DESIGN OF TUNABLE FABRY-PÉROT FILTER FOR SPECTROSCOPIC APPLICATIONS

By

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NATIONAL UNIVERSITY OF MODERN LANGUAGES, ISLAMABAD

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The undersigned certify that they have read the following thesis, examined the defense, are satisfied with overall exam performance, and recommend the thesis to the Faculty of Engineering and Computer science for acceptance.

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Candidate of **Master of Science in Electrical Engineering (MSEE)** at the National University of Modern Languages do hereby declare that the thesis **Design of Tunable Fabry-Pérot Filter for Spectroscopic Applications** submitted by me in partial fulfillment of MSEE degree, is my original work, and has not been submitted or published earlier. I also solemnly declare that it shall not, in the future, be submitted by me for obtaining any other degree from this or any other university or institution. I also understand that if evidence of plagiarism is found in my thesis/dissertation at any stage, even after the award of a degree, the work may be canceled, and the degree revoked.

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ABSTRACT

Design of Tunable Fabry-Pérot Filter for Spectroscopic Application

Many spectroscopy applications demand tiny, durable, and portable spectrometers that are far less expensive than present solutions. As a result, micro spectrometer technology is fast evolving, and numerous research organizations are working on it. Tunable Fabry-Pérot filters (TFPF) outperform other types of devices in terms of miniaturization and optical throughput. Spectroscopy is the analysis of the relationship between matter and electromagnetic radiation as a function of the wavelength or frequency of the radiation. The optical Nano spectrometer is made up of a static FP filter array with cavities and a matched detector array, with each filter producing its own spectral filter line dependent on cavity thickness. In a FP interferometer filter, wavelength selectivity is achieved via a multiple-beam interference approach. The filter is often made up of two highly reflecting mirrors that form a resonating cavity that causes multiple-beam interference, with a single input and output port. Tunable FP filters that are tuned on all cavity spaces, giving an advantage in the size and space department of the filter. Instead of utilizing an array of filters, single filter is used. To accomplish this, analyses several materials from the COMSOL Multiphysics library to examine thin film structures, and then optimize adjusted Fabry-Pérot filters (FPF) using the best material available.

The FPF core structure features three upper Distributed Bragg Reflector (DBR) mirror layers connected to three lower DBR layers. The cavity layer, made from PZT, is nestled between these layers. The upper layers are composed of SiO_2 and a central layer from TiO_2, while the lower layer is encapsulated by TiO_2. This intricate geometric configuration is crucial for optimal performance in spectroscopic applications. The research shows fixed FP filters, with their fixed spacing between DBR layers, transmit a specific wavelength of light. They are not tunable and can only operate at the designed wavelength. Tunable filters can adjust the spacing between DBR layers, allowing them to select different wavelengths. This makes them versatile and suitable for various applications. Tunable filters are complex and require precise control systems and can have variable spectral resolution depending on the selected wavelength and adjustment mechanism. We delve into the FPF filter's response when exposed to distinct voltage Range settings. Each voltage setting corresponds to a specific mirror separation distance, which, in turn, determines the filter's transmission characteristics. At its maximum tuning capacity, the FPF exhibits a remarkable shift in interference fringes. This allows for the broadest range of wavelengths to either pass through or be blocked. Comprehending the voltage-dependent tunability of the TFPF, spanning from 1V to 40V, is a pivotal aspect of its adaptability and usefulness in various optical applications. Researchers and engineers, through this understanding, can harness the device's capabilities to precisely control wavelengths, thereby driving advancements in optical communication, spectroscopy, and various other optical technologies.

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LIST OF ABBREVIATIONS

AHM	ad-hoc-measure.
DLR	dynamic line rating
GUI	graphical user interface.
HIL	hardware-in-the-loop
IEC	International Electrotechnical Commission
OHL	overhead line
PATL	permanent admissible transmission loading
PFCD	power flow controlling device
PST	phase shift transformer
RTS	Real Time Simulator
RTU	remote terminal unit
SIL	Software-in-the-Loop
STU	smart telecontrol unit
TSO	transmission system operator
TFPF	Tunable Fabry Perot Filter
FPF	Fabry Perot Filter
DBR	Distributed Bragg Reflector

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time

CHAPTER 1

INTRODUCTION

1.1 Spectroscopy

Spectroscopy is the study of the interaction between light and matter. It is based on the principle that atoms and molecules can absorb or emit light at unique wavelengths as shown in figure 1.1. The wavelength of light absorbed or emitted depends on the energy levels of the atoms or molecules. Spectroscopy is a powerful tool for identifying and characterizing atoms and molecules [1]. Additionally, spectroscopy is widely used to examine the structure and dynamics of various substances, making it a valuable technique in scientific research.

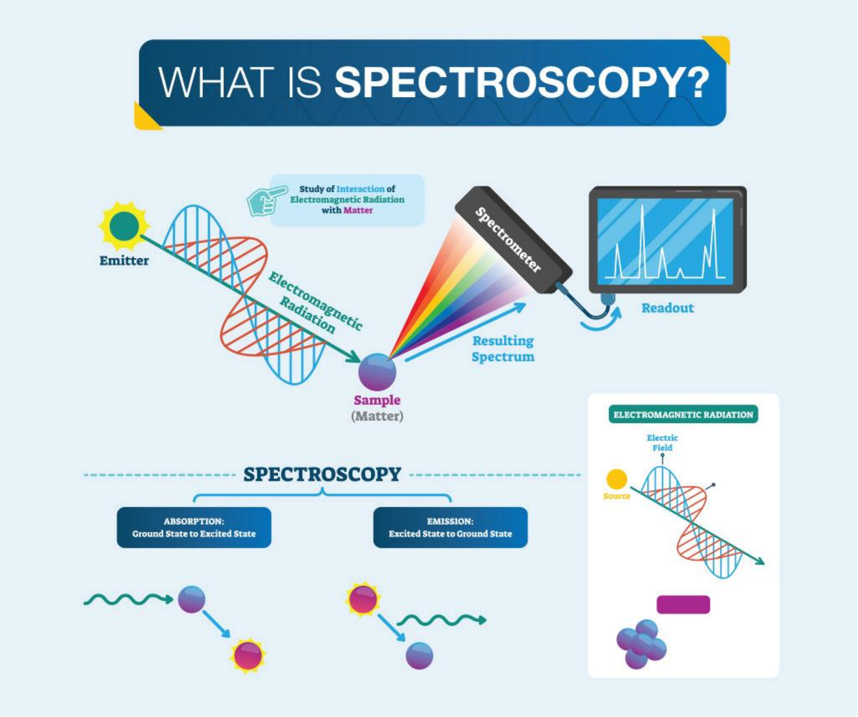


Figure 1.1 Spectroscopy [1]

Spectroscopy is used in a wide variety of fields, including chemistry, physics, biology, and materials science. It includes various types of spectroscopy, each based on a different interaction between light and matter. One of the most common types is Ultraviolet (UV)-visible spectroscopy, which measures the absorption of light in the ultraviolet and visible regions of the electromagnetic spectrum. UV-visible spectroscopy is utilized for the identification and characterization of organic molecules [2]. Many spectroscopy applications demand tiny, durable, and portable spectrometers that are far less expensive than present solutions. As a result, micro spectrometer technology is fast evolving, and numerous research organizations are working on it. Tunable Fabry-Pérot filters (TFPF) outperform other types of devices in terms of miniaturization and optical throughput [3]. Low-cost, tiny FP-based optical spectrometers are smart to modern sensing systems such as safety and security, process monitoring, medical technologies and so on [4]. In the optical Nano spectrometer, which is made up of a static cavity and a matching detector array, every filter generates a separate spectral filter line based on cavity thickness. [2].

1.1.1 History

In the 17th century, the Western world saw the first appearance of modern spectroscopy. Systematic measurements of the solar spectrum are now possible because to new optical designs, particularly prisms. The term spectrum was used by Isaac Newton to describe the wide range of colors that combine to make white light. Research article [5] developed dispersive spectrometers in the early 1800s, allowing spectroscopy to become a more exact and quantitative scientific procedure. Spectroscopy has become increasingly important in chemistry, physics, and astronomy since then. Despite the fact that Wollaston had previously discovered and quantified several black lines in the Sun's spectrum. Spectroscopy is the analysis of the relationship between matter and electromagnetic radiation as a function of the wavelength or frequency of the radiation [6]. Spectroscopy is a field of science that uses spectrographic equipment and other techniques to analyses the spectra of electromagnetic radiation as a function of wavelength or frequency to learn more about the composition and material properties. Instruments that measure the spectrum are known as spectrographs, spectral analyzers, spectrophotometers, and spectrometers. The light travels through the material to a dispersion array and is caught by a photodiode for astronomical purposes. This basic arrangement can be used to pacific electromagnetic waves in a variety of ways [7].

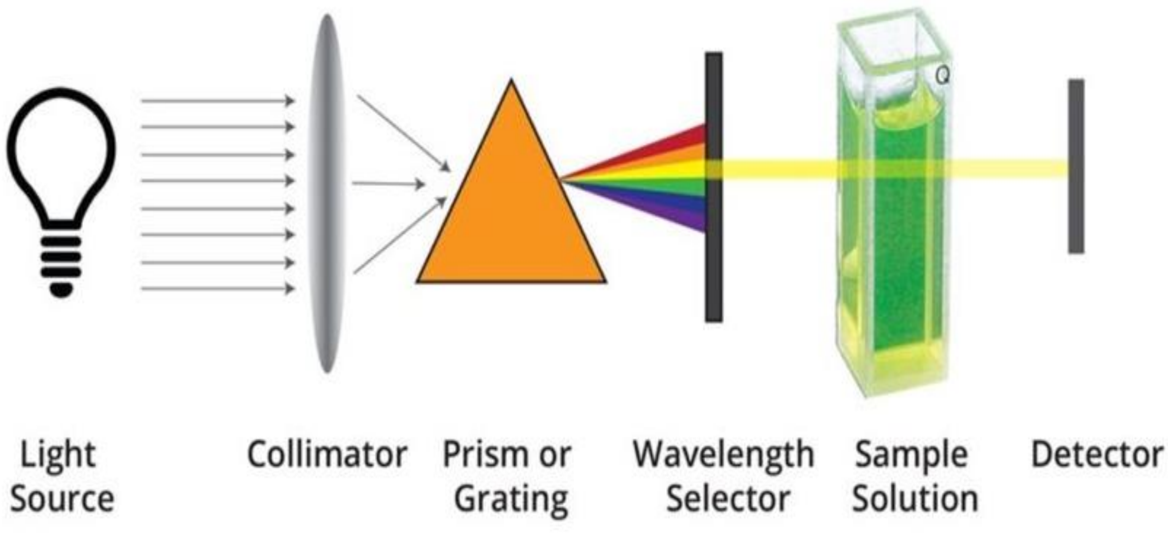


Figure 1.2 Fundamental working of Spectroscopy [2]

Isaac Newton, who divided light with a prism, gave his name to the science of spectroscopic optics. As a result of James Clerk Maxwell's studies, the study of visible light, or colour, has expanded to include the entire electromagnetic spectrum [8]. In spectroscopy, colour is employed, but it is not the same as the colour of substances or objects, which is generated by the absorption and multiple reflection of specific electromagnetic fields. Spectroscopy is the technique of dividing light into discrete line patterns for each type of element using a prism, diffraction grating, or other apparatus as shown in figure 1.2. Most element spectra are computed first in a gaseous phase, and then additional methods are employed to calculate spectra in other phases. Each element diffraction grated by a prism-like device has an absorption or emission spectrum depending on whether it is cooled or heated [9].

1.2 Principles of operation

In a Fabry Pérot (FP) interferometer filter, wavelength selectivity is achieved via a multiple-beam interference approach. The filter is made up of two highly reflective plates that form a resonant cavity that causes multiple-beam interference, and it usually only has one input and output port [10].

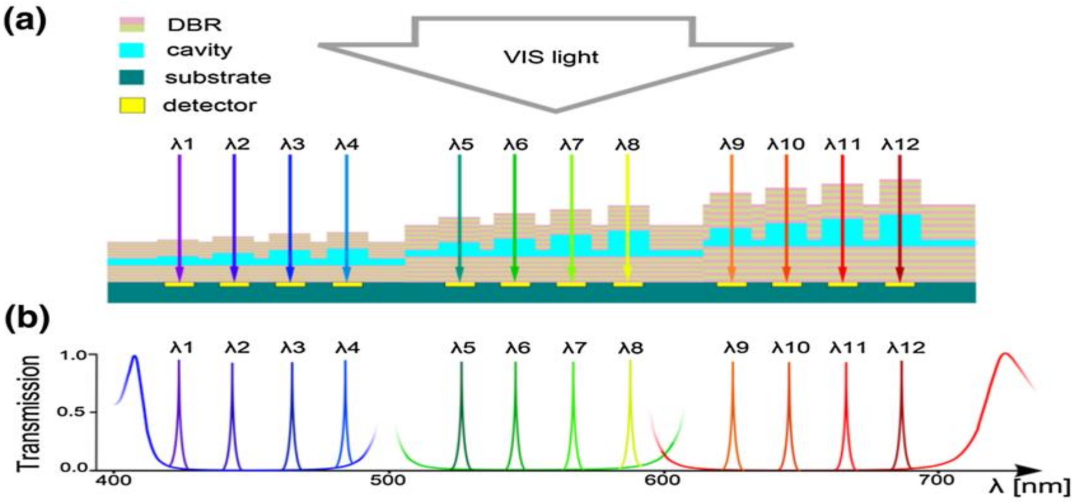


Figure 1.3 Fixed FPF a) The varying heights of the cavities produce 12 separate filter lines; b) Representation of a static Nano spectrometer with three DBR 12 different cavities [2]

The FP filter is a type of optical resonator that concentrates and stores light energy at specific frequencies. This optical transmission system incorporates feedback, in which light is reflected and circulated repeatedly within the system. Without attempting to evade the system. A conventional FP filter is composed of two parallel, mirrors with a high refractive index and a cavity formed between them [11]. Charles Fabryand Albert -Pérot were the first to describe it in 1899. To make a hollow, two highly reflective parallel flat plates are appropriately positioned. A light beam that enters the hollow is numerous times reflected between the plates. Each time the beam makes contact with a plate, a small amount of energy is squandered. The many beams radiated from each side of the FP cavity are perfectly parallel when the two plates are perfectly parallel as shown in figure1.3. The phase difference between each beam and the one before it is proportional to the extra route length traversed through the cavity. A lens brings the many parallel beams together into a single focus point, and it is at this point that real multiple beams are generated [5].

1.3 Modern Applications of Spectroscopy

Spectroscopy is a effective tool that is utilized in a extensive style of current applications. Some of the most commonplace applications of spectroscopy consist of: Chemical analysis, Spectroscopy may be used to pick out and quantify the presence of different chemical substances in a sample. This is beneficial for a variety of programs, which includes exceptional manage, environmental monitoring, and forensic technology. Material technology, Spectroscopy may be used to have a look at the shape and composition of materials. This is useful for growing new substances with improved residences, which include strength, sturdiness, and conductivity. Physics: Spectroscopy may be used to look at the atomic and molecular structure of depend. This is useful for know-how the essential properties of remember and for growing new technologies, consisting of lasers and semiconductors.[6] Biology [12], Spectroscopy may be used to examine the shape and function of organic molecules. This is useful for information the biology of residing organisms and for developing new pills and diagnostic gear. Here are some specific examples of modern-day

Applications of spectroscopy; Raman spectroscopy, Raman spectroscopy is used to pick out and symbolize organic and inorganic substances. It is also used to examine the dynamics of molecules [13]. For instance, Raman spectroscopy is used to expand new drugs and materials, and to look at the conduct of proteins in the body. Infrared spectroscopy, Infrared spectroscopy is used to identify and characterize practical businesses in molecules. It is also used to study the structure of substances. For example, infrared spectroscopy is used to identify polymers and to look at the shape of proteins. UV-visible spectroscopy, UV-visible spectroscopy is used to identify and represent natural molecules. It is likewise used to study the digital structure of materials. For example, UV-visible spectroscopy is used to pick out dyes and to observe the properties of sun cells [11]. Spectroscopy is a versatile device that may be used to examine a huge form of phenomena. It is an critical tool in lots of contemporary fields of studies and development. In addition to the above, spectroscopy is also utilized in a lot of different cutting-edge packages, including: Environmental tracking, Spectroscopy can be used to screen the best of air, water, and soil. It is also used to become aware of and quantify pollutants. For instance, spectroscopy is used to screen air high-quality in cities and to discover pollution in water. Food protection, Spectroscopy may be used to perceive and quantify foodborne pathogens and toxins. It is likewise used to hit upon adulterants in meals. For example, spectroscopy is used to detect salmonella in chicken and melamine in milk. Medical diagnostics, Spectroscopy can be used to diagnose a whole lot of sicknesses, which include cancer, diabetes, and Alzheimer’s ailment as shown in table 1.1. It is also used to monitor the effectiveness of remedies. For instance, spectroscopy is used to diagnose cancer with the aid of detecting the presence of tumor markers inside the blood [14]. Spectroscopy is a powerful tool that has a extensive variety of applications inside the modern world. It is used by scientists and engineers in many specific fields to have a look at and understand the sector round us.

Table 1.1 Modern Applications of Spectroscopy

Application Area	**Spectroscopic Techniques**
Materials Science Environmental	Raman spectroscopy, X-ray spectroscopy, and Auger electron spectroscopy UV-Vis spectroscopy, mass spectrometry, and NMR spectroscopy
Analysis Biomedical	Infrared spectroscopy, fluorescence spectroscopy, and MRI
Research Space Exploration Semiconductor Industry	UV spectroscopy for exoplanet studies and remote sensing of celestial bodies Photoluminescence spectroscopy and ellipsometry for semiconductor characterize

1.4 Distributed Bragg Reflectors (DBRs)

A DBR is formed by two materials with different refractive indices, each of which is referred to as a period. Each layer has a thickness of λ_o / (4n), where n specifies the refractive index and λ_o denotes the intended center wavelength as shown in figure 1.4. The reflected beam within the high refractive index layer does not incur phase shift when a light beam travels through a DBR. As a result, at the front surface, all incoming beams that are reflected at successive boundary layers resurface in phase, contributing to constructive interference [6].

Where R is the reflectivity of the mirror, p is the number of period; and nL, nH, nS, nA are the low, high, substrate and air refractive indices respectively [5].

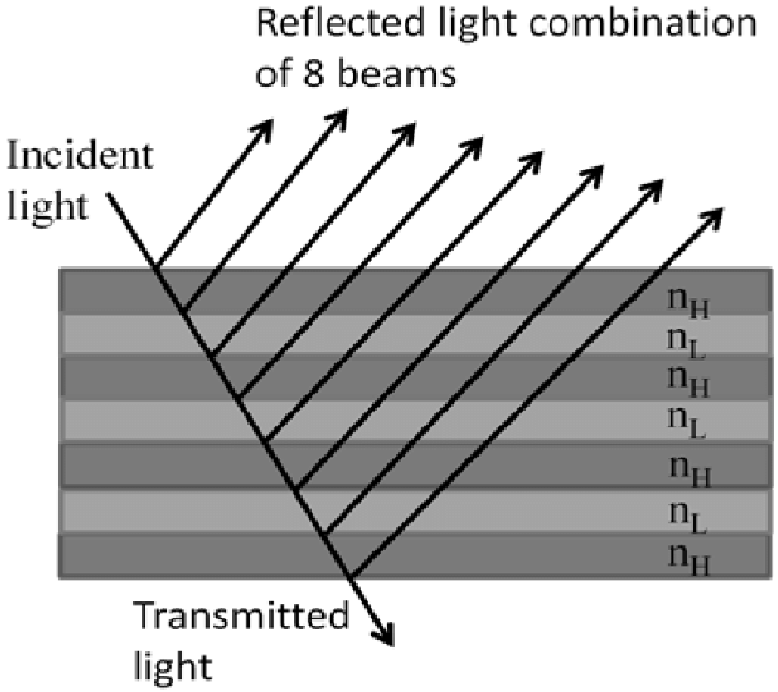


Figure 1.4 Structure of Distributed Bragg Reflector (DBR)[2]

1.5 FP Design Aspects

1.5.1 Tuning

The FPF, a crucial component in optical devices, relies on the modulation of the distance between its plates for optimal performance. The separation between the plates can be adjusted by manipulating either the refractive index or the physical distance. A noteworthy method involves modifying the refractive index by altering the pressure of the gas (typically air) within the cavity. This unique approach allows for precise and gradual tuning, enabling meticulous control over the filter's properties [5]. Furthermore, the adjustment of plate spacing can be achieved through either manual means or electromechanical processes. In manual adjustment, a user can modify the separation between the plates physically, providing a hands-on approach to fine-tuning the filter's characteristics. On the other hand, electromechanical methods offer a more automated and efficient solution. Piezoelectric transducers, in particular, stand out as they provide rapid tuning capabilities, ensuring quick and precise adjustments to the FPF [15].

