

STUDY THE EFFECTIVENESS OF LONGITUDINAL STRESS ON CASCADE OPTICAL FIBER SENSOR

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Abstract. *In this work, the transmission wavelength, full width at half maximum (FWHM), and transmission power were investigated for both compressed and stretched configurations of the intermediate No Core Fiber (NCF) in a Single Mode–No Core–Single Mode (SNS) fiber structure. The transmission characteristics were analyzed under varying external media. Numerical simulations were performed using the Beam Envelope Method in COMSOL Multiphysics 5.5.*

The study focuses on understanding how the diameter of the NCF affects the fiber's modal structure and its ability to resolve wavelength shifts, particularly at the standard wavelength of 1550 nm. By modeling the fiber's response to changes in diameter and the surrounding refractive index, the trade-offs between sensitivity to external changes and wavelength resolution were explored. The results show that larger fiber diameters enhance resolution by producing a narrower FWHM, while smaller diameters offer greater tunability and higher sensitivity to changes in the external medium. Furthermore, the self-imaging length increases with fiber diameter, allowing for a longer light propagation distance.

This research provides valuable insights into optimizing optical fiber sensors by balancing resolution and sensitivity according to specific application needs, such as in telecommunications and environmental sensing.

Keywords: Self-image length, Full Width at Half Maximum (FWHM), Tunability, Resolution, Sensitivity.

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1. INTRODUCTION

Cascade optical fiber sensors typically involve a series of optical fiber components, such as interferometers or fiber Bragg gratings (FBGs), arranged in a cascade configuration to achieve more sensitive, precise measurements for various parameters like strain, pressure, temperature, or displacement.

The cascade configuration could allow the measurement of multiple variables simultaneously or the enhancement of the sensor's sensitivity.

When an optical fiber sensor is exposed to longitudinal stress, the stress is applied along the length of the fiber, which can lead to Elastic deformation: The fiber stretches or compresses depending on the direction of the applied stress. Plastic deformation: If the stress exceeds the material's yield strength, the fiber may deform permanently, leading to irreversibility. Change in refractive index: Longitudinal stress can alter the refractive index of the fiber's core, thereby affecting the transmission properties (show figure 1).

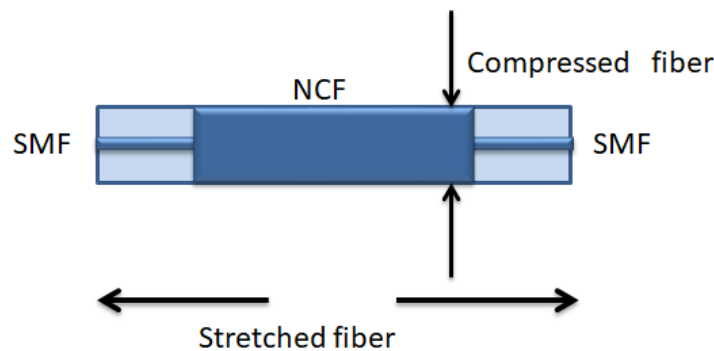


Figure 1 the studied structure

The proposed sensor offers several advantages: it is inexpensive, easy to fabricate, and can be conveniently integrated into a fiber laser system. Additionally, it can be modified to operate at the desired wavelength. The cascaded SNS structure, when surrounded by different materials, acts as a sensing medium. The refractive index (RI) of the magneto-optic material varies with changes in the magnetic field.

The optical field within the cascaded structure was simulated to evaluate the self-imaging length, which is a critical design parameter. The length of the No Core Fiber (NCF) should be equal to, or an integer multiple of, the self-imaging length to achieve maximum transmission at the operating wavelength. This is essential for determining the optimal NCF length.

The effect of changes in the external RI on the propagation field was studied, as well as the influence of the NCF diameter on the transmission bandwidth and tunability. As the core diameter increases, the bandwidth decreases and tunability is reduced. The impact of external RI on the transmission bandwidth was also analyzed; the bandwidth remained relatively unchanged, while the wavelength tunability (i.e., spectral shift) varied with the external RI. The closer the external RI is to the RI of the NCF, the more significant the wavelength shift.

The study also explored the effect of self-image order on tunability and bandwidth through simulation. The objective is to design a tunable magneto-optic, cascaded optical fiber-based MMI (Multimode Interference) structure. The study began with a general investigation to identify the optimal design that achieves both high tunability and narrow bandwidth in the transmission spectrum.

