculate the effective refractive index of the guided mode in the optical fiber. In our case, the value of the effective index remains constant, confirming that the fiber operates in a single-mode regime.

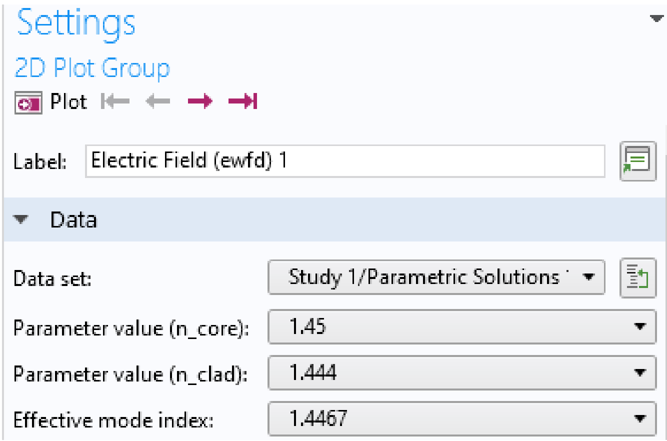


Figure 4.6: Effective Index

The computed effective index lies between the refractive indices of the core (1.45) and the cladding (1.444), ensuring efficient light guidance within the fiber.

4.5.3 Confinement Analysis

The simulation shows that the energy is well confined within the core region(s), which confirms the effectiveness of the light guidance

The confinement of the electromagnetic field in the fiber depends on the refractive index contrast between the core and the cladding. A higher contrast ensures better confinement, while a lower contrast allows more field leakage into the cladding. The closer the effective index (n_{eff}) is to the core index, the stronger the field confinement.

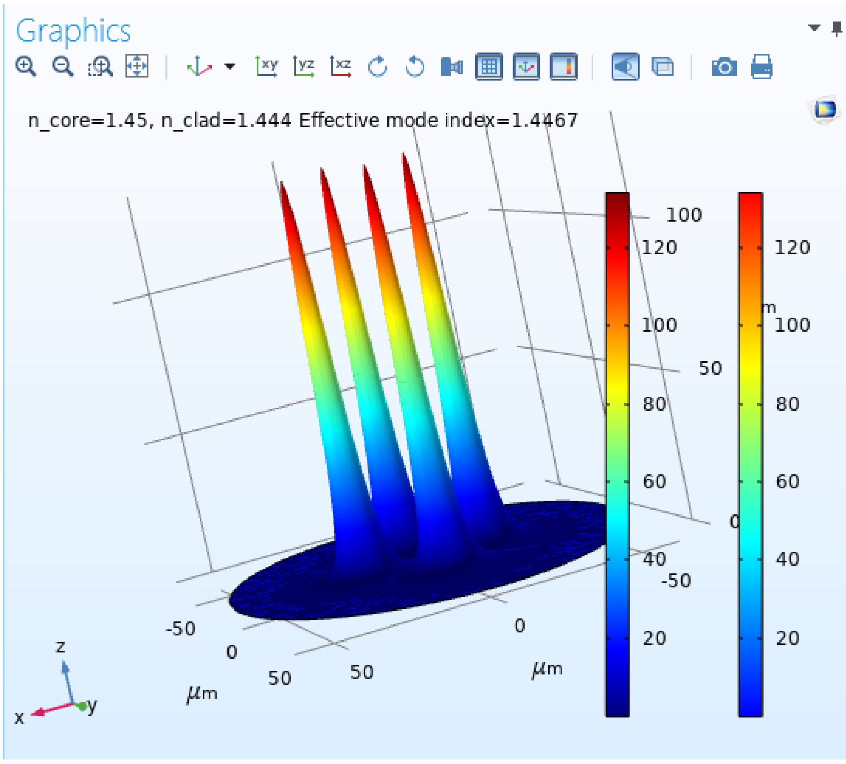


Figure 4.7: Electromagnetic Field Distribution in a Multicore Optical Fiber

4.5.4 Analytical Calculations of the Optical Fiber Parameters

4.5.4.1 Numerical Aperture (NA)

The numerical aperture, quantifying the fiber's light acceptance capability, is calculated as:

$$\text{NA} = \sqrt{n_{\text{core}}^2 - n_{\text{clad}}^2} = \sqrt{1.45^2 - 1.444^2} \approx 0.132$$

4.5.4.2 V-number

The V-number determines the modal regime of the fiber and is given by:

$$V = \frac{2\pi a}{\lambda} \times \text{NA} = \frac{2\pi \times 4 \times 10^{-6}}{1.55 \times 10^{-6}} \times 0.132 \approx 2.14$$

Since $V < 2.405$, the fiber operates in the **single-mode** regime at the studied wavelength.