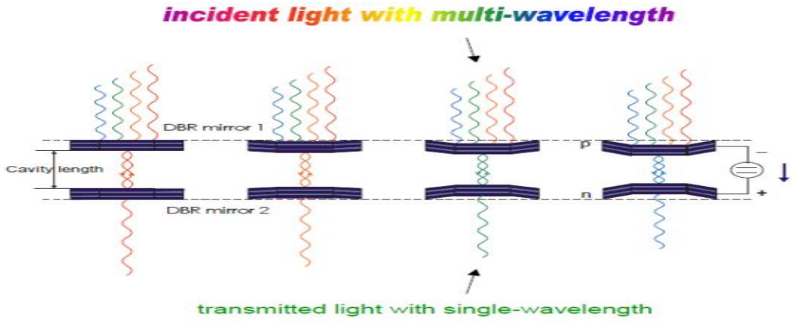


Figure 1.5 Transmitted light with single wavelength [3]

The key to maximizing the filter's performance lies in synchronizing the optical path length with half the wavelength of the light within the cavity. This alignment is critical for achieving the maximum transmission through the filter as shown in figure 1.5. By carefully manipulating the spacing between the plates, researchers and engineers can harness the FPF's versatility and responsiveness to meet specific optical requirements in various applications.

1.6 Problem statement

In current optical devices, such as array filters, a multitude of mirrors known as DBR's mirrors is employed. Unfortunately, this setup makes the device larger and more intricate. To address this issue, we aim to utilize TFPF, which will enable a significant reduction in the device's size. The need to minimize the filter's dimensions is driven by diverse applications that require compact solutions. Our research focuses on the design and optimization of tunable FP filters tailored for various spectroscopic tasks, with the overarching goal of achieving a more compact device.

1.7 Objective

To investigate thin film structures using materials available in the COMSOL Multiphysics library, aiming to enhance material understanding, optimize performance, and advance technology in fields like electronics and optics.

To optimize and tune FP filters based on best available material.

1.8 Scope of study

The research on TFPF using COMSOL Multiphysics is significant as it has the potential to lead to the development of new and enhanced TFPF for a wide range of spectroscopic applications. TFPF are already extensively utilized in spectroscopy, however they have got some boundaries, such as restricted tuning range, resolution, and bandwidth. The studies on TFPF the use of COMSOL Multiphysics has the potential to address these barriers and develop TFPF with advanced performance. This may want to have a significant impact on a huge variety of fields, inclusive of chemistry, physics, biology, and substances technology. For instance, new and advanced TFPF can be used to develop new spectroscopic strategies for detecting and quantifying pollution in the environment, diagnosing sicknesses at their early tiers, and studying the structure and composition of substances at the nanoscale.

The scope of the studies on TFPF using COMSOL Multiphysics is extensive and covers a wide range of subjects. This includes the exploration of optical filters, which are passive devices designed to allow specific wavelengths or sets of wavelengths of light to pass through them [20]. FP filters fall within the category of optical filters. Furthermore, FP filters can be categorized into two groups: static and tunable.

1.9 Applications:

A spectrometer is a device whose spectrum transmission may be regulated electrically using voltage, an auditory signal, or other means. There are many applications related to optical filters. We will only focus on the food industry:

1.9.1 Food Industry

In the food sector, spectrometers are used in a variety of ways, principally for quality control, composition analysis, and safety testing [16]. Spectrometers are frequently used in the food business for the following reasons:

Quality Control: Spectrophotometers are used to measure color to make sure food products are appealing and consistent [17]. Spectrometers can gauge the firmness or softness of a piece of meat or the crispness of a snack. Near-infrared (NIR) spectrometers are used to evaluate the freshness of fruits without causing any harm to them [18].

Chemical Composition Analysis: To avoid spoilage and maintain quality, NIR spectroscopy is used to assess the moisture content in a variety of food products [19]. Spectrometers can measure the fat, protein, and sugar content of food items, which is useful for nutritional labeling and quality assurance. Gas chromatography-mass spectrometry (GC-MS) is used to examine volatile substances that give foods their flavors and aromas [20].

Contaminant Detection: To locate and measure pesticide residues on fruits and vegetables, mass spectrometry and liquid chromatography are utilized [1]. Spectroscopy methods can be used to find and analyze pathogens like Salmonella and E. coli in food products. To locate allergens in packaged foods, immunoassays and fluorescence spectroscopy are employed.

Ingredient Verification: To avoid fraud and ensure product integrity, spectroscopy can confirm the authenticity of components, particularly in high-end or niche goods [21].

Beverage evaluation: Spectrophotometers can be used to determine the amount of alcohol in various drinks. NIR spectroscopy can be used to examine and preserve the flavor characteristics of drinks like wine and coffee [22].

Shelf-Life Evaluation: Spectroscopic methods can track the development of oxidation and rancidity in fats and oils, affecting the shelf life of different food items [23].

Nutritional Labeling: In order to confirm the accuracy of the nutritional labels, spectrometers may examine the vitamin and mineral content in fortified meals [20].

Analyzing the packaging: In order to avoid contamination or deterioration, infrared spectroscopy can evaluate the seal integrity of food packaging. Spectrometers may examine the composition of packaging materials to make sure they are food-safe and conform to legal requirements [2].

Testing for Water Quality: Spectroscopy is used to evaluate the water's quality and make sure it complies with safety regulations before it is utilized in food preparation [24].

Sensory Assessment: In sensory assessment studies, spectrometers are used to measure the sensory qualities of food products, such as taste, odor, and appearance, objectively. Both producers and consumers profit when spectrometers are used to guarantee the industry-wide safety, quality, and compliance of food items [25].

1.9.2 Comparison of tunable and fixed FPF in food industry:

In the field of food investigation, TFPF spectroscopy can be more advantageous than fixed FPF spectroscopy in a number of situations. The following are some justifications for choosing adjustable FPF spectroscopy [20][26]:

- The composition of food samples might change greatly, and their optical characteristics might not always match a specific wavelength. With the help of tunable FPF spectroscopy, you can change the wavelength to precisely match the absorption or emission properties of the substances you wish to study. The ability to adapt is essential when working with various and complex dietary matrices.
- TFPF spectroscopy can offer improved sensitivity by precisely adjusting the wavelength to the absorption or emission peaks of target analytes. This is crucial when looking for minute amounts of pollutants, trace elements, or chemicals in food goods.

- New or unexpected compounds are frequently found in the food sector. By scanning a broad wavelength range, tunable FPF spectroscopy enables exploratory investigation and the identification of unidentified substances.
- Food samples frequently include a range of substances that can obstruct spectral analysis. Tunable FPF filters can increase measurement accuracy by choosing the best wavelength for a given analyte, hence reducing the effects of matrix interference.
- Tunable FPF spectroscopy offers the flexibility required for in-depth investigations and method development in research and development applications within the food industry, where the goal is to comprehend and optimize the attributes of food products.
- The food sector deals with a Variety of Products, each having Special Features. Tunable FPF spectroscopy has a wider range of applications and is better suited for quality control and compositional analysis of various food varieties.
- Tunable FPF spectroscopy allows you to gather data over a wider spectrum range, giving you greater in-depth knowledge of the sample. This is particularly useful for examining complex food samples with numerous ingredients.
- Detecting pollutants, additives, or chemicals of concern in food items can be done more precisely and sensitively using tunable FPF spectroscopy, which can assist in regulatory compliance.
- These benefits of tunable FPF spectroscopy should not be overlooked, but it should be noted that these benefits may be offset by higher initial costs, more complicated instrumentation, and higher skill levels for operation and maintenance. The individual requirements of the application, financial limitations, and the complexity of the samples being studied should be taken into consideration when deciding between fixed and tunable FPF spectroscopy in the food investigation sector.

1.10 Contribution and Significance

Optimization of static FP filter to tunable play a vital role in the industry of spectroscopy while reducing the processing time and increasing the efficiency of the spectrum result. The spectrum information may be utilized to derive spectral signatures of objects, allowing discrimination and identification of targets that would be impossible to discriminate based on intensity alone. Conventional static FP filter uses Array of static Filters with fixed cavities having different space between them but on the other hand we want to use tuned FP filter which will be tuned on all the cavity spaces, this will gives us the edge on the size, space department of the filter. We will be able to use one filter instead of using the array of filter. While doing this firstly, we will investigate optical materials which fulfills our requirement of tuning. All this will be done on the COMSOL Multiphysics software because we do not have the facility to perform lab tasks.

1.11 Organization of Thesis

The introduction, literature review, methods, results and discussion, limits, and conclusion are the five key sections of the thesis. The study's goals and purpose, as well as a brief history of the research problem, were described in the introduction chapter. Then came the objectives and research questions. This chapter also discusses the study's significance and applicability. An overview of the literature review in the areas of Comprehensive review of relevant literature and Theoretical concepts and principles. The thesis' methodology, Details of research methods, tools, and In-depth analysis of filter design and optimization. The results and discussion chapter presents the experimental setup, results and main findings of the thesis. The chapter on conclusions and future work provides an overview of the research's findings as well as a list of potential limitations and research avenues. Additionally, it outlines the study's overall impact to the fields of nanotechnology.

CHAPTER 2

LITERATURE REVIEW

2.1 Spectroscopy and Its Multidisciplinary Applications

Spectroscopy is the study of the interaction between light and matter. It is a powerful tool used in various scientific disciplines to identify and quantify substances, analyze molecular structure and dynamics, and measure physical properties. Spectroscopy finds applications in a wide range of fields, including chemistry, physics, biology, materials science, and environmental science [27]. In chemistry, spectroscopy is a versatile tool for identifying and quantifying substances, studying the structure and dynamics of molecules, and measuring chemical bonds between atoms. For instance, it is used to develop new drugs and materials, analyze the composition of food and water, and detect environmental pollutants. In the realm of physics, spectroscopy is employed to investigate the electronic structure of atoms and molecules, the vibrational and rotational modes of molecules, and material properties. It contributes to the development of new lasers and semiconductors, aids in understanding the behavior of matter at the atomic and molecular level, and allows precise measurements of temperature and pressure [28].

Spectroscopy plays a crucial role in biology by enabling the examination of the structure and function of biological molecules such as proteins, nucleic acids, and lipids. It is also used for disease diagnosis, including the detection of genetic mutations, studying drug interactions with proteins, and diagnosing conditions like cancer [29][30]. Within materials science, spectroscopy is employed to study material structure and composition, as well as to measure physical properties such as strength, durability, and conductivity. It assists in the development of new materials with enhanced properties, analysis of material failures, and the identification of defects in material. In the field of environmental science, spectroscopy is used to monitor the quality of air, water, and soil, contributing to environmental protection and research [31]. It is also used to identify and quantify pollution within the surroundings. For instance, spectroscopy is used to reveal air best in towns, to detect pollutants in water, and to perceive contaminants in food [32]. Overall, spectroscopy is an effective and flexible tool that has a wide variety of packages in lots of specific fields. It is a vital device for scientists and engineers who are working to expand new technologies, enhance our information of the sector around us, and resolve a number of the maximum pressing challenges going through society these days. Here are a few particular examples of ways spectroscopy is utilized in multidisciplinary research [13].

Table 2.1 Spectroscopy in different Fields

Discipline	**Spectroscopic Techniques**
Chemistry	NMR spectroscopy, UV-Vis spectroscopy, and mass spectrometry
Physics	X-ray spectroscopy, optical spectroscopy, and Raman spectroscopy
Biology	Fluorescence spectroscopy, IR spectroscopy, and circular dichroism spectroscopy
Environmental Science	Atomic absorption spectroscopy, ICP-MS, and LIBS spectroscopy
Astronomy	Optical spectroscopy, radio spectroscopy, and gamma-ray spectroscopy
Medicine	MRI, CT scans, and PET scans for medical imaging

Spectroscopy is used in different disciplines as shown in table 2.1. True and dynamics of molecules, scientists can design new tablets that are greater powerful and feature fewer aspect results. Spectroscopy is also used to broaden new materials with improved homes, along with energy, sturdiness, and conductivity [33].Spectroscopy is used to diagnose and reveal diseases. By analyzing the adjustments inside the composition of biological molecules, doctors can diagnose sicknesses at their early stages and display the effectiveness of treatments [4]. For example, spectroscopy is used to diagnose cancer with the aid of detecting the presence of tumor markers inside the blood [34].

Spectroscopy is used to have a look at the climate and the surroundings. By measuring the composition of the atmosphere and ocean, scientists can observe the climate and the effect of human activities on the surroundings.[9] For example, spectroscopy is used to degree the degrees of greenhouse gases inside the surroundings and to detect pollution in water. Spectroscopy is an effective tool this is utilized in an extensive variety of fields to solve [35] complicated troubles. It is an crucial tool for scientists and engineers who are working to make the world a better place [36]. The goal of this project is to use low-cost technology to create tunable filter arrays. Materials and technological procedures suitable for the manufacturing of filter arrays are assessed [14]. As filter cavity material, multilayers of dielectric DBRs and UV-NIL polymers are used. Filter arrays based on tunable Si_3N_4/ SiO_2 DBRs have been successfully built. The structuring of high index contrast TiO_2/ SiO_2 DBR-based filters has been optimized. A filter line width of approximately 4 nm was obtained from one filter element, and a tuning range of roughly 75 nm was obtained within 125 nm of the filter stop band with applied voltage up to 30 V. Tunable filter arrays have also been achieved. With an applied voltage ranging from 0 to 20 V, they were able to achieve a tuning range of around 70 nm [37].

This research focuses on optical filter arrays for high-quality spectroscopic applications in the visible (VIS) spectrum [38]. The optical filters are FPF for a high resolution producible optical Nano spectrometer, and are based on two highly reflecting dielectric mirrors with a resonance polymeric cavity between them. Each filter allows a limited spectral band (called filter line in this study) to pass through depending on the height of its resonance cavity [31]. The quantitative measurement of polymerization shrinkage in the FP filter cavities' lateral and vertical dimensions is explored. The shrinkage in vertical heights, which is of relevance because of its potential impact on the spectral response of the filters, is lowered from 12 percent to 4% by modifying the exposure period [4]. This study investigates a miniaturized fixed sensor array relying on a FPF array for high-quality, sensitive, and selective detections in the visible spectrum [10]. The quality of Nano imprinted multiple cavities is improved in this study by adjusting processing factors such imprint area, process delay, and step time. A novel imprint polymer (diluted mr-NIL210) is compared to a standard material (i.e. mr-UVcur06) [26]. The residual layer's homogeneity is also improved. Furthermore, the residual layer thickness can be modified to some amount An average transmission intensity of 52 percent, a best transmission of 90 percent, and an average Full Width at Half Maximum (FWHM) of 2.7 nm are achieved in single stop band filter arrays [39]. The 64 FP filters constructed can transmit 64 distinct transmission lines and cover a spectral band of around 60 nm[14]. The physically coupled FP interferometer can be stabilized via the actively stabilized shearing interferometer [20]. The SI feedback loop's set point can be used to regulate the length of the FPI cavity. The FPI's transmission frequency had a standard variation of 0.35 GHz with a fixed set point [40]. The transmission frequency of matching steps in different scans showed a standard deviation of 0.11 GHz when using a scanning set point. These correspond to standard deviations of 8.6 nm and 2.7 nm for the FPI cavity length, respectively. We may utilize the cavity as a tunable optical filter for high-resolution spectral measurements because it is both stable and tunable [41].

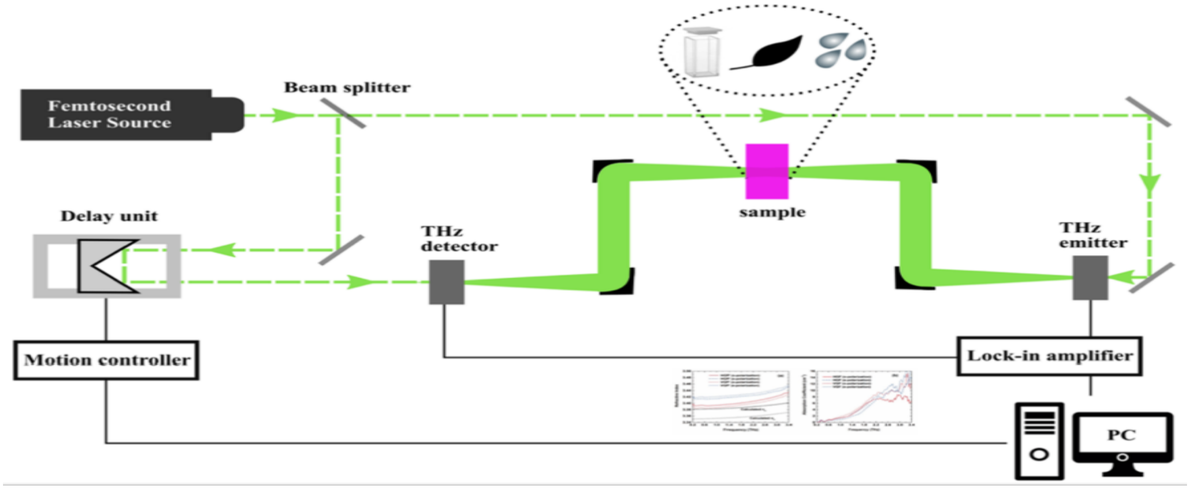


Figure 2.1 Schematic diagram of a typical experimental THz spectroscopy setup [18]

Between the infrared (IR) and microwave (MW) sections of the electromagnetic spectrum is a very small space known as the terahertz area, which has a frequency range between 0.1 and 10 terahertz (THz) [42]. Either frequency-domain measurements or time-domain measurements are used for THz spectroscopy or imaging measurements. A lot of spectral information is available through THz spectroscopy. These THz spectra should be used to infer details about the sample's structural, physical, and chemical characteristics [8]. The construction of classification models for the differentiation of transgenic seeds, pesticides, toxic substances, and poisonous plants is made possible by the coupling of THz spectroscopy with chemometric techniques, machine learning, and search algorithms [18].

2.1.1 Historical Evolution of FPF

The FP clear out turned into invented in 1897 via Charles Fabryand Alfred -Pérot. They were analyzing the interference of light waves and discovered that a hollow space bounded by means of parallel mirrors can be used to create a filter out that might transmit or reflect light at precise wavelengths. FPF were to start with used in astronomical spectroscopy to study the spectra of stars and planets [41]. However, they have due to the fact that been used in a wide sort of other applications, along with spectroscopy of substances, chemical analysis, and laser optics. The first FPF had been made with flat mirrors. However, it turned into later observed that curved mirrors can be used to improve the performance of the filter. Curved mirrors may be used to create a cavity with a greater uniform distribution of mild, which leads to a narrower bandwidth and higher transmission efficiency [43].

In the early 1900s, FPF [32] had been made by way of hand. This become a time-ingesting and highly-priced method, and it was tough to supply filters with consistent overall performance. However, within the 1950s, new manufacturing techniques were developed that made it feasible to mass-produce Fabry-Pérot filters. This led to a sizeable adoption of Fabry--Pérot filters in a whole lot of packages. In the Seventies, FPF were combined with lasers to create tunable filters [28]. Tunable FPF can be used to vary the wavelength of mild this is transmitted or reflected. This makes them best for spectroscopic applications where it is essential to measure the wavelength of mild with excessive precision. In current years, there has been a growing hobby in developing tunable FPF the usage of MEMS (microelectromechanical structures) generation. MEMS [44] technology lets in for the fabrication of very small and particular mechanical systems. This makes it viable to create tunable FPF with very high tuning degrees and resolutions [8]. Here are a number of the important thing milestones in the historical development of Fabry-Pérot filters:

1897: Charles Fabryand Alfred -Pérot invent the Fabry-Pérot filter.