The impact of refractive index on the tunability of the transmission spectrum was evaluated across several core sizes ranging from 50 μm to 200 μm in 25 μm increments. Field propagation was simulated to determine the precise self-imaging length, enabling accurate determination of the optimal NCF length.

As the diameter increased the resolution of the self – image become less ; since the loss increased due to the mode conversion increase the mode number[1] and the aberration due to that not all the interfered modes in phase.[2]

2. MATERIALS AND METHODS

2.1. MATERIALS

In general, a study for the resolution between the transmission at different external wavelength λ and the

diameter of the NCF at $D=1550$ nm wavelength, each diameter has its own self- image length. The study focus on the tenability at external RI from 1 to 1.4 and study the FWHM at $RI = 1$.

Penetration depth (z)[2]

$$z = \frac{\lambda}{2\pi n_{NCF} \sqrt{\sin^2 \vartheta - \left(\frac{n_2}{n_{NCF}}\right)^2}} \quad (1)$$

Where ϑ is the angle of incident, n_{NCF} is the RI of the NCF and n_2 is the RI of the external medium
The transmitted wavelength for the MMI as the following relation[3]

$$\lambda = \frac{n_{NCF}(D+2Z)^2}{L} m \quad (2)$$

Where λ is the wavelength of interference, D is the NCF diameter, L is the NCF length, m is the number of interference order. This indicates the effective core diameter becomes $(D + 2Z)$ producing a shift in the wavelength, m integer.

2.2. METHODS

Step 1: Modeling the Fiber

- Develop or use existing models that describe the propagation of light in an optical fiber with varying diameter and refractive index. This might involve solving Maxwell's equations for the fiber's modes, considering the influence of the external RI.

Step 2: Varying Fiber Diameter

- Investigate how different diameters (NCF) influence the fiber's modal structure, self-imaging length, and resolution. Use simulations or analytical solutions to calculate mode profiles and the impact on transmission.

Step 3: Varying External RI

- Study the impact of varying the external RI from 1 to 1.4 on the fiber's transmission characteristics. This can be modeled by adjusting the refractive index of the medium surrounding the fiber.

Step 4: Measurement of FWHM

- For each set of parameters (diameter, external RI), measure the FWHM of the transmission curve. This can be done through experimental setups or numerical simulations of the fiber's response.

Step 5: Resolving Transmission vs. Wavelength

- Perform a resolution study, looking at how the fiber's ability to distinguish between different wavelengths changes with fiber diameter, external RI, and wavelength.

3. RESULTS AND DISCUSSION

3.1. RESULTS

The transmission spectrum of several diameters were studied, for each diameter its self-image length, the diameters are studied from 50 to 200 μm , 25 μm each step. the results are shown in figures (2,3). The transmission spectrum of each structure was evaluated at the external RI of 1, 1.33, 1.36, 1.4, and 1.44. The length of the fourth self-image position where determined the results are recorded in table 1

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3.2. DISCUSSION

1. Self-Image Length (NCF Length):

- Self-Image Length is a characteristic distance over which the fiber repeats or "focuses" its optical field.
- As the NCF diameter increases, the self-image length also increases. This means that larger diameters provide longer self-imaging lengths. This is typical because larger diameters tend to support more modes, which may result in longer propagation distances before the light field repeats or converges again.

Key Observations:

- Smaller Diameters (50 μm): A shorter self-image length (0.945 cm).
- Larger Diameters (200 μm): The self-image length increases substantially (14.952 cm).

The relationship between NCF diameter and self-image length is likely influenced by the number of modes the fiber can support. Larger diameters typically support more modes and result in longer self-imaging lengths.

2. FWHM at RI = 1:

- Full Width at Half Maximum (FWHM) is a key measure of the sensor's resolution. A narrower FWHM indicates a higher resolution.
- As the fiber diameter increases, the FWHM decreases, implying that the fiber becomes more capable of distinguishing smaller wavelength differences.
 - For example, for 50 μm , the FWHM is 66 nm, while for 200 μm , it is 6.8 nm.
 - This indicates that smaller diameters (single-mode fibers) have broader resonance peaks, while larger diameters (multi-mode fibers) tend to have narrower resonance peaks, improving the resolution.