4.5.4.3 Effective Index

The effective index is calculated as:

$$n_{\text{eff}} \approx n_{\text{clad}} + \left[\frac{1}{1 + \left(\frac{2.4}{V}\right)^2}\right] \cdot (n_{\text{core}} - n_{\text{clad}})$$

$$n_{\text{eff}} \approx 1.444 + \frac{1}{1 + \left(\frac{2.4}{2.14}\right)^2} \cdot (1.45 - 1.444) \approx 1.4467$$

The simulated effective index is:

$$n_{\text{eff}} = 1.4467$$

This confirms the consistency between the analytical estimation and the simulated result, reinforcing the validity of the simplified model for this fiber structure which $\mathrm{n_{eff}} lies between n_{\text{clad}} =$ 1.444 and $n_{\text{core}} = 1.45$, confirming proper guidance and strong confinement of the electromagnetic field within the core.

4.5.4.4 Attenuation

For pure silica fiber at $\lambda = 1.55\,\mu m$, typical attenuation is approximately:

$$\alpha \approx 0.20\,\text{dB/km}$$

indicating low losses over standard transmission distances.

4.5.4.5 Chromatic Dispersion

Chromatic dispersion, responsible for pulse broadening, is given by:

$$D = -\frac{\lambda}{c}\frac{d^2 n_{\text{eff}}}{d\lambda^2}$$

$$D \approx 17\,\text{ps/(nm} \cdot \text{km)}$$

4.5.5 Material-Dependent Refractive Indices

In the simulations, different materials were considered for the core and cladding, such as pure silica, germanium-doped silica, and optical polymers like PMMA. These materials present varying refractive indices, typically ranging from 1.44 to 1.50 at a wavelength of 1.55 μm.

Table 4.1: Comparison of refractive indices based on core and cladding materials

Core material	n_{core}	**Cladding material**	n_{clad}
Silica doped with GeO_2	1.450	Pure silica (SiO_2)	1.444
Silica doped with P_2O_5	1.460	Fluorine-doped silica	1.440
Silica doped with Al_2O_3	1.470	Boron-doped silica	1.430
PMMA	1.490	Teflon (PTFE)	1.380

This variation in refractive index directly influences light confinement and mode behavior in the fiber. By comparing these materials, we evaluate how material selection impacts the optical performance of multi-core fiber structures.

4.5.6 Impact on Mode Propagation

Simulation results show that the refractive index of the core significantly affects the electromagnetic field distribution. Higher core indices lead to stronger mode confinement, reducing scattering losses and enhancing signal stability.

Field maps confirm that high-index materials concentrate energy more effectively within the cores, while lower indices result in wider mode profiles and potential unwanted coupling between adjacent cores.

4.5.7 Impact on Effective Index and Confinement

The effective index (n_{eff}) increases with the refractive index of the core material, indicating improved light guidance. For example, core materials such as germanium-doped silica and PMMA result in higher n_{eff} values compared to pure silica.

Additionally, higher refractive indices lead to better mode confinement, enhancing signal isolation within each core. This is particularly beneficial for multi-core fibers designed for multiplexed transmission systems.