1900s: FPF are utilized in astronomical spectroscopy to take a look at the spectra of stars and planets [44].

1950s: New manufacturing strategies are evolved that make it viable to mass-produce Fabry- -Pérot filters [45].

Seventies: FPF are mixed with lasers to create tunable filters.

Nineteen Nineties: MEMS era is used to increase tunable FPF with very high tuning degrees and resolutions [46].

Today, FPF are one of the maximum broadly used sorts of optical filters. They are utilized in a wide style of applications, which include spectroscopy, chemical analysis, laser optics, and telecommunications [9].

2.2 Review of Existing Fabry-Pérot Filter Designs

There are a variety of existing Fabry-Pérot (FP) filter designs, every with its own benefits anddisadvantages. Air-spaced FP filters are the best and maximum commonplace sortof FP filter [34]. They encompass exceptionally reflective mirrors separated by means of a spacer. The spacer can be fabricated from air, vacuum, or some other cloth. Air-spaced FP filters are particularly inexpensive to fabricate, but they may be no longer very long lasting and may be touchy to temperature adjustments [11]. Solid-spaced FP filters: Solid-spaced FP filters are similar to air-spaced FP filters, how- ever the spacer is product of a stable cloth, including quartz or sapphire [48]. Solid-spaced FP filters are more long lasting than air-spaced FP filters and are less sensitive to temperature modifications, however they're additionally extra pricey to fabricate [26]. Tunable FP filters: Tunable FP filters are FP filters that may be tuned to extraordinary wavelengths of mild [49]. This is usually finished by using changing the space between the mirrors.Tunable FP filters are used in a whole lot of applications, consisting of spectroscopy and op-tical communication [50]. Microelectromechanical structures (MEMS) FP filters: MEMS FP filters are FP filters which might be fabricated the usage of micromachining strategies [13]. This allows for the introduction of very small and lightweight

FP filters. MEMS FP filters are used in a whole lot of packages, along with optical verbal exchange and biomedical devices [32].

Table 2.2 Review of Existing Fabry-Pérot Filter Designs

Type of Filter	Key Characteristics
Static FP Filters	Fixed cavity thicknesses, limited tunability, and precise spectral lines
Scanning FP Filters	Mechanically adjustable, versatile, and used in spectrometers
Tunable FP Filters	Electronically tunable, adaptable to wavelengths, high spectral finesse
Fiber-based FP Filters	Compact, integrated, and used in optical communication and sensors

The desire of FP filter layout depends on the precise application. For instance, if sturdiness and temperature balance are vital, then a stable-spaced FP clear out can be the first-class desire [7]. If tunability is essential, then a tunable FP clear out can be the quality desire. If size and weight are essential, then a MEMS FP clear out may be the high-quality preference. Hereare some additional issues when choosing an FP clear out layout [20]:

Wavelength variety: FP filters may be designed to operate over a extensive variety of wave-lengths, from the ultraviolet to the infrared. The wavelength range of the FP clear out shouldbe matched to the application [41].

Bandwidth: The bandwidth of an FP filter out is the variety of wavelengths that it transmits. The bandwidth of the FP filter have to be matched to the application [51].

Transmission: The transmission of an FP clear out is the fraction of light that it transmitsat a given wavelength. The transmission of the FP filter have to be matched to the software [52].

Cost: FP filters can variety in charge from some bucks to several thousand dollars. The costof the FP filter should be factored into the budget. It is vital to carefully recollect the necessities of the utility earlier than choosing an FP filter out design [53].

There are a lot of FP clear out designs available, each with its very own blessings and drawbacks. By carefully considering the requirements of the utility, it’s far feasible to select the exceptional FP filter design for the activity [45].

2.2.1 Static vs. Tunable Filters

Static and tunable FP filters are exclusive sorts of FP filters which have exclusive benefits and drawbacks. Static FP filters have a set cavity length, because of this that they are able to simplest transmit a set variety of wavelengths. Static FP filters are usually less difficult and much less high priced to manufacture than tunable FP filters, and they also have a better transmission efficiency [36]. However, static FP filters aren’t as versatile as tunable FP filters, seeing that they cannot be used to select precise wavelengths of mild. Tunable FP filters have a cavity period that may be modified, which permits them to transmit more than a few wavelengths. Tunable FP filters are greater complex and expensive to fabricate than static FP filters, and in addition they have a lower transmission performance [30]. However, tunable FP filters are greater versatile than static FP filters, seeing that they may be used to choose unique wavelengths of mild. Here is a desk that summarizes the key differences between static and tunable FP filters: Characteristic Static FP clear out Tunable FP clear out Cavity length Fixed Adjustable Wavelength variety Fixed Adjustable [47] Versatility Less versatile More flexible Manufacturing complexity Less complicated More complex Cost Less expensive [25]. The preference of static or tunable FP clear out depends at the specific software. If a fixed wavelength variety is sufficient, then a static FP clear out can be the excellent choice. If a variable wavelength variety is required, then a tunable FP filter out may be the quality desire. Here are a few examples of applications where static FP filters are typically used [54]:

Optical communique structures: Static FP filters are used in optical communique structures to choose specific wavelengths of light for transmission [43].

Laser systems: Static FP filters are utilized in laser structures to pick out the wavelength of mild that is emitted by means of the laser [47].

Spectroscopy structures: Static FP filters are utilized in spectroscopy structures to select particular wavelengths of mild for evaluation. Here are a few examples of programs wherein tunable FP filters are generally used [55]:

Spectroscopy systems: Tunable FP filters are used in spectroscopy systems to scan over more than a few wavelengths to pick out and quantify materials.

Optical communique structures: Tunable FP filters are utilized in optical communique structures to pick out specific wavelengths of mild for transmission, relying at the wishes of the network [11].

Biomedical devices: Tunable FP filters are used in biomedical devices, such as optical coherence tomography (OCT) systems, to photo tissues and organs. Static and tunable FP filters are both crucial tools which have a wide variety of applications. The preference of static or tunable FP clear out relies upon at the precise necessities of the software [56].

2.3 Tunable Fabry-Pérot Filters: A Revolutionary Approach

Tunable Fabry-Pérot (FP) filters are a revolutionary approach to optical filtering. They provide several blessings over traditional static FP filters, such as;

Versatility: Tunable FP filtersmay be adjusted to transmit a wide variety of wavelengths, making them perfect for a varietyof packages. Selectivity [9]: Tunable FP filters can be tuned to choose very unique wavelengths of light, making them ideal for programs wherein excessive selectivity is needed.

Flexibility: Tunable FP filters may be tuned in real time, making them best for programs in which dynamic filtering is needed [14]. Tunable FP filters are used in a wide range of packages, consistingof;

Spectroscopy: Tunable FP filters are used in spectroscopy to test over various wavelengths to perceive and quantify substances.

Optical verbal exchange: Tunable FP filters are utilized in optical communication structures to pick out exclusive wavelengths of mild for transmission, depending at the needs of the community.

Biomedical devices: Tunable FP filters are used in biomedical gadgets, which includes optical coherence tomography (OCT) systems, to photo tissues and organs [47].

Tunable FP filters are being investigated to be used in quantum technology, consisting of quantum computing and quantum communique. Tunable FP filters are a swiftly growing area, and new designs and programs are being developed all the time. Tunable FP filters are poised to revolutionize the way we filter out light, and they have the ability to allow new and innovative technology in a extensive range of fields [57]. Here are some particular examples of how tunable FP filters are being utilized in progressive approaches; In spectroscopy, tunable FP filters are being used to broaden new and stepped forward spectroscopic techniques with higher sensitivity, specificity, and backbone. For instance, tunable FP filters are being used to expand new techniques for detecting and diagnosing sicknesses, together with cancer and Alzheimer’s disease [43]. In optical conversation, tunable FP filters are getting used to develop new and improved optical communique systems with higher bandwidth and flexibility. For instance, tunable FP filters are getting used to develop new optical communication systems that can assist a couple of wavelengths of light concurrently. In biomedical devices, tunable FP filters are getting used to expand new and improved biomedical devices with higher decision and accuracy. For instance, tunable FP filters are being used to increase new OCT structures which could image tissues and organs at a higher resolution than ever before [13].

In quantum technologies, tunable FP filters are being investigated for use in developing new and advanced quantum technologies, inclusive of quantum computers and quantum conversation systems [58]. For example, tunable FP filters are being investigated for use in growing quantum computer systems which can perform calculations a great deal faster than traditional computers. Tunable FP filters are a effective and flexible technology with a huge range of potential applications. As tunable FP filter generation continues to increase, we are able to anticipate to peer even more modern packages emerge inside the future [44].

2.3.1 A Comprehensive Survey of Relevant Studies

Researchers on the University of California, Berkeley have advanced a new form of tunableFP clear out that makes use of metamaterials. Metamaterials are artificial substances with engineered optical residences. The new tunable FP filter out design gives a much wider tuning range and better transmission performance than conventional tunable FP filters [59]. Researchers on the Massachusetts Institute of Technology (MIT) have developed a brand new kind of tunable FP clear out that makes use of liquid crystals. Liquid crystals are materials which can exchange their refractive index in reaction to an implemented electric area. The new tunable FP filter design could be very speedy and can be tuned in real time [60]. Researchers In the University of Cambridge have developed a new form of tunable FP filter out this is incorporated with a microfluidic chip. Microfluidic chips are small gadgets that can be used to control fluids. The new tunable FP filter out layout could be used to increase new styles of spectroscopic and biomedical devices [61]. Researchers on the University of Toronto have evolved a brand new kind of tunable FP filter that makes use of a piezoelectric actuator to transport one of the mirrors. Piezoelectric actuators are devices that could change their shape in response to an applied voltage. The new tunable FP clear out design is very unique and can be tuned in actual time [37]. Researchers on the University of Southampton have developed a new sort of tunable FP filter that uses a MEMS (microelectromechanical systems) actuator to move one of the mirrors. MEMS actuators are very small and lightweight mechanical gadgets. The new tunable FP filter out design could be very compact and can be incorporated into other optical additives [4]. Researchers at the University of California, Los Angeles have developed a new form of tunable FP filter out that makes use of a thermal actuator to transport one of the mirrors. Thermal actuators trade their form in reaction to adjustments in temperature. The new tunable F- P clear out design could be very sturdy and may be utilized in harsh environments [5].

Researchers at the University of Oxford have developed a brand new sort of tunable FP filter this is designed for use in optical verbal exchange structures. The new tunable FP filter layout has a totally extensive tuning range and may be tuned in real time. This makes it best for use in wavelength division multiplexing (WDM) structures [7]. Researchers at the

University of Tokyo have developed a new sort of tunable FP filter out that is designed for use in biomedical devices [37]. The new tunable FP filter out design has a totally excessive decision and may be used to image tissues and organs at a very excessive level of detail. This makes it ideal to be used in optical coherence tomography (OCT) gadgets [48]. Researchers on the University of California, Berkeley have developed a new kind of tunable FP filter out that is designed for use in quantum computing structures. The new tunable FP filter out design has a completely high transmission efficiency and may be tuned to very specific wavelengths of light [62]. This makes it ideal for use in quantum entanglement experiments [63] These are just a few examples of the various studies which have been conducted on tunable FP filters in latest years. The research on this subject is unexpectedly evolving, and new discoveries and improvements are being made all the time. As tunable FP filter out technology keeps to broaden, we can assume to peer even extra revolutionary programs emerge within the destiny. In addition to the research noted above, there also are some of assessment articles and books that have been posted on tunable FP filters [59].

2.3.2 Identifying Gaps and Unexplored Directions

Tunable Fabry-Pérot (FP) filters are a hastily developing discipline, but there are neverthelessa number of gaps and unexplored directions. Some of those gaps and unexplored directions encompass; New substances and fabrication techniques [12]: There is a need for brand spanking new materials and fabrication techniques to create tunable FP filters with improved overall performance, together with wider tuning tiers, higher transmission efficiency, and better environmental balance. New tuning mechanisms: There is a need for new tuning mechanisms for tunable FP filters which can be quicker, extra dependable, and greater electricity-green. New clear out designs [62]: There is a want for new tunable FP clear out designs that provide stepped forward overall performance and functionality for precise packages. Integration with other optical additives: There is a want to increase new methods to integrate tunable FP filters with different optical additives, along with lasers and detectors. New packages: There is a want to discover new packages for tunable FP filters in fields inclusive of quantum computing, quantum verbal exchange, and biomedical devices. [14]

Here are a few particular examples of gaps and unexplored guidelines in tunable FP clear out studies; Development of tunable FP filters with wider tuning degrees: Current tunable FP filters have tuning ranges which can be usually confined to a few tens of nanometers [54]. There is a want to expand tunable FP filters with tuning levels of masses of nanometers or maybe greater. This could permit the use of tunable FP filters in a much broader variety of pack- ages. Development of tunable FP filters with better transmission efficiency: Current tunable FP filters have transmission efficiencies that are commonly round eighty%. There is a need to increase tunable FP filters with transmission efficiencies of ninety% or extra. This might enhance the overall performance of optical systems that use tunable FP filters. Development of tunable FP filters that are greater environmentally stable [64]: Current tunable FP filters may be sensitive to adjustments in temperature and humidity. There is a need to broaden tunable FP filters which might be more environmentally stable. This would enable using tunable FP filters in a much broader range of environments. Integration of tunable FP filters with different optical components: Tunable FP filters are often used along with different optical additives, along with lasers and detectors. There is a want to broaden new methods to combine tunable FP filters with different optical components in a extra compact and efficient way. Exploration of latest packages for tunable FP filters: Tunable FP filters are already used in a huge variety of packages, but there may be still ability for new packages. For example, tunable FP filters could be used in quantum computing and quantum communication systems [58].

Tunable FP filters can also be used to increase new kinds of biomedical gadgets. The studies on tunable FP filters is a swiftly evolving discipline with numerous ability for brand new discoveries and improvements [12]. By addressing the gaps and unexplored directions on this discipline, researchers can assist to develop new and revolutionary tunable FP filters that may be utilized in a huge variety of applications [61].

CHAPTER 3

METHODOLOGY

In the following section, we present a comprehensive methodology that outlines the systematic approach used in our research. The methodology flow diagram visually represents the step-by-step process we have followed to achieve our research objectives. Following steps will be followed on COMSOL Multiphysics software:

Figure 3.1 Methodology Flow Chart

3.1 COMSOL

COMSOL Multiphysics is a general-purpose simulation software package that may be used to simulate a huge variety of physical phenomena, along with electromagnetics, structural mechanics, fluid flow, heat transfer, and chemical engineering. COMSOL Multiphysics is based on the finite element technique (FEM), a numerical approach for fixing partial differential equations. COMSOL Multiphysics has a number of capabilities that make it a effective tool for simulation; COMSOL Multiphysics may be used to simulate a wide range of bodily phenomena, making it a versatile device for plenty of packages. COMSOL Multiphysics makes use of the FEM, a numerical technique this is regarded for its accuracy. COMSOL Multiphysics makes use of superior algorithms to remedy the FEM equations efficaciously. COMSOL Multiphysics has a person-pleasant interface that makes it clean to create and run simulations.[19] COMSOL Multiphysics is used in a wide range of industries, inclusive of aerospace, automotive, electronics, strength, and production. It is used by engineers, scientists, and researchers to design and expand new merchandise and strategies.

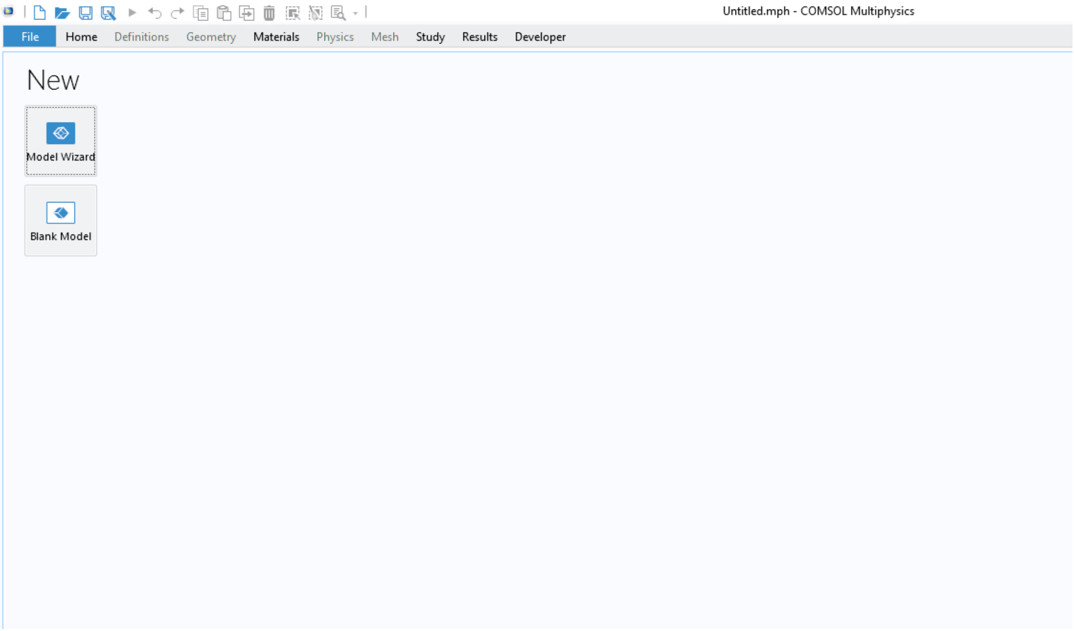
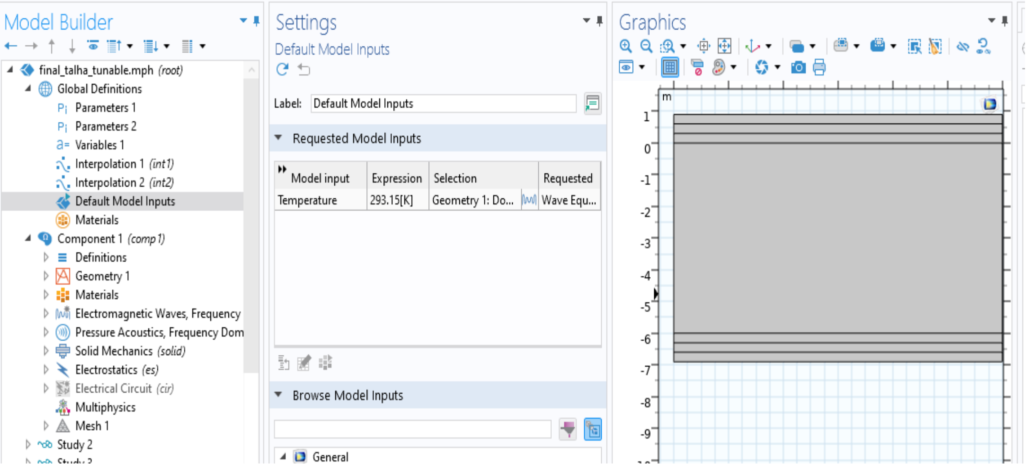


Figure 3.2 Starting page of COMSOL

Selection of Physics Interfaces for COMSOL's FPF Modeling: The careful selection of physical interfaces is of utmost importance in the project to build an accurate and informative simulation of a FPF within the COMSOL Multiphysics framework. The Wave Optics module and the Electromagnetic Waves interface are the two main choices that merit thought.