Key Observations:

- Smaller Diameters: Broader FWHM (66 nm for 50 μm), indicating less resolution.
- Larger Diameters: Narrower FWHM (6.8 nm for 200 μm), indicating better resolution.

The decrease in FWHM with increasing diameter could be due to mode confinement and the interaction between the core modes and the surrounding medium, improving spectral resolution for larger fibers.

3. Tunability (RI between 1 and 1.4):

- Tunability measures how much the fiber's wavelength response shifts as the external refractive index (RI) changes from 1 to 1.4.
- Larger NCF diameters tend to exhibit lower tunability compared to smaller diameters.
 - For 50 μm , the tunability is 65 nm, while for 200 μm , it is 15 nm. This suggests that fibers with smaller diameters are more sensitive to changes in the surrounding medium (refractive index) compared to larger fibers.
 - Smaller diameters (more confined modes) are more sensitive to the external environment, resulting in higher tunability, while larger diameters might be less sensitive due to the broader support for modes.

Key Observations:

- Smaller Diameters: Higher tunability (65 nm for 50 μm), indicating higher sensitivity to external RI changes.
- Larger Diameters: Lower tunability (15 nm for 200 μm), indicating lower sensitivity to changes in external RI.

Expected Trends and Conclusion:

- Resolution and FWHM:
 - The fiber diameter plays a crucial role in determining the resolution (or FWHM). Smaller diameters tend to have broader FWHM, meaning lower resolution, while larger diameters provide narrower FWHM, improving the fiber's ability to resolve smaller wavelength shifts.

- The FWHM decreases significantly as the fiber diameter increases, which suggests that larger fibers may have better resolution. This is especially important for sensing applications where fine wavelength detection is needed.
- Sensitivity to External Refractive Index (Tunability):
 - The tunability of the fiber is more pronounced in smaller diameters, where a slight change in external RI causes a noticeable shift in the transmission characteristics. Larger diameters show reduced tunability, making them less sensitive to external changes in the environment.
 - Smaller fibers are more sensitive to changes in external refractive index, while larger fibers become more stable and less sensitive to external medium variations.

3.3. Figure and tables

Figures 2 and 3 show the field propagation of the fourth self-image position and the transmission at RI between 1 and 1.4, for two diameter ((50 μm and 200 μm). figure 4 and Table 1 show the FWHM of the NCF at different NCF diameters, at RI=1 and the tunability at RI between 1 and 1.4. This image shows a mode interference pattern for a no-core fiber (NCF) structure, simulated using COMSOL Multiphysics at a wavelength of 1.55 μm . Here's a breakdown of what you're seeing:

X-axis: Propagation distance along the fiber (in units of $\times 10^4 \mu\text{m}$), i.e., from 0 to about 1 cm (10,000 μm).

- **Y-axis:** Transverse spatial dimension of the NCF, from $-15 \mu\text{m}$ to $60 \mu\text{m}$.
- **Color Map:** Electric field norm (V/m).
 - Red/Yellow indicates high field intensity.
 - Blue indicates low intensity.