Table 4.2: Influence of Core-Cladding Index Contrast on Effective Index

$n_{\textbf{core}}$	$n_{\textbf{clad}}$	$n_{\textbf{eff}}$	$\Delta n_{\textbf{core-clad}}$	$\Delta n_{\textbf{core-eff}}$
1.450	1.444	1.4467	0.006	0.0033
1.450	1.440	1.4461	0.010	0.0039
1.450	1.430	1.4384	0.020	0.0116
1.460	1.444	1.4492	0.016	0.0108
1.460	1.440	1.4484	0.020	0.0116
1.460	1.430	1.4472	0.030	0.0128
1.470	1.444	1.4577	0.026	0.0123
1.470	1.440	1.4573	0.030	0.0127
1.470	1.430	1.4566	0.040	0.0134
1.490	1.380	1.4839	0.110	0.0061

At constant n_{core}, we observe that when n_{clad} decreases, the effective index n_{eff} slightly decreases . This may seem counterintuitive, as a lower cladding index is usually expected to improve mode confinement.

However, this behavior can be explained by modal structure effects. When the refractive index contrast becomes too high, part of the guided mode may extend further outside the core. As a result, even though the core becomes more optically attractive, the mode's energy distribution shifts outward, causing a slight decrease in n_{eff}.

On the other hand, when n_{core} increases (with or without changes in n_{clad}), n_{eff} generally increases slightly. However, this increase is not proportional to the refractive index contrast ($\Delta n_{\text{core}-\text{clad}}$).

4.5.8 Study of Pitch Variation

In multicore optical fibers (MCFs), the *pitch* is defined as the distance between the centers of two adjacent cores. This parameter plays a crucial role in the overall optical behavior of the fiber. It primarily influences the following characteristics:

- **Inter-core coupling:** A smaller pitch increases the interaction between adjacent cores, which may lead to unwanted crosstalk.
- **Modal confinement:** A larger pitch improves the confinement of the optical mode within each core.
- **Dispersion properties and effective index distribution:** The pitch affects the chromatic dispersion and the effective refractive index (n_{eff}) of the guided modes.

In this section, we investigate how variations in the pitch impact the effective index and modal behavior, using numerical simulations.

4.5.9 Analyses et Discussion

Pitch (µm)	n_{eff} **(Fundamental Mode)**
15.0	1.4462
17.5	1.4465
20.0	1.4467
22.5	1.4469
25.0	1.4470
27.5	1.4471
30.0	1.4472

Table 4.3: Evolution of the effective refractive index n_{eff} as a function of pitch

Pitch (µm)	**Dispersion** D **(ps/(nm · km))**
15.0	18.5
17.5	17.8
20.0	17.0
22.5	16.5
25.0	16.2
27.5	16.0
30.0	15.8

Table 4.4: Variation of chromatic dispersion D as a function of pitch

Increasing the pitch slightly raises the effective index, improving mode confinement by reducing core coupling. Meanwhile, dispersion decreases, which helps limit signal distortion. Thus, there is a balance between core density and optical performance when choosing the pitch.

4.6 Comparison Between Conventional and Multi-Core Fibers

This section presents a direct comparison between the previously simulated multi-core optical fiber and a conventional single-core fiber, both designed with identical refractive indices and boundary conditions to ensure a fair analysis.

4.6.1 Structural Comparison

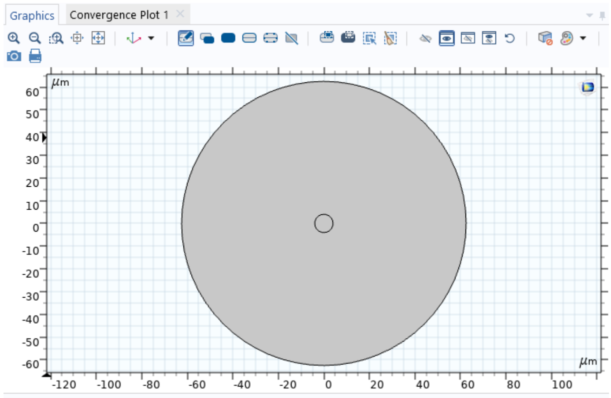


Figure 4.8: The single-core fiber model

The single-core fiber model features a cylindrical structure with a central core having the same radius as the individual cores in the multi-core fiber. The cladding index is kept identical in both cases, ensuring that the comparison focuses solely on the structural differences between the two fiber types.