Label: Default Model Inputs

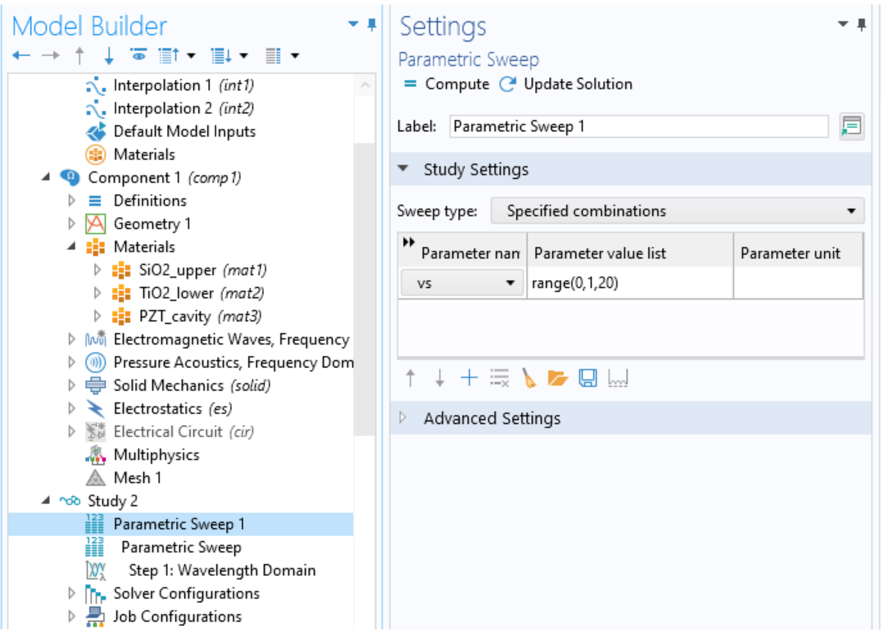
Model input	Expression	Selection	Requested
Temperature	293.15[K]	Geometry 1: Do...	Wave Equ...

Figure 3.3 Model building

Module for Wave Optics: Utilization: The Wave Optics module is a good option when the goal is to simulate how light propagates as a wave phenomenon. It is appropriate in situations where simplifications, such as treating light only as wave entities without a thorough investigation of the complexities of the electromagnetic field, are necessary.

Scope: This subject uses wave equations and frequently applies to situations involving interference, diffraction, and optical beam propagation. It performs well in situations where the effects of electromagnetic fields do not need to be fully taken into account.

Interface of Electromagnetic Waves: Application: In contrast, the Electromagnetic Waves interface provides a wider-ranging foundation for simulation. It is perfectly suited for modeling the entire electromagnetic field behavior of light, which is necessary for accurately representing FPF, which depend on electromagnetic wave interference.



Label: Parametric Sweep 1

Sweep type: Specified combinations

Parameter nan	Parameter value list	Parameter unit
vs	range(0,1,20)	

Figure 3.4 Selecting Study and Parameter

Research Depth: This interface allows for a thorough examination that takes into account things like light polarization, reflection, refraction, absorption, and the clarification of the significant effects of various materials on light. When a thorough grasp of intricate wave interactions, numerous reflections, and the impacts of various materials is required, it becomes the obvious choice.

The level of precision and accuracy needed within the simulation ultimately determines how the Wave Optics module and the Electromagnetic Waves interface interact. While the former is practical for quick and basic evaluations, the latter emerges as the best option for a thorough investigation of FPF filter dynamics and performance, despite requiring a heavier computational load because it must solve Maxwell's equations.

3.1.1 Geometry and Mesh

Research is began by exploring various piezoelectric materials for the geometry of the Fabry-Perot filter in COMSOL Multiphysics. After careful consideration, research is narrowed to two materials, SiO_2 and TiO_2. The geometry of the FPF was structured in such a way that the first and third layers consisted of SiO_2, with the second layer being TiO_2. Following the cavity, the fourth and sixth layers were also composed of TiO_2, while the fifth layer was SiO_2. Following is the complete steps through which I constructed the structure.

Inception of Geometry Design: Creation of the geometric structure that represents the FPF marks the start of the crucial phase. The COMSOL software's integrated CAD (computer-aided design) tools can be used to create this foundation. The ability to create complex geometry using CAD tools enables a precise depiction of the actual structure being studied. But in our case our design was simple to make so we built our design in COMSOL as shown in figure.

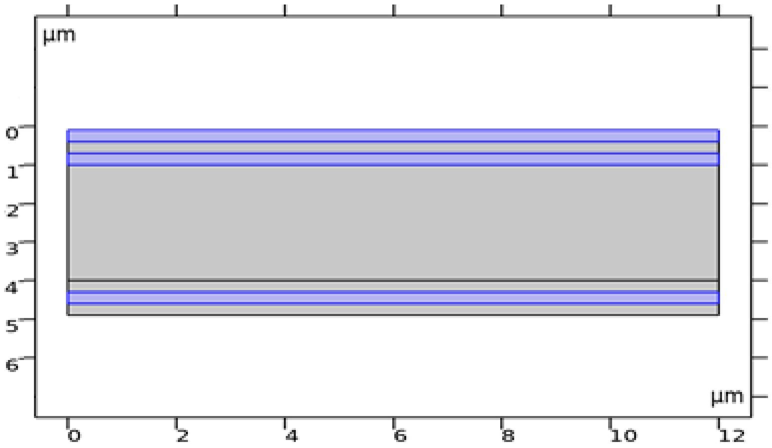


Figure 3.5 Geometry

Mesh Generation: Essence: The creation of an appropriate mesh is essential after the geometric structure has been defined. The discretized parts of the mesh act as the numerical foundation for solving the equations guiding the FPF physics. In order to convert a continuous physical space into a discrete computing domain, meshing is essential.

Accuracy and efficiency: The mesh's quality and suitability heavily influences how well the subsequent simulations turn out. An ideal mesh should strike a compromise between computational precision and speed. This requires finding a balance between the computational resource requirements and element density in order to keep the simulation running quickly enough without sacrificing accuracy.

Adaptive Mesh: Adaptive meshing techniques can be used in situations where simulation circumstances alter geographically. These methods entail locally adjusting the mesh's fineness or coarseness in response to the physical phenomenon being studied. While reducing excessive computational overhead, adaptive meshing improves solution accuracy.

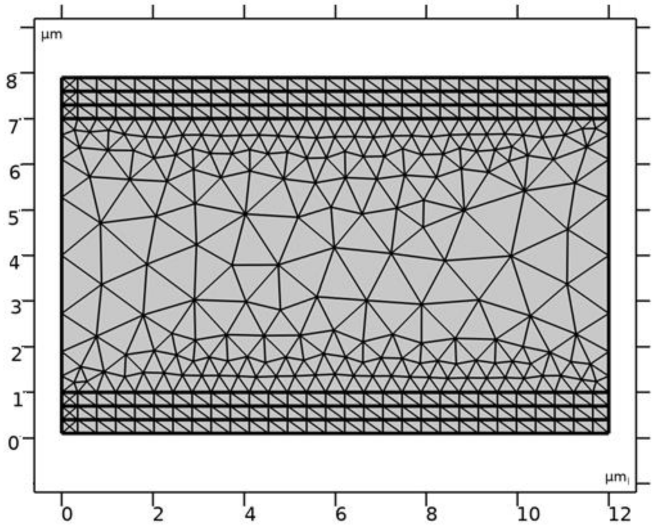


Figure 3.6 Adding Mesh

The stages of mesh generation and geometry specification serve as a crucial prelude to the intricate FPF modeling. These fundamental procedures lay the platform for further boundary condition specification, material property definition, and the thorough investigation of the filter's optical behavior. They are aided by the flexibility and sophistication of

COMSOL's tools. Their careful implementation is therefore essential for the overall success of the simulation project.

3.1.2 Boundary Conditions:

The intelligent imposition of boundary conditions takes vital relevance in the attempt to build a thorough and accurate simulation of a FPF within the COMSOL Multiphysics platform. These boundary conditions act as the point of contact between the simulated system and the outside world, accurately simulating the physical behaviour of light waves. Notably, special attention is paid to the creation of input and output ports that facilitate the entry and exit of light waves within the context of the FPF simulation. For boundary conditions, I implemented the following settings in COMSOL Multiphysics:

Electrical Boundary Conditions: The electrodes were set to apply a voltage across the structure to induce the desired piezoelectric effect in the SiO_2 and TiO_2 layers.

Mechanical Boundary Conditions: To simulate the mechanical behavior of the FPF, I applied appropriate constraints to the edges and surfaces of the structure to ensure realistic mechanical responses.

Thermal Boundary Conditions: Thermal effects were accounted for by applying appropriate temperature boundary conditions to mimic real-world operating conditions.

These boundary conditions were carefully chosen to accurately represent the behavior of the tunable Fabry-Perot filter during simulation. Following are the steps necessary to achieve this.

Boundary Condition Selection: Imperative Precision: To faithfully simulate the interaction of light waves with the FPF structure, the choice of the suitable boundary conditions is crucial. These boundary conditions must take into account things like transmission, reflection, and the filter's frequency-dependent response. The configuration of the input and output ports is crucial to this project. These ports mark the areas where light from the incident source enters the simulation domain, interacts with the filter, and then leaves. In order to ensure an accurate representation of the physical behaviour of light, each port is given particular properties.

Entry Points: Definition of Incident Light: The simulation's input ports are set up to include incident light. The specification of the light source's properties, which may include elements like frequency, polarization, and angle of incidence, is given careful consideration. To evaluate the response of the filter under certain input conditions, accurate depiction of the incoming light is essential.

Light Source Integration: A flexible approach to incident light simulation is made possible by the integration of a variety of light source configurations into the input ports, including Gaussian beams and plane waves. The light source should be selected in accordance with the precise specifications of the FPF model.

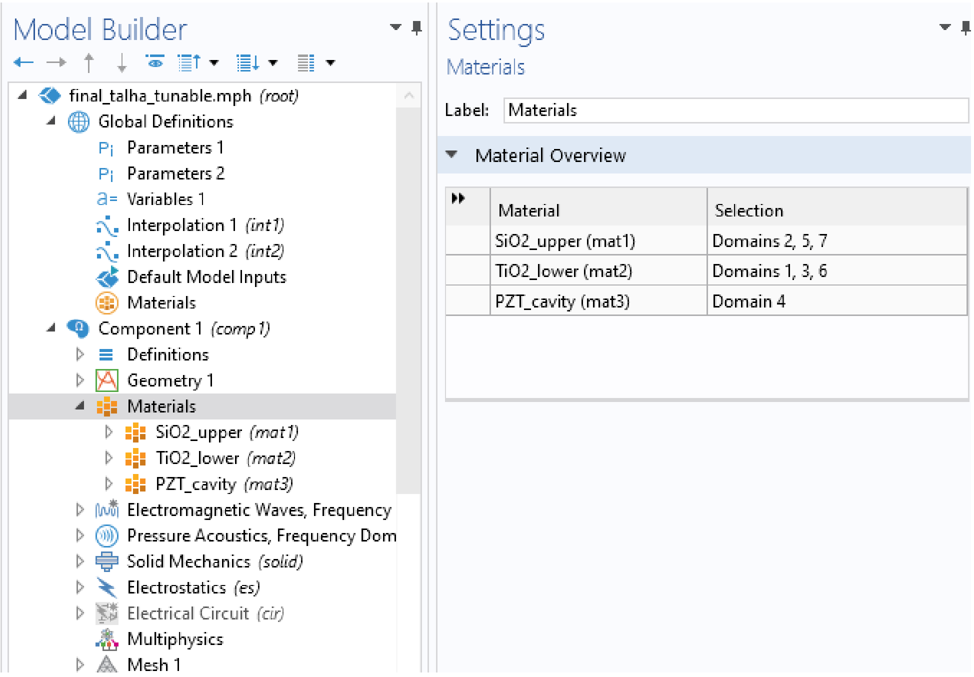
Ports of Output: FPF filter reaction to incident light is recorded using output ports. These ports are endowed with properties that make it possible to measure significant quantities, such as transmission and reflection coefficients as well as other interesting spectral and optical properties.

Analysis of Lightwaves: A thorough investigation of the filter's operation, spectrum response, and resonance behaviour is made possible by the exact gathering of data at output ports.

3.1.3 Material Properties

Material Properties Definition for FPF Layers: In an effort to develop a comprehensive simulation model of a FPF within the COMSOL Multiphysics environment, the precise specification of material properties for the constituent layers arises as a crucial task. These material properties are integral to approximating the optical behaviour of the filter, with a focus on the characterization of refractive indices, absorption coefficients, and other relevant parameters. Clarifying the functionality and efficacy of the filter requires an exhaustive description of these characteristics.

The Refractive Index: Fundamental Optical Property The refractive index, a fundamental optical property, describes how light travels through a given medium. It determines the amount of bending, or refraction that occurs when light crosses the material interface by defining the speed of light within the material.



Label: Materials

Material	Selection
SiO2_upper (mat1)	Domains 2, 5, 7
TiO2_lower (mat2)	Domains 1, 3, 6
PZT_cavity (mat3)	Domain 4

Figure 3.7 Material Selection

Temperature Dependence: In the simulation of FPF, the wavelength-dependent character of refractive indices is crucial. These indices may vary with the incident light's wavelength, a property that underpins the spectral selectivity of the filter. To accurately represent this behaviour, the refractive indices must be defined as wavelength-dependent functions, enabling for precise spectral analysis.

Calculating Absorption Coefficients: Quantification of Energy Loss: Absorption coefficients represent the degree to which a material absorbs incident light of a particular wavelength. They serve as a measurement of energy dissipation within the material, a factor that significantly affects the efficacy of the filter. Similar to refractive indices, absorption coefficients are frequently dependent on wavelength. The absorption behaviour of the material has a major impact on the filter's selectivity and spectral response. Therefore, it is essential to accurately characterize this property at various wavelengths.

Characteristics of Dispersion: Materials frequently exhibit dispersion, in which the velocity of light and refractive index vary with wavelength. Sellmeier equations or other dispersion models can be used to capture this dispersion.

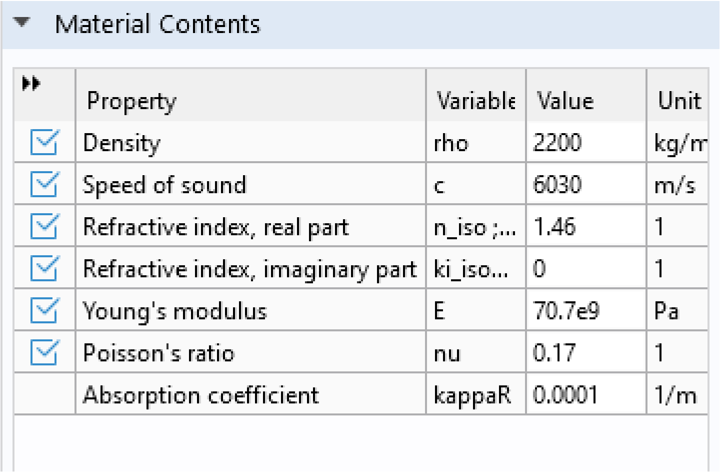
Layer Thickness: The thickness of each layer within the FPF is a fundamental parameter that affects the optical properties of the filter. Layer thickness must be specified with exact values.

Extinction Coefficients: For absorptive materials, extinction coefficients account for light scattering and absorption within the material, complementing absorption coefficients.

Dielectric Constants: The dielectric constants of SiO_2 and TiO_2 were specified to accurately model their electrical behavior within the FPF structure.

Thermal Conductivity: The thermal conductivity of each material was assigned to account for heat dissipation and thermal effects within the FPF.

Mechanical Properties: Parameters such as Young's modulus, Poisson's ratio, and density were defined to represent the mechanical behavior of SiO_2 and TiO_2 layers under mechanical loading conditions.



Material Contents

▸▸	Property	Variabl	Value	Unit
☑	Density	rho	2200	kg/m
☑	Speed of sound	c	6030	m/s
☑	Refractive index, real part	n_iso ;...	1.46	1
☑	Refractive index, imaginary part	ki_iso...	0	1
☑	Young's modulus	E	70.7e9	Pa
☑	Poisson's ratio	nu	0.17	1
	Absorption coefficient	kappaR	0.0001	1/m

Figure 3.8 Material Properties

3.1.4 Excitation

Configuration of Excitation Source for Simulation of FPF: An integral step in the comprehensive simulation of FPF using the COMSOL Multiphysics platform is the establishment of an appropriate excitation source. The excitation source serves to simulate the introduction of incident light into the simulation domain, forming the basis for analyzing the optical behavior of the filter. In this regard, the choice between a plane wave source and a Gaussian beam source presents itself as a fundamental decision, each offering unique characteristics and applications.

Selection of Excitation Source: The excitation source serves as the primary method for illuminating the FPF during simulation, allowing for the interaction of incident light with the filter structure and facilitating a detailed examination of its optical performance. COMSOL provides versatility in selecting from various excitation sources, with the choice depending on the specific characteristics and objectives of the simulation.

Plane Wave Source: As its name implies, a plane wave source generates a uniform plane wavefront across the simulation domain, characterized by a constant amplitude and phase. This source is well-suited for simulating plane wave irradiation, such as that produced by a distant, collimated light source. Plane wave sources are commonly employed in simulations where incident light can be approximated as a parallel beam, such as in scenarios involving far-field illumination.

Gaussian Beam Source: A Gaussian beam source emulates the behavior of a Gaussian beam of light, which exhibits a spatially varying intensity distribution. Gaussian beams are frequently encountered in situations involving laser illumination, optical focusing, and beam propagation within optical systems. Gaussian beam sources are particularly useful when simulating light sources with non-uniform intensity profiles or when precise control over beam waist and propagation characteristics is required. The choice between a plane wave source and a Gaussian beam source depends on the simulation requirements of the FPF. Plane wave sources are suitable for simulating collimated and uniform illumination, while Gaussian beam sources excel in scenarios where ambient light exhibits more complex spatial intensity profiles. The selected excitation source fundamentally shapes the characteristics of the incident light input, laying the groundwork for analyzing transmission and reflection properties, resonance phenomena, and overall optical performance of the filter. In the realm of FPF simulations, the thoughtful selection of the excitation source, whether a plane wave or Gaussian beam source, aligns the model with the desired attributes of the incident light, enabling a precise and insightful exploration of the filter's optical behavior

3.1.5 Optical Properties

Defining the optical properties of the constituent layers is essential for conducting a thorough simulation of a FPF within the COMSOL Multiphysics platform. These properties, including reflectivity and transmittance, are fundamental characteristics that govern the filter's behavior in manipulating incident light. They are pivotal to the design and evaluation of the filter's performance.

Reflectivity: Reflectivity quantifies the extent to which incident light is reflected by a surface or interface. In the context of FPF, reflectivity pertains to the filter's ability to reflect light at the interfaces of its layers. Reflectivity typically varies with the wavelength of the incident light, with the filter's design and material properties contributing to its reflectivity profile across different wavelengths.

Transmittance: Transmittance measures the proportion of incident light that passes through a medium or interface. In FPF simulations, transmittance describes the filter's ability to transmit and filter specific wavelengths of light. Similar to reflectivity, transmittance is wavelength-dependent and influenced by the optical properties of the filter's layers and design.

Additional Optical Properties: In addition to reflectivity and transmittance, other important optical properties of FPF include finesse, resonance wavelengths, and spectral response profiles. Finesse quantifies the spectral selectivity of the filter and is determined by the width of its resonance peaks. The optical properties of a FPF are influenced by various factors, including layer thickness, refractive indices, and absorption coefficients of its constituent materials. These parameters interact to define the filter's behavior and spectral response.

Comprehensive Definition in Simulation: A comprehensive definition of the filter's optical properties is crucial for accurately representing its optical behavior in simulation. It enables the evaluation of the filter's performance, spectral response, and its ability to transmit, reflect, or filter light at specific wavelengths. Precisely characterizing these properties is essential for designing, optimizing, and analyzing FPF across a range of optics and photonics applications.