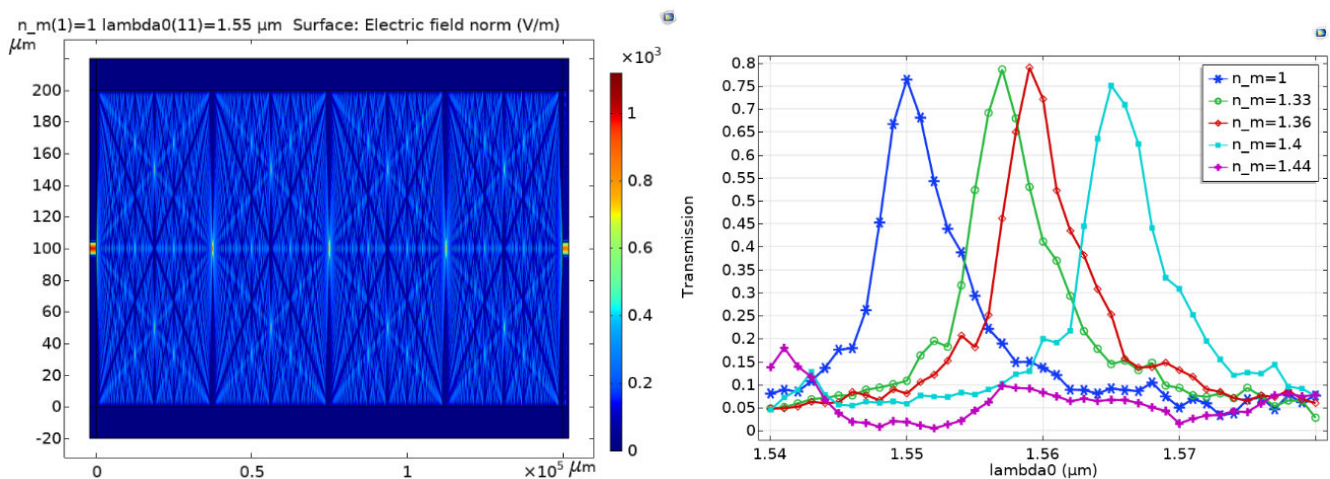


Figure 3 The field propagation of the fourth self-image position and the transmission at RI between 1 and 1.4 for $D=50 \mu\text{m}$.

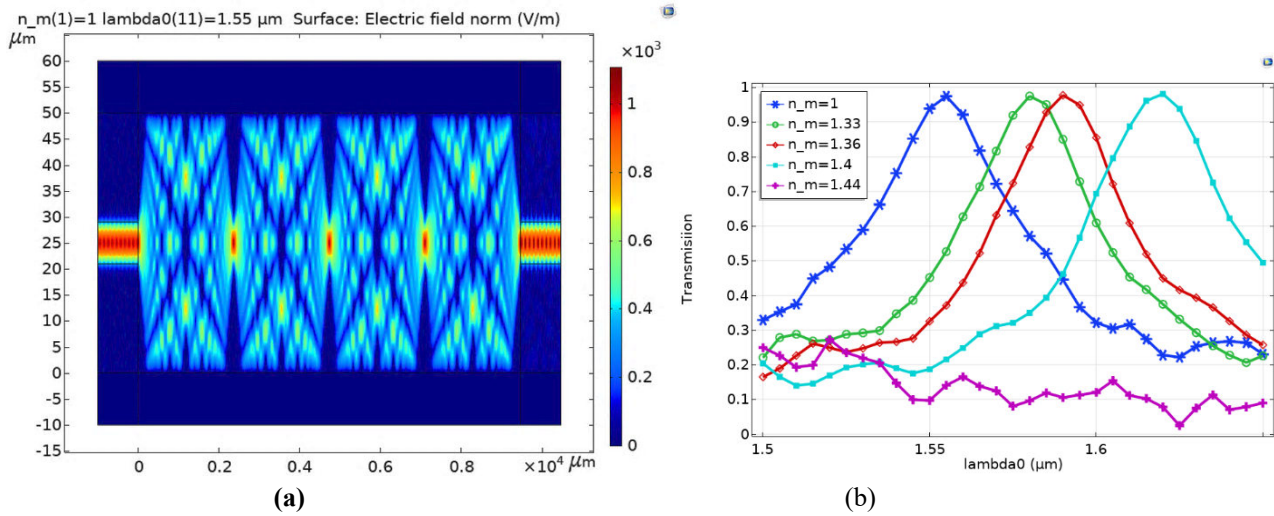


Figure 4 The field propagation of the fourth self-image position and the transmission at RI between 1 and 1.4 200 μm

Table 2 The fourth self-image length of the NCF at different NCF diameters, the FWHM at RI=1 and the tunability at RI between 1 and 1.4.

NCF Diameter (μm)	NCF Length (cm)	FWHM (nm)	Tunability (nm)
50	0.945	66	65
75	2.118	30	40
100	3.754	17	31
125	5.85	11	25
150	8.42	7	20
175	11.45	6.4	17
200	14.952	6.8	15