Parameters

Name	Expression	Value	Description
r_core	4.5[um]	4.5E-6 m	core radius
r_clad	62.5[um]	6.25E-5 m	cladding radius
n_core	1.4575	1.4575	core refractive index
n_clad	1.444	1.444	cladding refractive index
L	1.55[um]	1.55E-6 m	wavelength

Figure 4.9: Parameters defined

4.6.2 Performance Metrics Comparison

The performance comparison highlights that multi-core fibers enable higher data density, at the cost of increased design complexity and coupling management. When using the same materials, the effective indices remain comparable between single-core and multi-core fibers. However, attenuation and dispersion tend to vary more in multi-core configurations due to inter-core interactions.

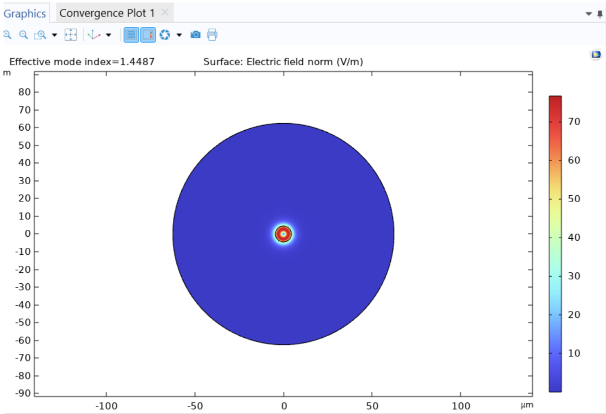


Figure 4.10: Transverse electric field distribution

The analysis of the results shows that the effective index calculated for the multicore fiber is $n_{\text{eff}} = 1.4467$, while for the conventional fiber, it is slightly higher, with a value of $n_{\text{eff}} = 1.4487$. This slight difference can be explained by the inherent nature of the structures: in the multicore fiber, the presence of multiple cores induces optical coupling between them and a more complex distribution of the electromagnetic field, which tends to reduce the average effective index perceived by the guided mode. In contrast, the conventional fiber, with a single core, allows better confinement of the optical mode, resulting in a higher effective index.

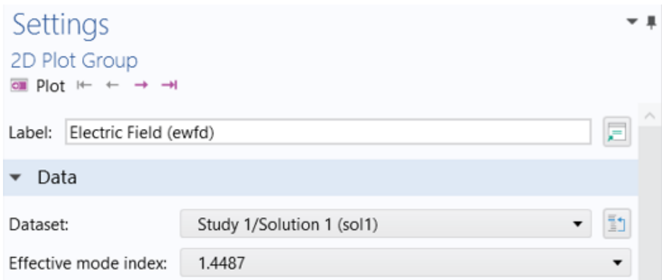


Figure 4.11: Effective index of a single fiber

These results confirm that, even when the base refractive indices are identical, the fiber geometry significantly influences the propagation properties, notably the effective index. This characteristic is crucial to consider during the design and optimization of optical fibers according to their intended applications.

4.7 Conclusion

This chapter was dedicated to the modeling and simulation of a multicore optical fiber, with the aim of evaluating its electromagnetic behavior and transmission performance. Using COMSOL Multiphysics, we were able to observe the optical field distribution, determine the effective index of the guided modes, and analyze the impact of geometric parameters on light confinement. The results obtained are consistent with theoretical expectations and confirm the relevance of this multicore architecture for high-speed optical networks. This simulation represents a key step in guiding future technological choices, with a view to real-world fabrication and optimization tailored to the needs of ultra-high-speed networks. The resulting perspectives open the way to innovative solutions for increasing transmission capacity without compromising cable compactness.

General Conclusion

This dissertation focused on the design and modeling of a novel multicore optical fiber aimed at enhancing the performance of next-generation telecommunication networks. In a context where the demand for bandwidth and transmission capacity is steadily increasing, innovation in optical fiber technology has become a major strategic priority.

In the first part of this study, we examined the fundamental principles of light propagation in optical fibers, including waveguide theory, refractive index profiles, and single-mode operation. We also reviewed the materials commonly used in fiber design, such as pure silica, doped silica, and various optical polymers, along with an overview of fiber fabrication techniques like Modified Chemical Vapor Deposition (MCVD) and the drawing process. This foundation allowed us to define the technical parameters necessary for the design of an advanced fiber structure.