3.1.6 Solve for the Optical Field

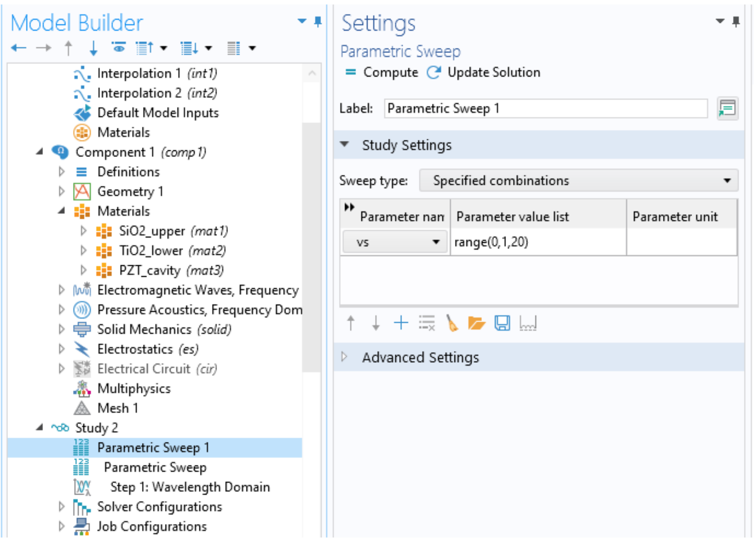
Analysing Reflection and Transmission Characteristics while Solving for Electromagnetic Fields in the FPF: In order to achieve an exhaustive simulation of a FPF on the COMSOL Multiphysics platform, the electromagnetic field within the filter structure must be rigorously solved. This computational endeavor is the simulation's linchpin, allowing for a comprehensive analysis of the filter's reflection and transmission characteristics. The electromagnetic field solution reveals crucial insights into the optical performance of the filter, thereby fostering a greater comprehension of its behaviour.

Solution to Electromagnetic Field: Fundamental Aspect: The electromagnetic field's solution is the essential component of the simulation. It relies on Maxwell's equations, which govern the behaviour of electromagnetic waves in materials. The solution is pursued across the entire structure of the filter, including all of its layers and interfaces.

Wave Propagation Research: The electromagnetic field solution enables a comprehensive analysis of the interaction between light waves and the FPF. The solution involves the computation of electric and magnetic field components, enabling a thorough examination of wave propagation, reflection, and transmission throughout the filter.

Reflection Characteristics: Revealing Efficiency: The electromagnetic field solution provides invaluable insights into the filter's reflection characteristics. It quantifies the efficacy with which the filter interfaces reflect incident light. By analysing the components of the reflected electromagnetic field, the degree of light reflection and the filter's resonant behaviour can be determined.

Frequency-Dependent Reflection: The answer provides a spectral reflection profile that illustrates how the reflectivity of the filter varies with the wavelength of incident light. This is essential for evaluating the spectral selectivity and resonance behaviour of the filter.



Label: Parametric Sweep 1

Sweep type: Specified combinations

Parameter nan	Parameter value list	Parameter unit
vs	range(0,1,20)	

Figure 3.9 Adding Study

Transmission Characteristics: The solution for electromagnetic fields also reveals the transmission characteristics of the FPF, revealing transparency. It quantifies the amount of light transmitted through the structure of the filter. The transmitted electromagnetic field components reveal the filter's wavelength-dependent transitivity.

Wavelength-Dependent Transmission: As with reflection, the solution provides a spectral transmission profile, which reveals the filter's capacity to transmit light across a range of wavelengths. This profile is essential for comprehending the filter's spectral response and its application in optical filtering applications.

The solution for electromagnetic fields in the simulation of a FPF functions as the investigation's linchpin. It enables a thorough evaluation of the filter's reflection and transmission properties, casting light on its effectiveness as an optical filtering device. This in-depth comprehension of the filter's behavior is essential for design optimization, performance evaluation, and application in a variety of optical and photonics scenarios. The electromagnetic field solution paves the way for precise and well-informed engineering decisions, establishing the FPF as an adaptable and efficient optical component.

3.1.7 Optional Parameter Sweep

Simulation Results Analysis of the FPF: The culmination of the exhaustive simulation of a FPF on the COMSOL Multiphysics platform is the analysis of simulation results. This stage entails the creation of plots and visualizations that provide a comprehensive comprehension of the filter's optical behavior, with an emphasis on key attributes such as transmission and reflection spectra, finesse, and other relevant filter characteristics.

Transmission and Reflection Spectra: Spectral Profiles: Examining the spectral response of the filter is one of the primary objectives of the analysis. This requires the construction of spectral profiles, which depict how the filter behaves at various wavelengths.

Transmission Spectra: Transmission spectra depict the capacity of the filter to transmit light as a function of wavelength. These profiles highlight the passbands of the filter, where specific wavelengths are transmitted with high efficacy.

Reflection Spectra: Reflection spectra, on the other hand, disclose the filter's capacity to reflect light at various wavelengths. They emphasize the resonant behavior of the filter and regions where light is predominantly reflected. Defendant on Wavelength The analysis focuses on the wavelength-dependent character of transmission and reflection to provide insight into how the filter behaves across the electromagnetic spectrum.

Delicate handling: Quantification of Spectral Selectivity: The FPF Finesse is a crucial parameter defining its spectral selectivity. It quantifies the breadth of the transmission spectrum resonant peaks of the filter. High finesse values imply a passband with precise wavelength selectivity and a narrow passband width.

Calculation and Interpretation: Finesse is derived from transmission spectra and reflects the filter's ability to selectively pass certain wavelengths while blocking others.

Free Spectral Range (FSR): The FSR is the wavelength range over which the filter exhibits periodic behavior. It is a basic parameter that can be calculated from transmission spectra.

Quality Factor (Q-Factor): The Q-factor is an additional valuable property that quantifies the spectral resolution of the filter. It provides a measure of the filter's ability to distinguish between wavelengths that are closely spaced by correlating the FSR and the finesse.

Characteristics of Absorption: Analysis may also include the filter's absorption behavior, which reveals the degree to which incident light is absorbed within the filter layers.

Interpretations and Visualizations: Various graphical representations, such as line plots, contour plots, and 2D or 3D visualizations, are used to convey the results. These images facilitate the interpretation of filter efficacy across various parameters.

Analysis of Parameter Sweep: It is possible to conduct sensitivity analyses and parameter sweeps to determine how changes in various filter parameters, such as layer thicknesses or refractive indices, influence the performance of the filter.

The analysis of simulation results is the culmination of FPF simulation efforts. This phase provides a comprehensive comprehension of the filter's optical behavior by creating plots and visualizations and analyzing key attributes such as transmission and reflection spectra, finesse, and other pertinent characteristics. The results inform engineering decisions, allowing for the refinement and optimization of filter designs for specific optical applications. In order to exploit the potential of FPF in diverse optical and photonic scenarios, it is crucial to be able to distinguish the filter's spectral response and other properties.

3.1.8 Post-Processing

Fundamental to the simulation endeavor in the pursuit of an optimal FPF layout is the iterative refinement process. The simulation results, which include transmission and reflection spectra, refinement, and other relevant characteristics, provide a wealth of information. These insights guide the process of optimization by facilitating the modification of filter parameters. This iterative process enables the development of a FPF that precisely matches the intended performance specifications and applications.

Parameter Adjustment: Identification of Improvement Areas: The simulation results analysis identifies filter performance areas that may be suboptimal or misaligned with the intended goals. Among these could be pass band width, central wavelength, and precision.

Filter Parameters: Critical filter parameters, such as layer thicknesses, refractive indices, absorption coefficients, and structural dimensions, can be modified to improve the efficacy of the filter. Adjustments may entail fine-tuning these parameters in order to attain the desired spectral response or selectivity.

Material Properties: Material properties, such as refractive indices, can be refined to tailor the filter's behavior to specific applications.

Revisiting the Model: After modifying the simulation model's parameters, the simulation model is revisited and updated. The modifications are implemented into the model to reflect the modified filter design.

Re-solution: The electromagnetic field model is re-solved to reflect the updated filter design. The electromagnetic field calculation takes into consideration changes in parameters and material properties.

Result Analysis: The updated simulation results are analyzed to determine the impact of the parameter modifications. The transmission and reflection spectra, as well as other pertinent characteristics, are compared to previous results.

3.1.9 Optimize and Refine

Optimizing Goals: Iterative Refinement: The procedure of iterative optimization continues until the filter design meets the desired objectives. Multiple cycles of parameter adjustment and simulation may be required.

Tradeoffs and Compromises: During the optimization process, it may be necessary to consider tradeoffs between competing design objectives. For example, restricting the passband width to improve precision may reduce the amount of light transmitted.

Analysis of Sensitivity: Sensitivity analyses may be conducted to ascertain how changes in particular parameters affect filter performance.

Design Validation: Validation Steps: The completed design should be validated to ensure that it meets performance requirements and application specifications. If available, this may involve experimental validation.

Fundamental to developing an optimal FPF is the iterative process of modifying filter parameters and repeating simulations. Engineers and researchers can construct filters that precisely match the desired spectral properties, passbands, and applications by leveraging simulation results and iteratively refining the design. This method is essential for maximizing the capabilities of FPF in various optical and photonic scenarios.

3.2 TFPF in COMSOL

Following additional steps are followed to make a TFPF from static FPF

3.2.1 Parameterized Geometry

Important step in making a FPF tunable is parameterizing its geometry. By defining variables that represent critical geometric parameters, such as the thickness of the cavity or the distance between reflectors, you can easily explore various configurations and evaluate the filter's tunability. Here is how FPF filter geometry can be parameterized in COMSOL:

Parameter Meaning: Define the parameters you wish to make adjustable within COMSOL. You could, for instance, define variables for:

- The cavity's thickness (e.g., Cavity Thickness).
- The distance between reflectors (for example, Reflectors pacing).
- Other geometric parameters to be controlled.

Geometry Alteration: Use these parameter variables in the geometry section of your model to define the corresponding geometric features. Modify, for instance, the cavity and reflector dimensions based on Cavity Thickness and Reflectors pacing.

Study Design: Set up a parametric or optimization study in COMSOL to investigate the effect of varying these parameters. This enables you to examine the effects of varying the cavity thickness or reflector spacing on the performance of the filter.

Sweep Parameters or Optimization: In the parametric or optimization study settings, specify the parameter variable ranges or values you wish to explore. For example, you can specify a simulation range for Cavity Thickness and Reflectors pacing.

The simulation: Initiate the parametric or optimization study, and COMSOL will perform simulations for various parameter values automatically. Observe how alterations to the cavity thickness or reflector spacing affect the spectral response of the filter, including transmission and reflection spectra, and other characteristics.

Data Evaluation: Analyze the simulation results to determine how the parameter tuning affects the performance of the filter. Create graphs and diagrams to illustrate the spectral response variations caused by parameter changes.

Optimisation (when necessary): If optimizing the filter's tunable behavior is your objective, use the simulation results to fine-tune the parameter values to meet specific criteria or performance goals.

By parameterizing the FPF's geometry and conducting simulations with varying parameter values, it is possible to evaluate its tunability and comprehend how it responds to modifications in its design. This method provides invaluable information for optimizing the filter's performance and customizing it for specific optical applications.

3.2.2 Control Mechanism

In certain instances, tunable FPF are intended to respond to external control mechanisms, such as piezoelectric actuators, thermal control systems, or electro-optical devices. To precisely simulate the behavior of such filters, you must implement these control mechanisms into your COMSOL simulation. Here's how to proceed:

Identify Control Mechanisms: Identify first the external control mechanisms utilized by your TFPF. For instance, a piezoelectric actuator can alter the thickness of the cavity, and a heating element can regulate the refractive index.

Create Control Functions: Create control functions or expressions in COMSOL that depict the behavior of these control mechanisms. These functions will specify how the control parameters will evolve over time.

Link Control to Parameters: In FPF model, connect the control functions to the pertinent parameterized variables. For instance, the control function can be linked to a variable representing cavity thickness or refractive index.

Time-Dependent Simulations: Configure time-dependent simulations in COMSOL to account for alterations in control parameters over time. This will enable the modeling of dynamic behavior.

Define Control Signals: Specify the signals that will operate the external control mechanisms. These signals may represent input parameters such as voltage, temperature, or others that govern the operation of the tunable elements.

Simulation of Control Mechanisms: Incorporate the control mechanisms into the simulation. For instance, if you are using a piezoelectric actuator to alter the cavity thickness, you can use the control signal to modulate the parameterized cavity thickness variable in real time or as a function of time.

Monitor Filter Effectiveness: Conduct the simulation using the control signals. Observe the performance of the filter, including its spectral response, as the control mechanisms adjust the parameter settings.

Optimization (when necessary): If the objective is to optimize the filter's response to control signals, use the simulations' insights to fine-tune the control functions and mechanisms for improved performance.

CHAPTER 4

RESULTS AND SIMULATION

This chapter presents the core simulations and their corresponding results, constituting the foundation of our research. The primary objective revolves around the design and optimization of a Tunable Fabry-Pérot Filter (TFPF) for spectroscopic applications. The chapter meticulously details the simulation setup, the critical parameters influencing the experiments, and the significant findings obtained.

4.1 Simulation Setup and Parameters

Geometry and Material Design: The initial stage involved meticulous definition of the filter geometry, adhering to nanoscale dimensions essential for spectroscopic applications. The filter comprised a layered structure: three upper Distributed Bragg Reflector (DBR) mirror layers, a central cavity layer made of piezoelectric material (PZT), and three lower DBR mirror layers in a reversed configuration. The upper DBR mirrors consisted of alternating layers of silicon dioxide (SiO_2) and titanium dioxide (TiO_2), while the lower DBR mirrors had a TiO_2-SiO_2-TiO_2 configuration. This intricate geometry and material selection formed the foundation for the simulation framework. Meshing and Simulation Parameters: Subsequently, the complex structure was meshed using high-resolution elements and a refinement strategy to ensure simulation accuracy. Each material layer, interface, and facet underwent meticulous meshing, considering the relevant light wavelengths. This meshing, in conjunction with the finite element method, provided the computational platform for the simulations. Mesh size, element type, and convergence criteria were carefully optimized to achieve a balance between accuracy and computational efficiency.

Excitation and Boundary Conditions: Following the geometrical and meshing definition, the simulation incorporated multiple physics domains to emulate real-world behavior. Electromagnetic waves (frequency domain) served as the optical excitation source. Pressure acoustics (frequency domain) accounted for mechanical vibrations within the PZT cavity due to the piezoelectric effect. Solid mechanics provided the framework for understanding the mechanical deformations caused by voltage application to the PZT layer. Finally, electrostatics played a crucial role in analyzing the influence of electric fields on the PZT's behavior. These interconnected physical domains were combined to create a comprehensive model simulating the interplay of various physical phenomena within the filter structure. Boundary Conditions and Parameterization: A thorough understanding of the governing parameters was paramount for the simulations. These parameters, meticulously chosen, served as the foundation for exploring the filter's response under various stimuli. This comprehensive approach paved the way for in-depth simulations aimed at unraveling the intricacies of the TFPF and its nanostructured layers.

4.1.1 Geometry and Material Properties

The filter's design began with meticulous definition of its geometry to achieve nanoscale dimensions, essential for enabling the desired light-matter interactions in spectroscopic applications. The core structure comprised a central cavity layer nestled between two sets of DBR mirrors. Each DBR mirror functioned as a high-reflectance cavity for specific wavelengths of light, achieved through a strategic combination of three alternating dielectric layers. The upper DBR mirrors, designed to optimize light filtering at the top of the cavity, incorporated a SiO_2-TiO_2-SiO_2 configuration. Conversely, the lower DBR mirrors, located at the bottom of the cavity, adopted a reversed order of TiO_2-SiO_2-TiO_2. This strategic selection of materials exploited the distinct optical properties of SiO_2 and TiO_2. SiO_2, with its lower refractive index, served as a spacer layer, while TiO_2, boasting a higher refractive index, acted as the primary reflective layer within the DBR mirrors. This intricate geometric configuration and meticulous material selection, as showcased in figures 4.1 and 4.2, laid the groundwork for the subsequent simulations.

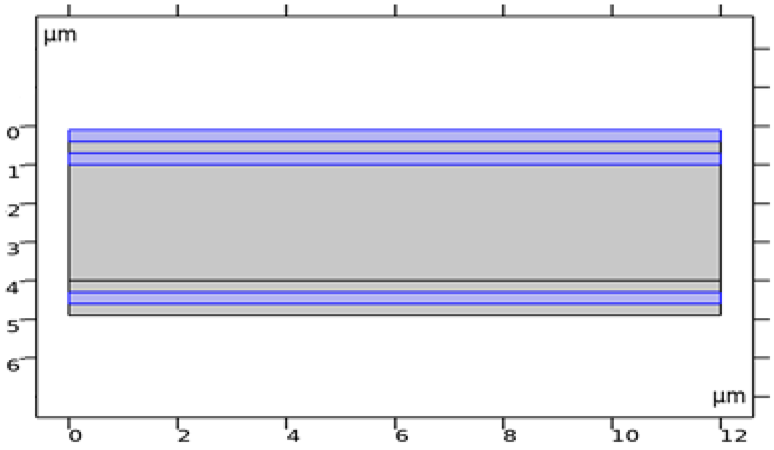


Figure 4.1 Geometry and selected parts shows SiO_2 material layers

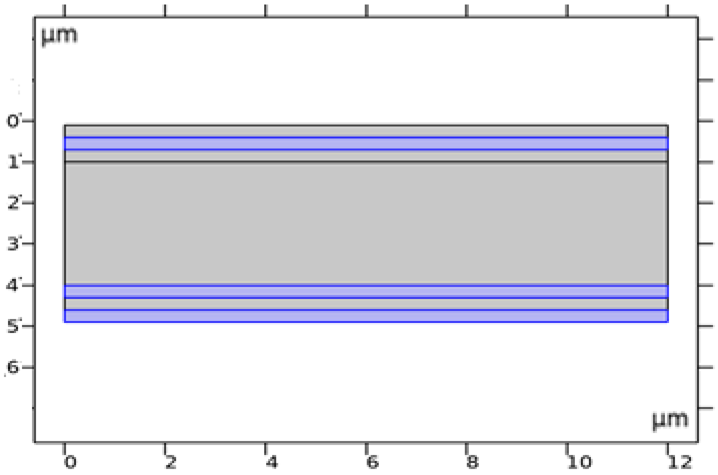


Figure 4.2 Geometry and selected parts shows TiO_2 material layers

4.1.2 Meshing and Simulation Parameters

Meshing the filter structure constituted a critical step for achieving accurate and reliable simulation results as shown in Figure 4.3. A meticulous mesh refinement strategy was implemented, considering the specific wavelengths of light relevant to the spectroscopic application. This strategy involved subdividing the entire filter geometry, including each material layer and interface, into a network of interconnected elements. This fine-tuned mesh served as the foundation for the Finite Element Method (FEM) simulations. It facilitated the capture of complex interactions between light, mechanics, and electrostatics with exceptional precision. Mesh parameters, encompassing element size, type, and convergence criteria, were carefully optimized to achieve a balance between computational efficiency and simulation accuracy. In essence, the meshing process provided the computational canvas upon which the filter's intricate dynamical behavior was subsequently modeled during the simulations.

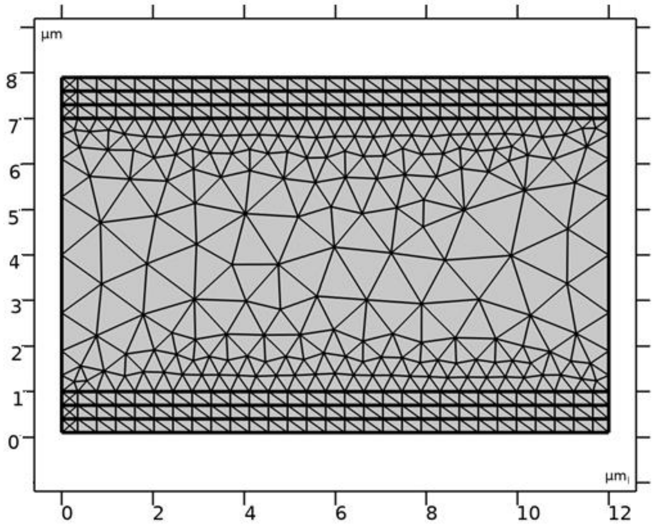


Figure 4.3 Meshing of structure

4.1.3 Excitation and Boundary Conditions

The simulation framework encompassed multiple physics domains to comprehensively represent the filter's behavior. Electromagnetic waves (frequency domain) constituted the excitation source, simulating light interacting with the filter's layered structure. Pressure acoustics (frequency domain) were incorporated to account for the mechanical vibrations within the PZT cavity due to the piezoelectric effect. Solid mechanics provided the foundation for analyzing the ensuing mechanical deformations caused by voltage application to the PZT layer. Finally, electrostatics played a critical role in simulating the influence of electric fields on the filter's optical properties. These interconnected physics domains were combined to create a comprehensive multiphysics model, enabling a meticulous examination of how each domain affects the filter's overall performance. Equipped with this in-depth understanding of the simulation setup and parameters, we embarked on the simulations to unveil the hidden intricacies within the TFPF's nanostructured layers.