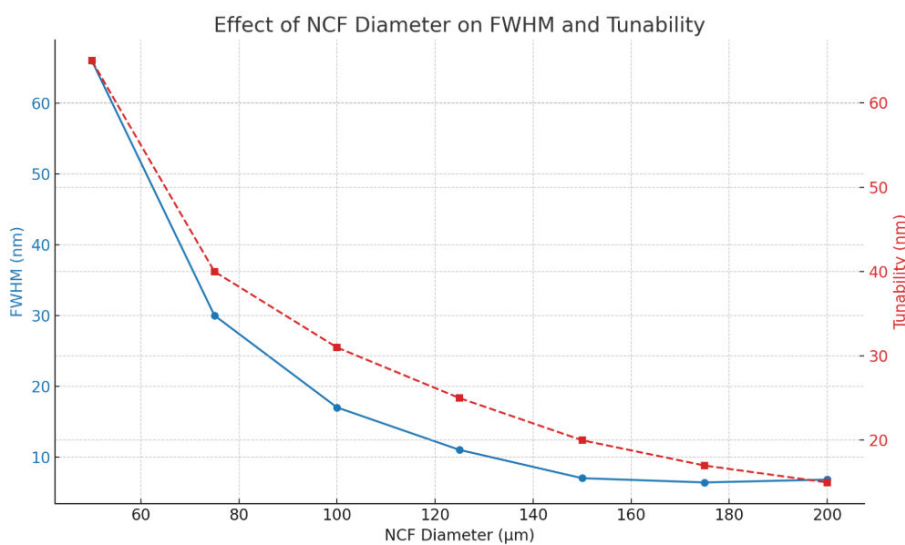


Figure 5 The relation between the self-image order and both the tunability and the FWHM

- **FWHM (blue line)** decreases significantly as the diameter increases, indicating improved resolution.
- **Tunability (red dashed line)** also decreases with diameter, showing reduced spectral flexibility.

From the results, The tunability increase with the core size increasing since the mode number increase and that will produce an increase in the self- image length.

The BW reduce with the increment in the diameter since the higher mode is cut off.

Figure (5) show how the **NCF length** (which corresponds to the **self-image length**) increases with **NCF diameter**.

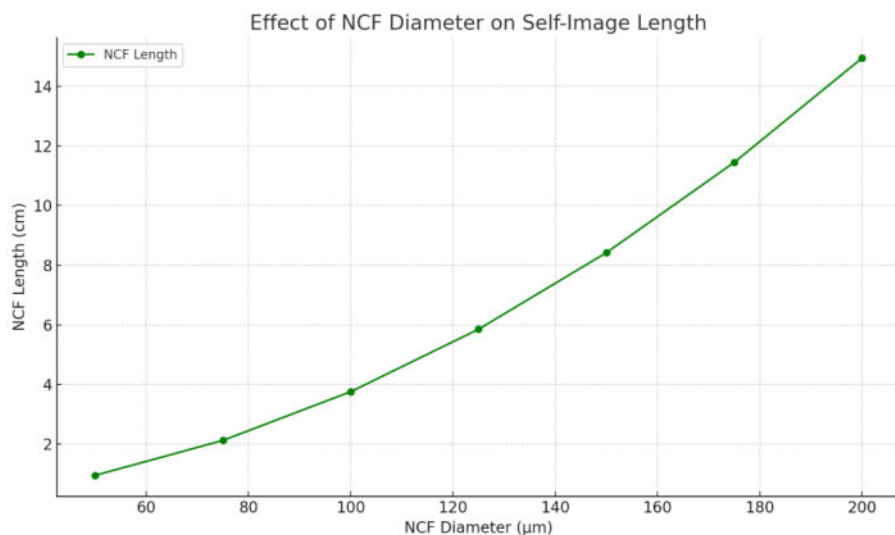


Figure 5 :NCF length (which corresponds to the self-image length) increases with NCF diameter.

The relationship is nonlinear, highlighting how larger diameters lead to significantly longer propagation paths required to form a self-image. Table 2 show the results compare with other related works.