The core of our work focused on the simulation and numerical modeling of a multicore optical fiber using COMSOL Multiphysics. The proposed structure consisted of four identical circular cores, each 8 µm in diameter, embedded symmetrically in a common pure silica cladding with a center-to-center spacing of 20 µm.The simulation results revealed a strong confinement of the fundamental mode within each core, low field overlap between adjacent cores, and promising characteristics in terms of mode separation and signal integrity. These findings confirm the potential of multicore fibers to meet the future demands of FTTH (Fiber To The Home) networks and high-speed optical infrastructures.

This research was conducted in partnership with OptiConnect, a company specializing in the deployment and maintenance of fiber optic infrastructure. This collaboration provided an applied dimension to our academic study, ensuring that the proposed solution aligns with real-world industrial needs and constraints. The integration of simulation tools and industry perspectives allowed us to evaluate both the theoretical feasibility and the practical potential of our design.

From a broader perspective, the development of multicore fibers presents several advantages: they allow for multiple transmission channels within a single fiber, increase data throughput, optimize spatial efficiency, and reduce deployment costs by minimizing the number of required cables. These benefits make them highly relevant for next-generation access networks, such as FTTH (Fiber to the Home), data centers, and long-haul communication systems.

For future work, several directions can be explored. These include the modeling of asymmetric or elliptical core geometries to improve mode isolation, the study of nonlinear effects, and the analysis of environmental influences such as bending losses and thermal variations. Additionally, moving from simulation to experimental fabrication and testing would be a crucial step in validating our findings and assessing the fiber's performance under real operating conditions.

In summary, this thesis contributes to the advancement of multicore fiber technologies by proposing a viable and efficient design, supported by simulation-based evidence. It opens the door to further exploration in the field of high-capacity optical communication, bridging the gap between theoretical innovation and practical implementation.

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Abstract

This dissertation presents the design and simulation of a novel multicore optical fiber aimed at enhancing transmission capacity and efficiency in optical networks. Conducted in collaboration with the OptiConnect project, the work addresses the growing demand for bandwidth, especially in Fiber To The Home (FTTH) applications.

A structure with four identical single-mode cores was proposed, symmetrically arranged within a pure silica cladding. Using COMSOL Multiphysics, simulations were carried out to analyze the electric field distribution, effective index, and optical performance of the fiber.

The results demonstrate good light confinement and confirm the potential of this design for future high-density optical communication systems.

Résumé

Ce mémoire présente l'étude, la conception et la modélisation d'une nouvelle fibre optique multicœur, dans le but d'améliorer la capacité de transmission et l'efficacité des réseaux optiques. En s'inscrivant dans le cadre du projet OptiConnect, ce travail vise à répondre aux besoins croissants en bande passante, notamment pour les applications FTTH (Fiber To The Home).

Une structure à quatre cœurs monomodes a été proposée, chacun étant disposé de manière symétrique dans une gaine en silice pure. À l'aide du logiciel COMSOL Multiphysics, des simulations ont été réalisées afin d'analyser la distribution du champ électrique, l'indice effectif et les performances optiques de la fibre.

Les résultats obtenus confirment le bon confinement de la lumière et montrent le potentiel de cette architecture pour les futures générations de réseaux optiques à haute densité.

الملخص

يعرض هذا البحث تصميم ومحاكاة نوع جديد من الألياف البصرية متعددة النواة، بهدف تعزيز قدرة وكفاءة نقل البيانات في شبكات الألياف البصرية. تم تنفيذ هذا العمل في إطار مشروع OptiConnect، استجابةً للطلب المتزايد على النطاق الترددي، خاصة في تطبيقات "الألياف حتى المنزل" (FTTH). تم اقتراح بنية تحتوي على أربع نوى متماثلة أحادية النمط، موزعة بشكل متماثل داخل غلاف من السيليكا النقية. باستخدام برنامج COMSOL Multiphysics، أُجريت محاكاة لدراسة توزيع المجال الكهربائي، ومعامل الانكسار الفعّال، وأداء الليف البصري.

وقد أظهرت النتائج فعالية في حصر الضوء، مما يؤكد إمكانيات هذا التصميم لاستخدامه في أنظمة الاتصالات البصرية عالية الكثافة في المستقبل.