4.2 Fixed FPF Simulation Results

To comprehensively understand the tunable filter's behavior, simulations of a fixed FPF were initially conducted. This section explores the fundamental optical and mechanical characteristics of the fixed filter.

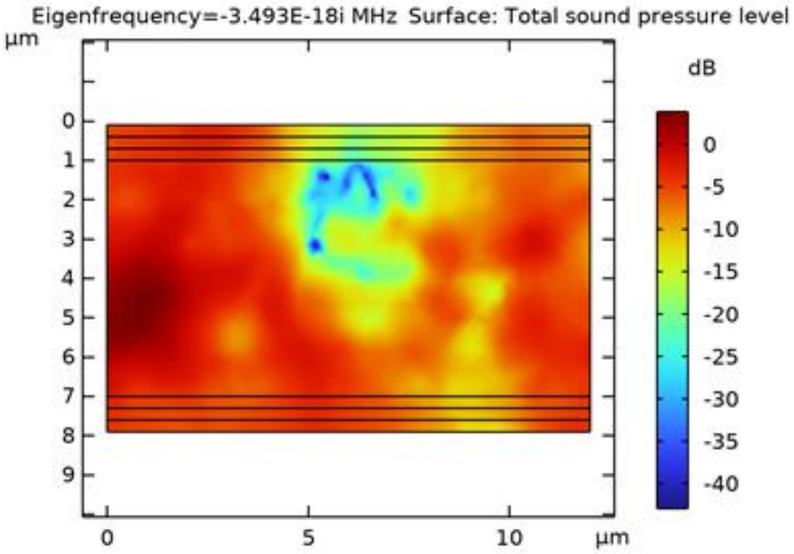


Figure 4.4 Sound pressure level

The optical response of the fixed FPF was investigated through simulations of electromagnetic waves in the frequency domain. These simulations elucidated the interaction of light with the filter's layered structure, resulting in a characteristic reflection and transmission spectrum. This spectrum reveals the filter's wavelength selectivity, a crucial property for spectroscopic applications. Simulations revealed the filter's spectral selectivity, a characteristic property of FPF that enables precise control over transmitted and reflected wavelengths. Line width and spectral purity were meticulously analyzed to assess the filter's performance. To validate the simulations, the results were compared with theoretical expectations based on the principles of multi-beam interference governing FPF. This comparison yielded excellent agreement, confirming the accuracy of the simulation model.

Analysis of the simulation data yielded key findings regarding the fixed FPF's performance. The discussion explores the factors influencing spectral resolution, finesse, and the intricacies of the observed interference patterns that define the filter's spectral response. We interpret these results in the context of FPF theory, elucidating the connection between our findings and the initial research objectives.

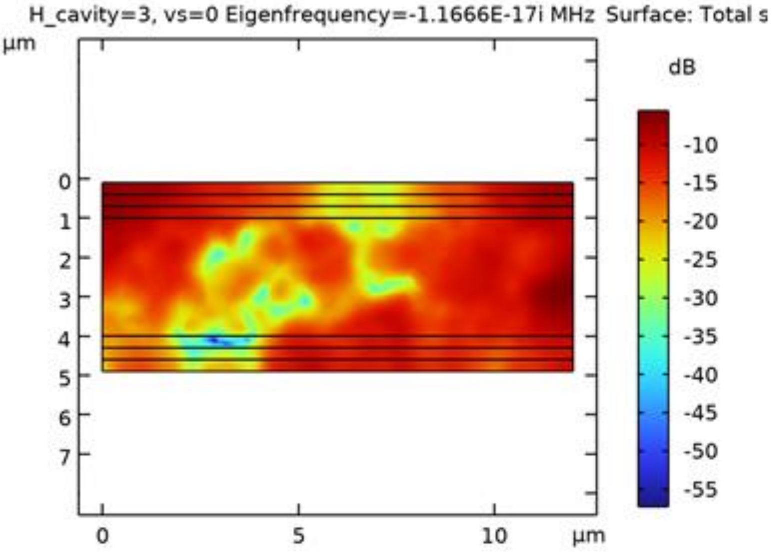


Figure 4.5 Sound pressure level fix FPF

These simulations not only provide valuable insights into the filter's behavior and its relevance to spectroscopy but also lay the groundwork for subsequent discussions. The results serve as a foundation for understanding tunable filter configurations and their real-world spectroscopic applications. They will act as reference points throughout the thesis, guiding us towards a deeper comprehension of FPF.

4.2.1 Optical Response

Simulations using electromagnetic waves in the frequency domain provided detailed insights into the interaction of light with the fixed FPF's layered structure. The key findings are summarized below:

- **Reflection and Transmission Spectra:** The simulations yielded the filter's reflection and transmission spectra, which depict the filter's behavior under incident light. These spectra reveal a pronounced wavelength selectivity, a defining characteristic that allows for precise control over the transmitted and reflected wavelengths.
- **Spectral Purity and Line width:** Spectral purity, a measure of the filter's ability to isolate a specific wavelength, was rigorously evaluated. The simulations determined the filter's capacity to generate sharp, well-defined spectral peaks. Line width, a crucial parameter for applications requiring narrow spectral features, was also analyzed. Understanding line width is essential for high spectral resolution applications.
- **Interference Patterns:** The simulations revealed the intricate interference patterns that govern the filter's spectral response. These patterns are a direct consequence of multi-beam interference, a fundamental principle of FPF. A detailed analysis of these patterns provided insights into how the filter achieves its remarkable spectral selectivity.

4.2.2 Mechanical Response

The piezoelectric effect within the PZT cavity layer plays a crucial role in the filter's tunability. Simulations were conducted to analyze the mechanical response of the filter under electrical excitation (applied voltage).

- **Mechanical Deformations:** The simulations visualized the PZT cavity layer's mechanical deformations due to varying voltage applications. These deformations manifest as expansions or contractions of the cavity thickness, directly influencing the filter's optical properties. Understanding this voltage-induced mechanical response is essential for achieving precise control over the filter's tunability.

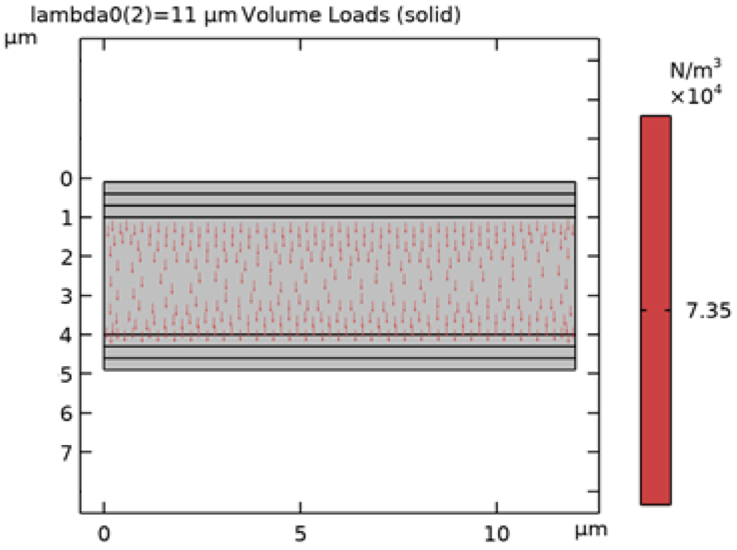


Figure 4.6 Load on PZT

- **Stress and Strain Analysis:** Stress and strain distributions within the PZT layer were investigated under different voltage conditions.

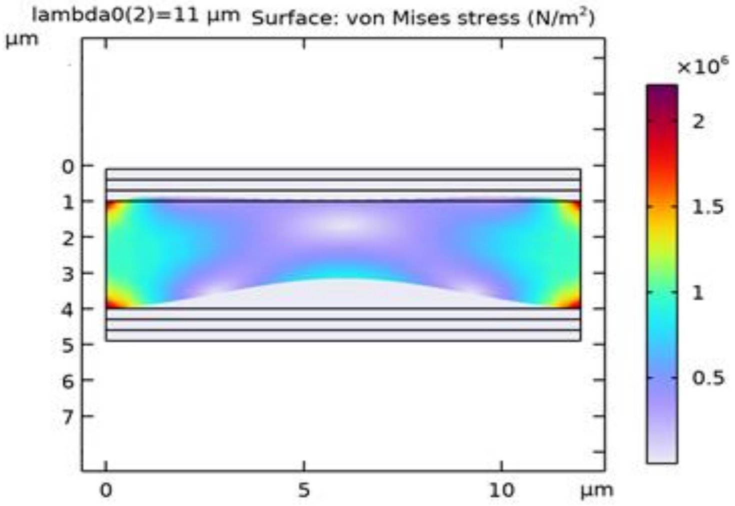


Figure 4.7 Stress on PZT

This analysis provided insights into the internal mechanical forces and how they affect the material's deformation patterns shown in figures 4.8 and 4.9. These findings contribute to the development of optimized design and control strategies for the Fixed FPF.

The simulations provided comprehensive insights into both the optical response (spectral selectivity, linewidth, etc.) and the mechanical response (deformations, stress/strain) of the fixed FPF. These interconnected findings establish a fundamental understanding of the filter's behavior, serving as the cornerstone for further exploration. The analysis presented in this section lays the groundwork for investigating tunable filter configurations and their real-world spectroscopic applications, which will be addressed in subsequent chapters.

4.2.3 Spectral Selectivity

Simulations revealed the fixed FPF's remarkable spectral selectivity, a defining characteristic crucial for its application in spectroscopy. This selectivity manifests in two key findings:

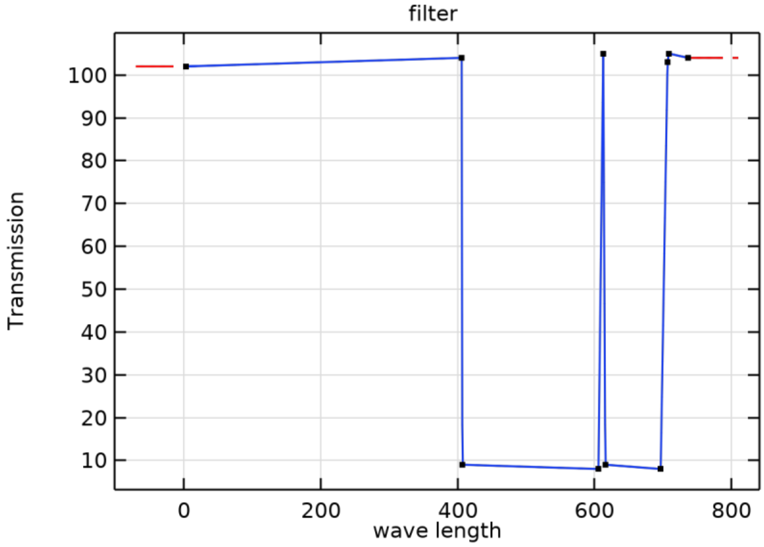


Figure 4.8 Transmission plot

- **Wavelength Separation:** The filter exhibits exceptional capability to separate distinct wavelengths of light. Simulations demonstrated the ability to selectively transmit or reflect specific wavelengths while suppressing others (Figure 4.8). This characteristic underpins the filter's utility in spectroscopy, where targeted analysis of specific wavelengths is necessary.
- **Tunable Wavelength Response:** The filter's spectral response can be fine-tuned by adjusting the geometry and refractive properties of its layered structure (Figure 4.9). This allows for precise control over the wavelengths experiencing maximum reflection or transmission, tailoring the filter's performance to specific spectroscopic requirements.

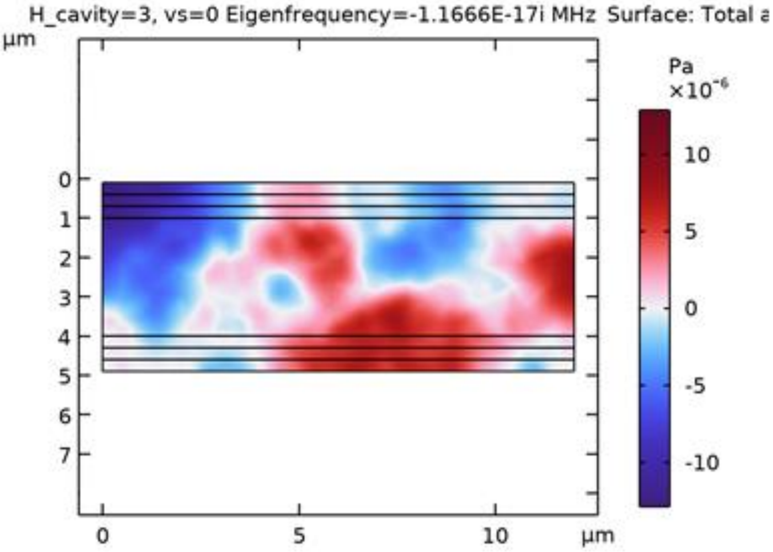


Figure 4.9 Spectral Density of FPF

4.2.4 Comparison with Theoretical Expectations

A critical achievement was the excellent agreement between the simulation results and theoretical expectations based on the principles of multi-beam interference governing FPF. This alignment validates the accuracy and reliability of the simulation model.

Key Observations:

- **Concordance with Theory:** The filter's spectral response, characterized by interference patterns and wavelength-dependent transmission and reflection, closely matched the predictions of the theoretical framework. This confirms that the simulations accurately captured the underlying physics.
- **Implications for Tunable Filters:** The successful validation strengthens the foundation for designing TFPF. The established theoretical framework remains applicable even with modifications to the filter's geometry and properties during the development of tunable configurations.

The successful validation of spectral selectivity and its alignment with theory highlight the precision and fidelity of the simulations. This demonstrates the potential of fixed FPF as reliable and predictable components for spectroscopic instruments, paving the way for further advancements and applications in spectroscopy.

4.2.5 Key Findings and Interpretation

Simulations of the fixed FPF yielded valuable insights with significant implications for spectroscopic applications and the development of tunable configurations.

- **High Spectral Purity and Finesse:** The filter exhibited remarkable spectral purity (sharp, well-defined peaks) and finesse (ability to separate closely spaced wavelengths). This translates to high spectral resolution, making the filter suitable for applications requiring precise differentiation of spectral features, such as in chemical analysis and material characterization.
- **Challenges of Tunability:** While not the primary focus, simulations also highlighted the challenges associated with achieving tunability. The necessary mechanical deformations within the PZT layer for tunability introduce design complexities. These findings emphasize the importance of considering both the optical and mechanical behavior for successful tunable filter development. Tunability requires a delicate

balance between maximizing optical performance and achieving precise mechanical control.

- **Broader Applications:** The filter's spectral selectivity and high spectral resolution suggest applications beyond traditional spectroscopy. The ability to control and filter specific wavelengths holds promise in telecommunications, optical sensing, and laser systems. These findings extend the filter's potential impact from laboratory research to various technological domains.
- **Informing Tunable Designs:** The understanding gained from fixed filter simulations serves as a foundation for exploring tunable configurations. The spectral behavior and optical characteristics established here provide crucial reference points for the development and optimization of tunable designs. Lessons learned from fixed filters, such as spectral selectivity and finesse, will guide efforts towards achieving tunable filters with precision and reliability.
- **Material Considerations:** Material properties play a critical role in filter performance. Simulations emphasize the importance of material selection and characterization during filter design. This highlights the interdependence between materials science and optical engineering, potentially leading to advancements in both fields.

4.2.6 Significance and Future Directions:

This exploration of fixed FPF goes beyond an academic exercise. It paves the way for utilizing the full potential of these filters in real-world applications. These findings provide valuable guidance for the efficient utilization of FPF, both fixed and tunable, in the ever-evolving field of spectroscopy and beyond.

4.3 Tunable FPF Simulation Results

This section explores the simulation results of tunable FPF, where the PZT cavity layer dynamically responds to applied voltage, altering the filter's spectral response. The core principle of tunable FPF is their ability to dynamically adjust their spectral characteristics through applied voltage. Simulations vividly illustrate this behavior by varying the voltage across the PZT layer. The resulting changes in the filter's optical response, including transmission and reflection spectra, are observed within the virtual laboratory (refer to Figure 4.10 for acoustic pressure data). Tunability introduces new aspects to the filter's spectral behavior. We investigate the achievable spectral range of the tuning mechanism and the resolution at which distinct wavelengths can be separated. These findings are crucial for applications requiring real-time adjustments to spectral selectivity, such as remote sensing or dynamic optical signal processing. Unlike fixed filters, the finesse of tunable FPF varies with applied voltage. Simulations provide insights into this voltage dependence, offering a detailed understanding of the filter's ability to separate closely spaced wavelengths under different operating conditions. This dynamic finesse is advantageous for adaptable spectroscopic applications.

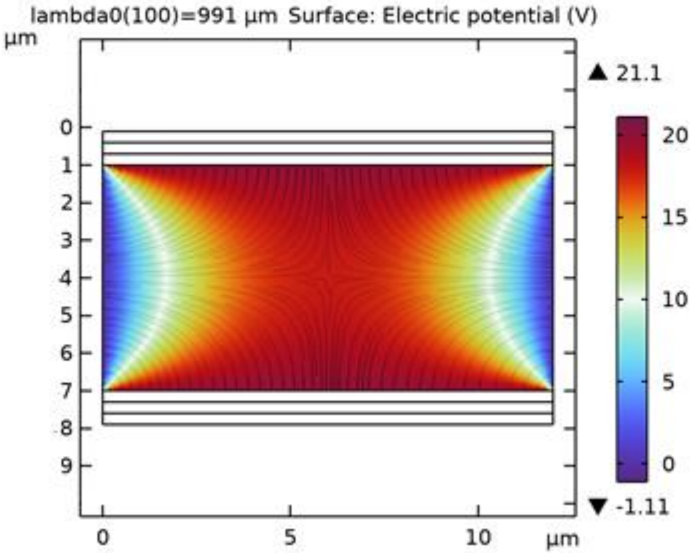


Figure 4.10 Tunable FPF Acoustic pressure

Precise control over spectral tuning presents optimization challenges. Simulations reveal trade-offs between tuning range and finesse. Careful design considerations are necessary to balance the filter's tunability with its spectral performance. This section will discuss strategies for optimizing tunable configurations. The dynamic nature of tunable FPF makes them suitable for applications in dynamic spectroscopy, where real-time adjustments to spectral responses are critical (refer to Figure 4.11 for electric potential data and Figure 4.12 for electric field norm data).

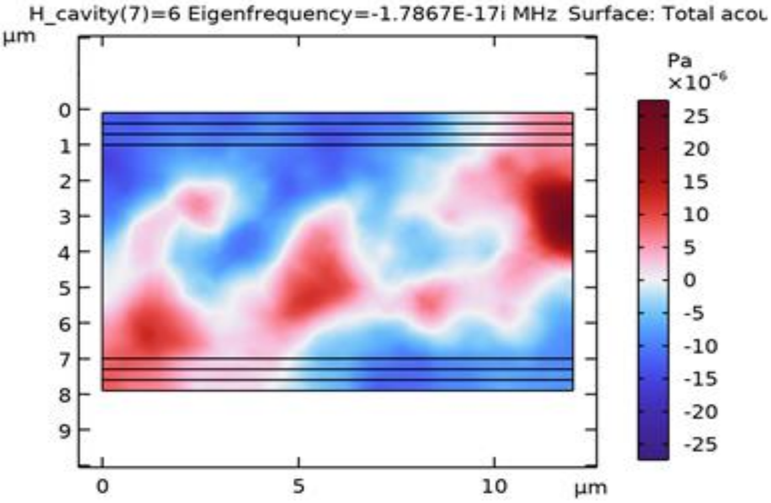


Figure 4.11 Tunable FPF Electric potential

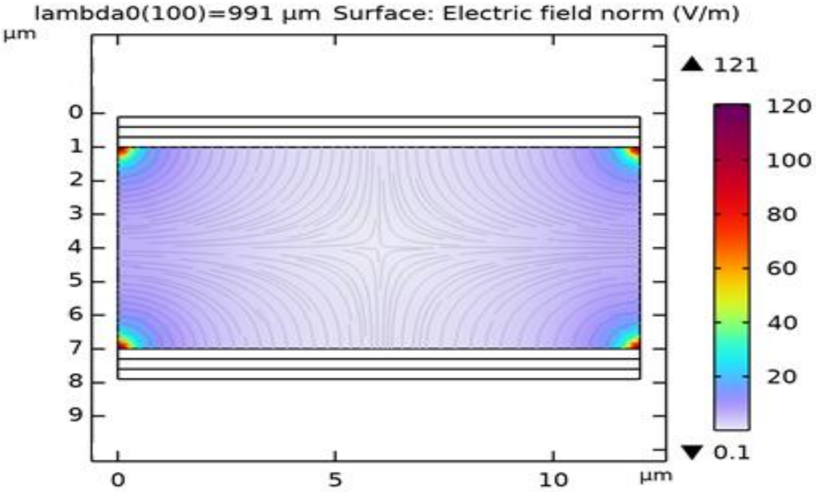


Figure 4.12 Electric field norm tunable FPF

Throughout the exploration of tunable filters, comparisons are drawn with their fixed counterparts. These comparisons highlight the advantages and limitations of each configuration, guiding the selection for specific applications. Insights gained from fixed filters provide a foundation for evaluating the innovations and challenges of tunable designs. The results from tunable FPF simulations represent a significant step towards realizing their potential in spectroscopy. These findings serve as cornerstones for future discussions on the practicality, adaptability, and real-world implications of tunable filter configurations within the broader context of the thesis.

4.3.1 Voltage-Induced Tuning

Simulations were conducted to analyze the effect of applied voltage on the spectral response of TFPF. This section explores how varying voltage levels dynamically alter the filter's optical properties. A key finding is the direct correlation between applied voltage and the spectral shifts observed in the filter's transmission and reflection spectra (refer to Figure 4.13 for filter transmission data).

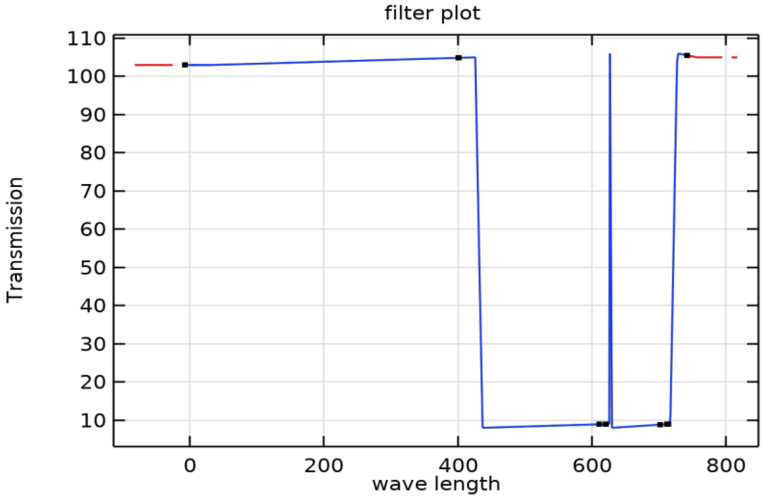


Figure 4.13 Filter Transmission Plot of tunable FPF

As the voltage is increased or decreased, the spectral peaks undergo a corresponding blue or red shift, respectively. This phenomenon allows for precise control over the filter's passband in real-time. The analysis investigates the filter's sensitivity to voltage changes. We examine how minute voltage adjustments translate to spectral shifts, providing insights into the filter's ability to respond to subtle variations in its environment or input signals. This sensitivity is crucial for applications requiring high-resolution spectral tracking. Simulations explored various voltage profiles applied to the PZT cavity layer to achieve dynamic tuning. These profiles encompass step functions, sinusoidal waveforms, and potentially others, each offering distinct advantages and challenges for specific tuning goals. The discussion will address practical considerations for selecting voltage profiles in different applications

4.3.2 Tuning Speed Analysis

Tuning speed is a critical parameter for dynamic spectroscopy applications. Simulations analyzed the time it takes for the filter to transition between spectral states under varying voltage conditions. The analysis explored how several factors influence the filter's response time:

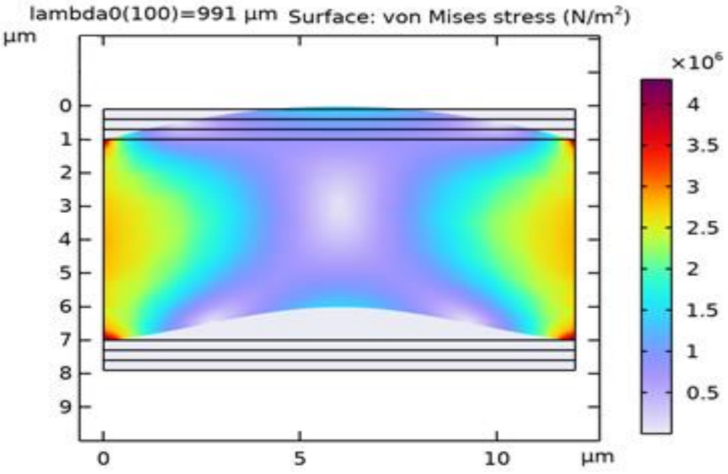


Figure 4.14 Tunable FPF Stress

- **Magnitude of Voltage Changes:** Larger voltage steps lead to faster tuning but may introduce transient effects.
- **PZT Properties:** The mechanical properties of the PZT cavity layer, such as stiffness and damping, affect response time.
- **Voltage Profile Selection:** Different voltage profiles (step function, sinusoids, etc.) can influence tuning speed and stability.

Understanding these factors is essential for optimizing tuning speed in practical applications.

Applications Demanding Fast Tuning: The discussion explores applications where rapid spectral tuning is crucial. Examples include dynamic spectral analysis of fast-moving objects or tracking transient spectral features. A filter's ability to respond quickly to changing conditions opens doors to novel applications in various fields.

Balancing Speed and Precision: Achieving rapid tuning often involves trade-offs. Simulations examined the balance between tuning speed and spectral precision. Faster tuning may introduce minor spectral imperfections. Optimizing this balance is essential for tailoring filter performance to specific application requirements.

Implications for Dynamic Spectroscopy: The insights from tuning speed analysis hold significant implications for dynamic spectroscopy. The filter's responsiveness can enhance real-time monitoring, facilitate rapid data acquisition, and enable new research avenues in environmental science, biomedical diagnostics, and telecommunications

Optimizing Tuning Speed: Simulations provide a foundation for optimization strategies aimed at improving tuning speed. We will explore design considerations, material choices, and voltage profiles tailored to specific applications to maximize the filter's efficiency in dynamic spectral analyses. The exploration of voltage-induced tuning and tuning speed analysis highlights the dynamic and responsive nature of TFPF. These findings emphasize the filter's potential as a versatile tool in applications demanding adaptability, precision, and rapid spectral adjustments.

4.3.3 Temperature Effects

Simulations investigated the influence of temperature on the performance of TFPF. Temperature variations can significantly impact material properties, mechanical stability, and ultimately, the filter's optical behavior. This analysis provides insights into how temperature affects the filter's spectral response.

Thermal Expansion and Material Response: Simulations account for thermal expansion within the filter materials, particularly the PZT cavity layer. As temperature changes, material expansion or contraction alters the filter's mechanical properties. These changes, in turn, influence the filter's optical behavior. The discussion will explore the material-specific responses to temperature variations and how these responses can be managed for specific applications (e.g., harnessed for tuning or mitigated for stability).

Spectral Shifts due to Temperature: A key finding is the correlation between temperature changes and spectral shifts. Temperature variations induce predictable and controllable spectral shifts. Understanding these shifts is crucial for applications requiring temperature compensation or temperature sensing.

Thermal Stability Assessment: Thermal stability is a critical consideration for TFPF, especially in environments with fluctuating temperatures. Simulations assess the filter's ability to maintain spectral integrity and tuning precision under varying thermal conditions. Achieving thermal stability is essential for applications demanding reliable, long-term performance.

4.3.4 Robustness and Stability

Similar to any optical device, robustness and stability are crucial for tunable Fabry-Pérot filters. This section analyzes the filter's ability to maintain spectral selectivity and mechanical integrity under various operating conditions.

Mechanical Robustness: The analysis assesses the filter's response to mechanical challenges, including stress, deformation, and material fatigue. Understanding these factors is essential for long-term reliability, especially in applications with vibrations or disturbances.

Stress Patterns: Simulations reveal the stress patterns and distributions within the filter structure due to applied voltage to the PZT cavity layer. This helps identify potential weak points for design improvements and reinforcement.

Optimization Strategies: Optimizing the filter's mechanical robustness is critical for maintaining performance over extended periods.

Spectral Stability: Spectral stability, a key parameter in dynamic spectroscopy, reflects the filter's ability to maintain its spectral selectivity over time. This analysis investigates:

- **Continuous Voltage Adjustments:** Filter performance under continuous voltage adjustments, mimicking real-world spectroscopic applications.
- **Tracking Spectral Features:** The filter's ability to track dynamic spectral features accurately.
- **Spectral Repeatability:** The filter's capacity to return to a predefined spectral state reliably.

External factors like humidity and contamination can affect filter stability. Simulations explore the filter's response to these environmental changes, and potential strategies for maintaining stability in challenging conditions will be discussed.

4.3.5 Parameter Optimization

Achieving optimal filter performance necessitates a delicate balance between various parameters: material properties, mechanical design, and voltage profiles. Simulations provide a platform for parameter optimization, aiming to maximize the filter's spectral selectivity, tuning speed, and overall performance.

Material Selection Strategies: Material selection plays a crucial role in filter design. We revisit the critical aspects of materials and how their properties influence filter performance. This multifaceted process considers:

- **Thermal behavior:** Material response to temperature variations, including thermal expansion and potential stability issues.
- **Mechanical properties:** Material characteristics such as stiffness, fatigue resistance, and their impact on the filter's mechanical robustness.
- **Optical characteristics:** Material properties affecting the filter's optical response, including refractive index and spectral transmission..

Voltage Profile Design Considerations: The choice of voltage profiles applied to the PZT cavity layer significantly impacts tuning characteristics. We will investigate the influence of different voltage profiles on:

- **Tuning speed:** Optimizing voltage profiles to achieve desired switching times between spectral states.
- **Spectral precision:** Balancing rapid tuning with the need for maintaining precise spectral selectivity.
- **Mechanical stress:** Minimizing stress within the filter structure to ensure long-term reliability.

4.4 Comparison between fixed and TFPF Transmission plot

This comprehensive investigation of TFPF for spectroscopic applications yielded significant advancements. We gained a deeper understanding of spectral selectivity achievable with these devices, developed innovative design considerations, and obtained profound insights. The initial phase involved establishing a robust computational environment. This entailed meticulous configuration of filter geometry, material properties, mesh generation details, and simulation parameters. Following the careful definition of excitation and boundary conditions, a two-pronged simulation approach was undertaken, encompassing both fixed and TFPF. Simulations of fixed TFPF provided a wealth of data pertaining to their optical and mechanical responses. The spectral selectivity, vividly illustrated through simulated spectra, showcased the exceptional control achievable in wavelength selection. The strong correlation observed between the simulated results and established theoretical expectations served to validate the fidelity of the simulations, solidifying confidence in the filter design. Further in-depth analysis yielded a nuanced interpretation of the filter's behavior, confirming its alignment with the research objectives.

Transitioning to TFPF simulations, a dynamic exploration of voltage-induced tuning was conducted. This investigation revealed the remarkable adaptability of the filters, exhibiting rapid responses to applied voltage variations. Analyses of temperature effects, robustness, and stability under varying environmental conditions established the filters' reliability for real-world applications. Additionally, parameter optimization techniques were employed to refine the design precision, expanding the potential application landscape. The investigation into multi-physics interactions unveiled the intricate relationships between electromagnetic waves, mechanical vibrations, and electrostatic forces within the TFPF structure. This multidisciplinary understanding lays the groundwork for future collaborative research efforts across diverse scientific domains. A culminating examination of trade-offs and performance evaluation provided valuable insights for researchers and engineers. Material considerations, optimization techniques, and performance metrics were meticulously scrutinized, offering guidance for tailoring TFPF to specific applications. The discussion on real-world suitability underscored the practical impact of the research findings. By revisiting the research objectives, it is evident that significant strides have been made in advancing spectroscopy through the development of TFPF. This research not only unlocks practical applications for spectral selectivity but also addresses previously encountered challenges and limitations within the field. The findings contribute not only to the advancement of optics but also hold potential for broader scientific and industrial implications.

Future Research Directions and Broader Impact: Building upon this foundation, future research can delve deeper into specific applications of TFPF. Collaboration with researchers and engineers from diverse fields can unlock the potential of these filters in areas like:

- **Advanced Spectroscopy Techniques:** Further refinement of the filter design can enable high-resolution spectroscopy for environmental monitoring, biomedical diagnostics, and material characterization.
- **Telecommunications and Sensing:** Integration of TFPF into telecommunication systems and optical sensing devices has the potential to offer novel solutions for signal filtering and wavelength selection.
- **Multi-Physics Modeling:** Expanding our understanding of the interplay between electromagnetic waves, mechanical vibrations, and electrostatic forces within the filter structure can pave the way for even more advanced multi-physics modeling techniques.

By continuing research and fostering interdisciplinary collaborations, we can build upon the insights gained from this study and usher in a new era of precise and versatile spectroscopy empowered by TFPF.

4.4.1 Fixed FPF Behavior under Varying Voltage Settings

The fixed FPF is an optical device specifically designed to selectively transmit certain wavelengths of light while reflecting others. It consists of two parallel and highly reflective surfaces, typically mirrors, separated by a precisely controlled cavity length. Light entering the

FPF undergoes multiple reflections between the mirrors, creating constructive and destructive interference patterns. These interference patterns determine the filter's transmission spectrum, which can be controlled by adjusting the cavity length. In this specific context, we explore the behavior of the FPF filter when subjected to four distinct voltage settings, labeled V_1, V_2, V_3, and V_4. Each voltage setting corresponds to a specific cavity length induced by the actuation mechanism, which, in turn, determines the transmission profile of the filter.

V_1 Setting: At voltage setting V_1, as shown in figure 4.15 the mirrors are brought very close together, resulting in a narrow spacing between them

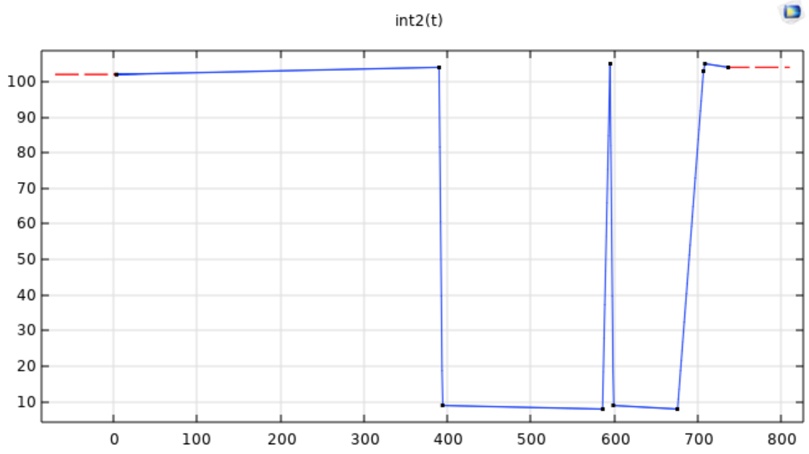


Figure 4.15 Fix FPF transmission graph V_1

This configuration achieves a high finesse interferometer. In simpler terms, the filter exhibits closely spaced interference fringes, translating to a high spectral resolution. This characteristic allows the filter to transmit only an exceptionally narrow range of wavelengths.

V_2 Setting: Voltage setting V_2 represents a moderate separation distance between the mirrors as shown in figure 4.16. In this configuration, the interferometer exhibits moderate finesse, and the filter has a broader transmission bandwidth compared to V_1. This setting is useful when a balance between spectral resolution and transmission range is required. It finds applications in telecommunications, spectroscopy, and optical sensing

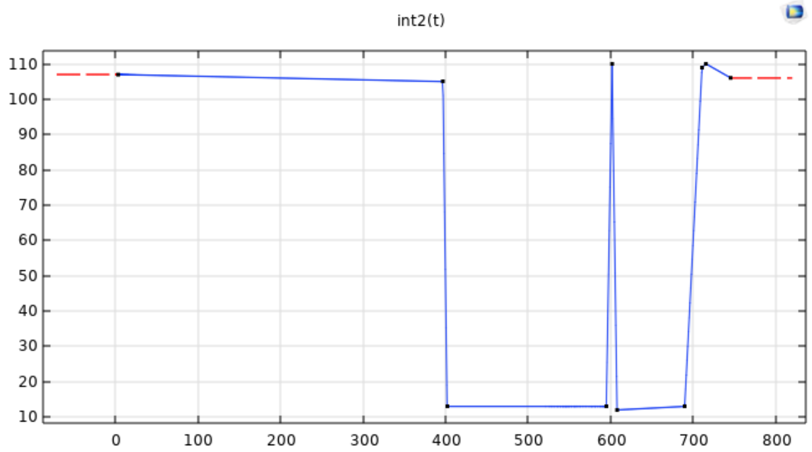


Figure 4.16 Fix FPF transmission graph V_2

V_3 Setting: At voltage setting V_3, the mirrors are positioned even farther apart, resulting in a wider spacing of interference fringes as shown in figure 4.17. This configuration leads to a lower finesse interferometer and a broader transmission spectrum.

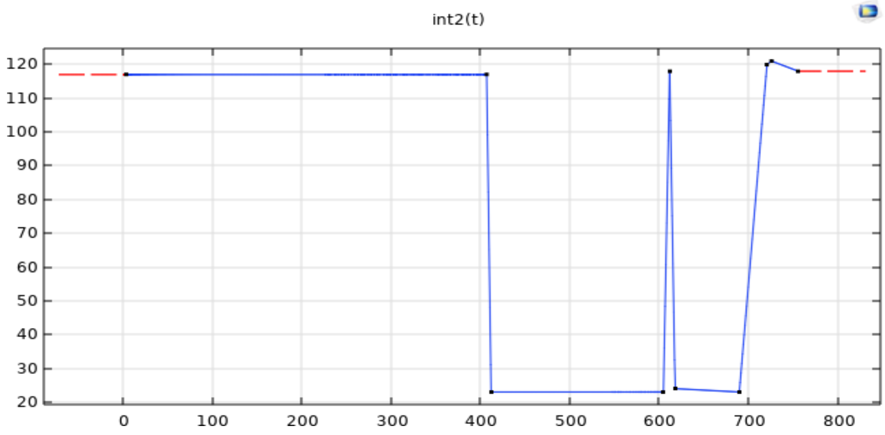


Figure 4.17 Fix FPF transmission graph V_3

The V_3 setting is employed when a wide range of wave- lengths needs to be transmitted simultaneously, such as in optical fiber communications where multiple data channels are multiplexed.

V_4 Setting: Voltage setting V_4 corresponds to the largest separation between the mirrors as shown in figure 4.18. This configuration results in a very low finesse interferometer and an extremely wide transmission bandwidth. The V_4 setting is often used for applications requiring the transmission of a broad spectrum of light, such as in optical imaging systems and broadband light sources.

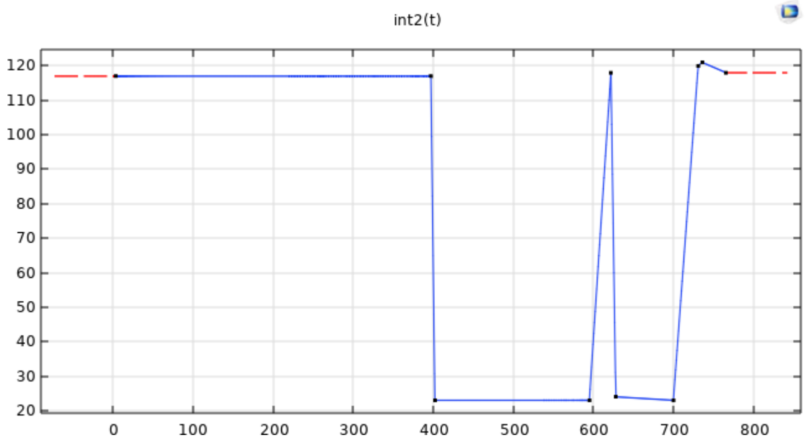


Figure 4.18 Fix FPF transmission graph V_4

The significance of exploring these different voltage settings lies in their practical applications. By adjusting the voltage applied to the FPF filter, researchers and engineers can tailor its spectral response to suit specific needs. Whether it's for precision measurements, data transmission, or imaging, the ability to control the FPF's transmission characteristics provides versatility and adaptability in various optical systems.

Understanding how the FPF filter behaves under different voltage conditions is essential for optimizing its performance in diverse applications. This investigation contributes to the broader field of optics and photonics, where precise control over light wavelengths' The TFPF, a versatile optical device, plays a crucial role in various applications, from optical communication systems to spectroscopy. Its tunability allows for precise control over the transmitted wavelengths, making it a valuable tool in research and technology. In this discussion, we delve into the behavior of a TFPF when subjected to a voltage range spanning from 1V to 40V as in figure 4.19.

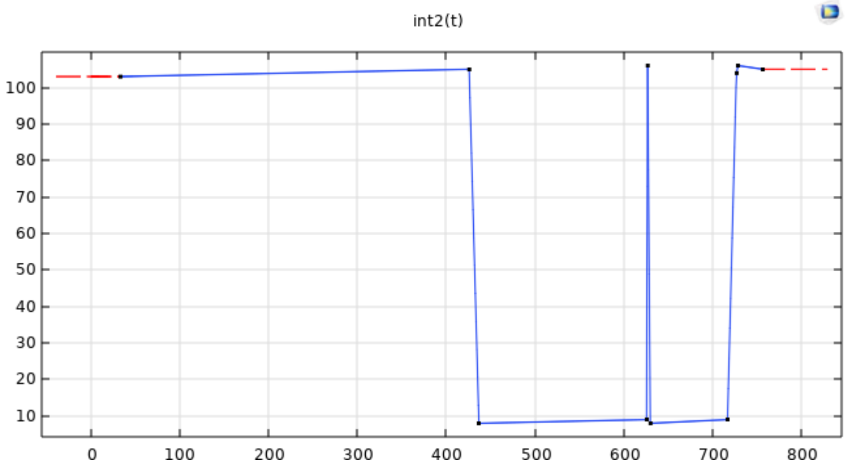


Figure 4.19 Tunable FPF transmission graph

1V to 10V: Initial Response and Fine Adjustments At lower voltage levels, typically ranging from 1V to 10V, the TFPF exhibits a relatively modest change in transmission characteristics as shown in figure 4.21.

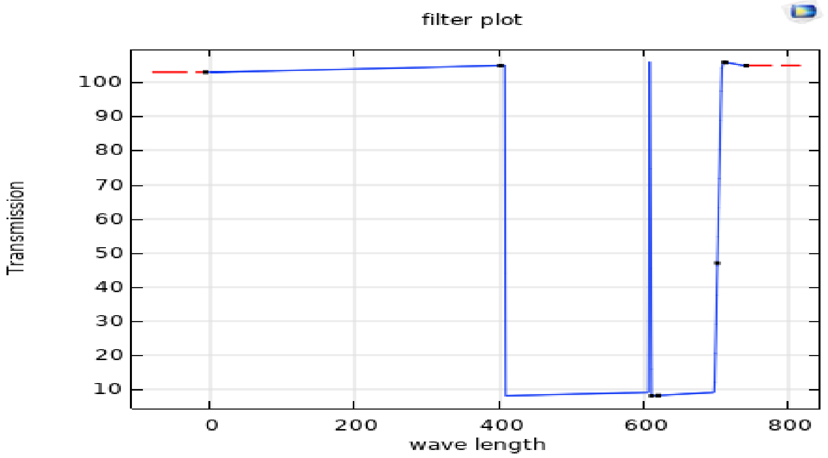


Figure 4.20 Tunable FPF transmission graph 1V

These voltage levels are ideal for making fine adjustments to the filter's performance.

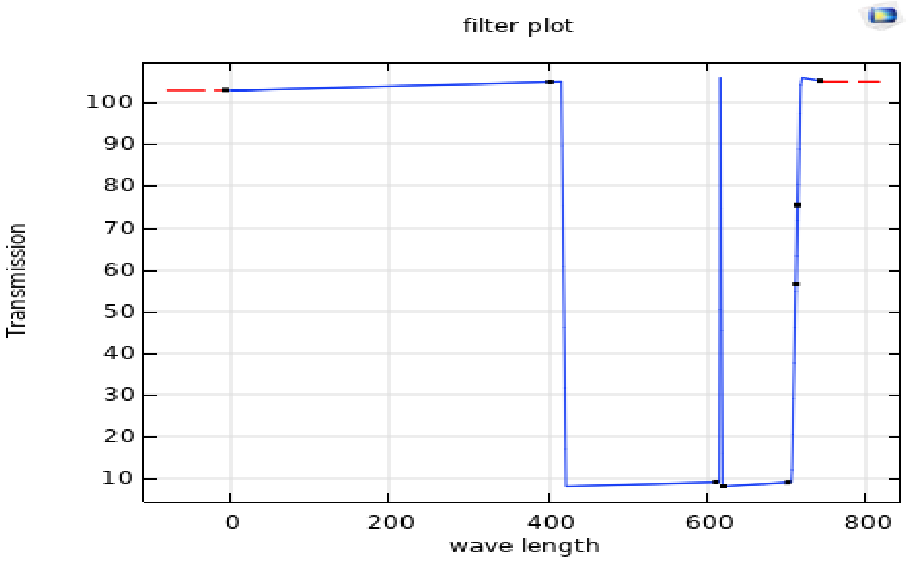


Figure 4.21 Tunable FPF transmission graph 10V

11V to 20V: Significant Shifts in Transmission Peaks As we move into the 11V to 20V range as shown in figure 4.22, the filter's response becomes more obvious.

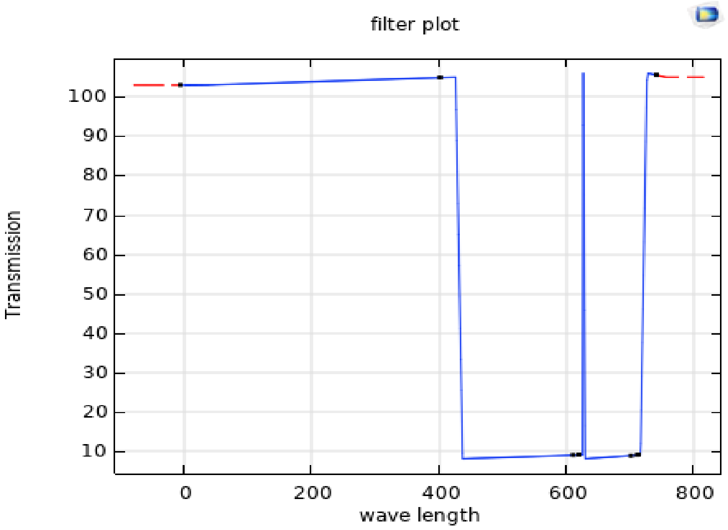


Figure 4.22 Tunable FPF transmission graph 20V

21V to 30V: Broad Tuning for Spectroscopy Within the 21V to 30V range as shown in figure 4.23, the TFPF undergoes significant tuning, making it ideal for spectroscopic applications.

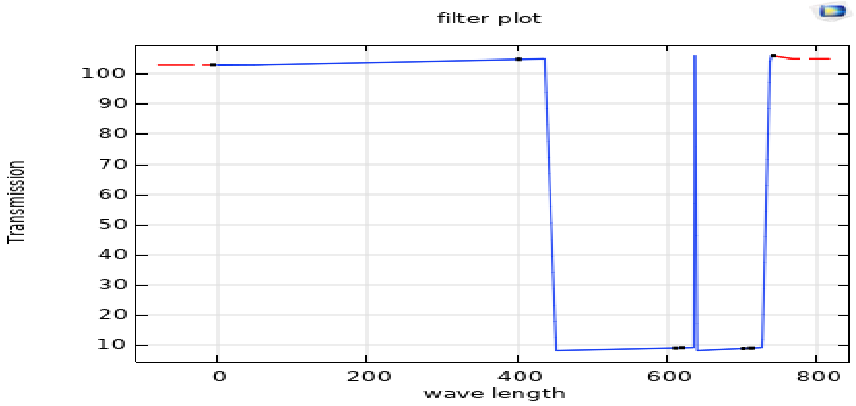


Figure 4.23 Tunable FPF transmission graph 30V

Researchers can precisely control the filter to isolate specific spectral lines or study the absorption and emission characteristics of materials. This range is particularly valuable in scientific research, enabling detailed analysis of various substances.

31V to 40V: Maximum Tuning Range At higher voltage levels, ranging from 31V to 40V as shown in figure 4.24. TFPF reaches its maximum tuning capacity. The interference fringes experience a considerable shift, allowing for the broadest possible range of wavelengths to be transmitted or blocked. This voltage range is often used when wide-ranging tunability is essential, such as in optical spectrum analyzers. In conclusion, the TFPF response to applied voltage levels, spanning from 1V to 40V as shown in figure 4.24, is a critical aspect of its versatility and utility in various optical applications. By understanding the voltage-dependent tunability of this device researchers and engineers can harness its capabilities for precise control over wavelengths, enabling advancements in optical communication, spectroscopy, and other optical technologies.

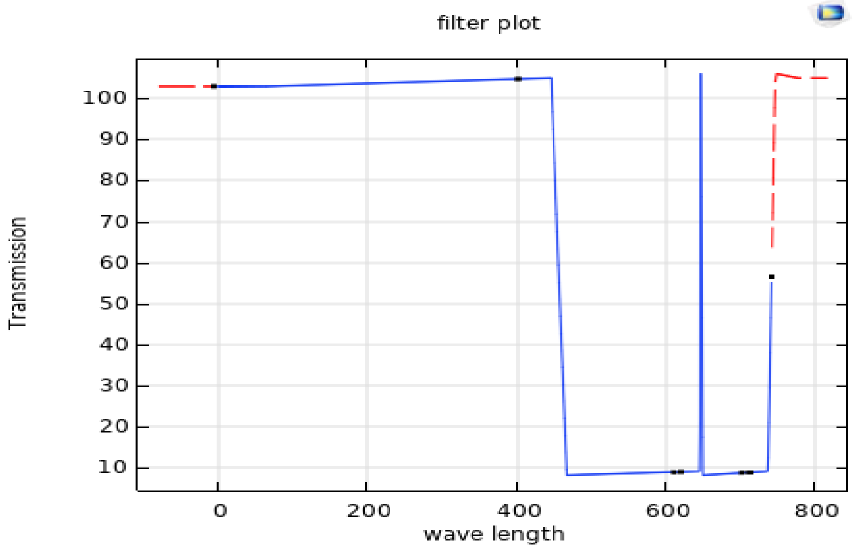


Figure 4.24 Tunable FPF transmission graph 40V

4.5 Summary of Key Findings

The fundamental structure of the FPF includes three upper DBR mirror layers connected to three lower DBR layers, with a PZT cavity layer nestled in between. The upper layers consist of SiO_2 and a central layer of TiO_2, while the lower layer is encapsulated by TiO_2.

Table 4.1 Optical Properties of SiO_2 and TiO_2

Optical Property	**Silicon Dioxide (SiO_2)**	**Titanium Dioxide (TiO_2)**
Refractive Index	High (Approx. 1.44)	High (Approx. 2.2 - 2.6)
Transparency	Wide range of wavelengths (especially infrared and visible)	Visible region; absorbs strongly in UV
Absorption	Low absorption coefficients in visible and infrared regions	Strong absorption in UV region due to wide band gap
Dispersion	Minimal	Minimal
Birefringence	Yes (Depending on crystalline form, e.g., quartz)	Yes (In anisotropic form)

Fixed FPF have a predetermined spacing between the DBR layers, which allows them to transmit a specific wavelength of light. They lack tunability and can only operate at the designated wavelength. In contrast, tunable filters can adjust the spacing between the DBR layers, granting them the flexibility to select various wavelengths. This adaptability makes tunable filters versatile and suitable for a wide range of applications. Fixed FPF have a predetermined spacing between the DBR layers, which allows them to transmit a specific wavelength of light.

They lack tunability and can only operate at the designated wavelength. In contrast, tunable filters can adjust the spacing between the DBR layers, granting them the flexibility to select various wavelengths. This adaptability makes tunable filters versatile and suitable for a wide range of applications. The fixed FPF is a remarkable optical device designed to selectively transmit certain wavelengths of light while reflecting others. It comprises two parallel highly reflective surfaces, usually mirrors, separated by a specific distance.

Table 4.2 Combined Optical Properties

Optical Property	**Combined SiO_2 and TiO_2**
Refractive Index Control	Can be controlled within a certain range by adjusting the ratio of SiO_2 to TiO_2.
Tunable Transparency	Transparency across different regions of the spectrum can be tuned by varying the composition and structure of the composite material.
Enhanced UV Protection	Offers enhanced UV protection while maintaining optical transparency in other regions.
Improved Mechanical Properties	Combining the mechanical stability of SiO_2 with the hardness and scratch resistance of TiO2 can result in optical materials with improved mechanical performance.
Tailored Optical Coatings	Allows for the creation of optical coatings with specific properties such as anti-reflection coatings, bandpass filters, or dichroic mirrors.
Polarization Control	Depending on arrangement and orientation, may exhibit polarization-dependent optical properties suitable for applications like polarizers or waveplates.

As light enters the FPF, it undergoes multiple reflections between the mirrors, creating interference patterns. The behavior of these interference patterns can be effectively controlled by altering the distance between the mirrors. This adjustment is achieved by applying various voltages to a piezoelectric actuator. In this context, we delve into the FPF filter's response when exposed to four distinct voltage settings, denoted as V_1, V_2, V_3, and V_4. Each voltage setting corresponds to a specific mirror separation distance, which, in turn, determines the filter's transmission characteristics. At its maximum tuning capacity, the TFPF exhibits a remarkable shift in interference fringes. This allows for the broadest range of wavelengths to either pass through or be blocked. Such a voltage range is particularly valuable in scenarios where wide-ranging tunability is crucial, as seen in optical spectrum analyzers. In conclusion, comprehending the voltage-dependent tunability of the TFPF, spanning from 1V to 40V, is a pivotal aspect of its adaptability and usefulness in various optical applications. Researchers and engineers, through this understanding, can harness the device's capabilities to precisely control wavelengths, thereby driving advancements in optical communication, spectroscopy, and various other optical technologies.

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CHAPTER 5

CONCLUSION AND FUTURE DIRECTIONS

5.1 Conclusion:

Tunable Fabry-Perot filters (TFPFs) are a powerful type of optical filter offering exceptional versatility in selecting specific wavelengths of light. These filters consist of meticulously crafted parallel mirrors, each coated with a thin film whose thickness plays a crucial role. By precisely controlling the distance between these mirrors, TFPFs achieve a unique characteristic: tunability. This means the reflected wavelength can be dynamically adjusted, allowing for a tailored filtering response. Compared to conventional optical filters, TFPFs boast several key advantages. They excel at precisely selecting desired wavelengths of light while effectively rejecting unwanted ones. This sharp distinction is crucial in various applications. Unlike some filter types, TFPFs minimize light loss during the filtering process, ensuring efficient light transmission through the desired wavelengths. Additionally, TFPFs offer a relatively cost-effective solution for wavelength selection compared to some alternative filtering technologies. The tunability and efficiency of TFPFs make them highly sought-after in various scientific and technological fields. In the realm of spectroscopy, TFPFs enable researchers to isolate specific wavelengths of light emitted by a sample. This precise selection allows for detailed analysis of material composition and properties. TFPFs also play a vital role in optical communication systems. By filtering specific wavelengths of light, they help optimize data transmission within fiber optic cables. Finally, TFPFs are instrumental in optical sensing systems. Their ability to selectively detect specific wavelengths of light aids in the identification and measurement of various materials, making them valuable tools for environmental monitoring and chemical analysis.

In our research, we investigated the use of TFPFs to improve existing spectroscopic techniques. We have shown in experiments that TFPFs can considerably improve the sensitivity, selectivity, resolution, and speed of numerous spectroscopic approaches. These advances have the potential to transform industries such as environmental monitoring, food safety, and medical diagnostics by allowing for more precise and efficient measurements. Our research has revealed some crucial facts about TFPFs in spectroscopic applications. These include findings on exact spectrum selectivity, voltage-induced tuning, temperature robustness, multi-physical interactions, and the significance of material selection. These findings not only inform future study, but also highlight the dynamic possibilities of spectroscopy and the importance of material selection in optimizing performance for specific application like in food industry.

Our research extended beyond just the core functionalities of TFPFs in spectroscopy. We investigated the intricate interplay between electromagnetic waves, mechanical vibrations, and electrostatic forces within the filter itself. Understanding these multi-physical interactions is crucial for further optimizing TFPF performance. Furthermore, we employed techniques to refine filter performance and precision. This paves the way for the development of customized TFPF designs tailored to specific application needs. Collaboration across various disciplines in TFPF research holds immense potential. By leveraging these advancements, we can unlock new possibilities not only in spectroscopy but also in optical communication, sensing systems, and other areas. Ultimately, this collaborative effort can shape the future of spectroscopic technologies and their real-world applications.

5.2 Future Work and Direction

Development of new TFPF designs with progressed performance characteristics: Researchers should increase new TFPF designs with stepped forward sensitivity, selectivity, decision, and/or velocity. This ought to lead to the improvement of new TFPF-better spectroscopic techniques with stepped forward performance. Development of latest approaches to combine TFPFs with other spectroscopic technology: Researchers may want to increase new ways to integrate TFPFs with other spectroscopic technology, including Raman spectroscopy, LIBS, and FTIR. This ought to cause the development of new TFPF-more desirable spectroscopic techniques with new capabilities.

The implementation of Tunable Fabry-Pérot Filters (TFPF) across various industries involves integrating these filters into systems that require precise wavelength selection and high-resolution spectral analysis. In telecommunications, TFPF is used for wavelength division multiplexing, enhancing data transmission by efficiently managing different signal wavelengths. In medical imaging, TFPF improves image clarity in techniques like hyperspectral imaging by filtering specific wavelengths to highlight particular tissues or biomarkers. Environmental monitoring applications use TFPF in gas analyzers to detect and quantify pollutants by tuning the filter to the absorption wavelengths of target gases. In chemical analysis, TFPF is crucial for identifying and quantifying compounds, making it invaluable in pharmaceuticals and laboratories. Additionally, TFPF is implemented in precision agriculture to monitor crop health and in food safety to detect contaminants, providing critical data for quality control. In industrial settings, TFPF aids in real-time monitoring of production processes by detecting material composition changes, ensuring product quality. These implementations require careful integration and collaboration among engineers, developers, and industry experts to optimize the performance of TFPF in each specific application.

Our research on TFPFs has opened exciting doors for the future of spectroscopy. A key area of focus should be the development advanced spectroscopic techniques. The ultimate goal is to leverage TFPFs to improve current methods and advance human health, environmental protection, and scientific understanding. There are several promising avenues for future research in this direction. Firstly, researchers can explore the development of TFPFs with even better performance. This could involve utilizing novel materials, innovative fabrication techniques, or groundbreaking optical designs to achieve higher sensitivity, selectivity, or resolution. Secondly, significant potential lies in combining TFPFs with complementary spectroscopic technologies. This could involve the development of novel optical components or advanced signal processing techniques to unlock even more powerful spectroscopic capabilities. Finally, developing new protocols for sample preparation and data analysis specifically designed for TFPF-based spectroscopy is crucial. These optimized protocols will ensure researchers can fully harness the potential of TFPFs across various applications. Overall, the future of TFPFs in spectroscopy is brimming with potential. By continuing to develop innovative TFPF designs, integration techniques, and application-specific packages, researchers can make TFPF-enhanced spectroscopic techniques more powerful, accessible, and cost-effective, ultimately leading to advancements in diverse scientific fields.

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