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Ref.	Structure Type	Tenability / Sensitivity	FWHM / Resolution	Key Features
This work	SNS with variable NCF diameters (50–200 μm)	65–15 nm (wavelength shift)	66–6.4 nm (decreases with diameter)	Easy fabrication; tunability vs. resolution trade-off; modeled in COMSOL
[13] Kim et al. (2021)	Cascaded SNS with RI-sensitive materials	~12–25 nm shift (based on RI)	Not explicitly mentioned	Sensing medium influences modal interference; good for RI detection

4. CONCLUSIONS

This study explores the impact of fiber diameter (NCF), external refractive index (RI), and the resulting Full Width at Half Maximum (FWHM) and tunability on the performance of an optical fiber sensor, particularly at the standard wavelength of 1550 nm. The following conclusions can be drawn from the analysis of the data:

1. **Impact of Fiber Diameter on Resolution:**
 - As the fiber diameter increases, the FWHM decreases, indicating improved resolution. Larger fiber diameters allow the fiber to support more modes, leading to narrower resonance peaks, which is beneficial for achieving higher wavelength resolution. This is particularly important for applications where precise measurements of wavelength shifts are required.
2. **Self-Image Length and Fiber Diameter:**
 - The self-image length increases with the fiber diameter, suggesting that larger fibers support a longer propagation distance before the optical field repeats or focuses. This can be crucial for applications where the fiber needs to interact with the external medium over longer distances.
3. **Tunability and External Refractive Index:**
 - Smaller fiber diameters exhibit higher tunability, meaning they are more sensitive to changes in the external refractive index (RI). This is beneficial for sensing applications where environmental changes need to be detected with high precision. Conversely, larger diameters show reduced sensitivity (lower tunability) to external RI changes, making them more stable but less sensitive to subtle variations in the surrounding medium.
4. **Trade-off Between Sensitivity and Resolution:**
 - A trade-off exists between sensitivity (tunability) and resolution. Smaller diameters (50 μm) offer higher tunability, which is advantageous for environmental sensing where small changes in the external medium need to be detected. However, they tend to have broader FWHM, leading to lower resolution.
 - Larger diameters (200 μm) provide better resolution due to narrower FWHM, but they are less sensitive to changes in external RI, making them better suited for applications where stability and high resolution are prioritized over sensitivity to the external environment.
5. **Application Implications:**
 - For applications that demand high-resolution measurements and stability (such as telecommunications or precise optical measurements), larger fiber diameters should be preferred.
 - For sensing applications where detecting changes in the external refractive index is critical (e.g., chemical or biological sensing), smaller diameters are more effective due to their higher tunability and sensitivity to external RI variations.

REFERENCES

- [1] X. Zhu *et al.*, "Detailed investigation of self-imaging in largecore multimode optical fibers for application in fiber lasers and amplifiers," *Opt. Express*, vol. 16, no. 21, p. 16632, 2008, doi: 10.1364/oe.16.016632.
- [2] Y. Tian, W. Wang, N. Wu, X. Zou, and X. Wang, "Tapered optical fiber sensor for label-free detection of biomolecules," *Sensors*, vol. 11, no. 4, pp. 3780–3790, 2011, doi: 10.3390/s110403780.
- [3] J. E. Antonio-Lopez, A. Castillo-Guzman, D. A. May-Arrioja, R. Selvas-Aguilar, and P. Likamwa, "Tunable multimode-interference bandpass fiber filter," *Opt Lett*, vol. 35, no. 3, pp. 324-6 ST-Tunable multimode-interference bandpas, 2010, doi: 10.1364/OL.35.000324.
- [4] Q. Wang, X. Liu, Y. Zhao, R. Lv, H. Hu, and J. Li, "Magnetic field sensing based on fiber loop ring-down spectroscopy and etched fiber interacting with magnetic fluid," *Opt. Commun.*, vol. 356, pp. 628–633, 2015, doi: 10.1016/j.optcom.2015.08.043.
- [5] H. Bhatt and R. Patel, "Optical Transport in Bidispersed Magnetic Colloids with Varying Refractive Index," *J. Nanofluids*, vol. 2, no. 3, pp. 188–193, 2013, doi: 10.1166/jon.2013.1058.
- [6] J. Zheng, J. Li, T. Ning, L. Pei, S. Jian, and Y. Wen, "Improved self-imaging for multi-mode optical fiber involving cladding refractive index," *Opt. Commun.*, vol. 311, pp. 350–353, 2013, doi: 10.1016/j.optcom.2013.08.070.
- [7] Jiang, Y., Zhang, Y., & Xie, L. (2020). "Effect of Longitudinal Stress on Fiber Bragg Grating Sensors and Their Application in Structural Health Monitoring." *Sensors*, 20(7), 2046.
- [8] Li, Z., Zhang, X., & Wei, W. (2021). "Influence of Longitudinal Strain on the Performance of Cascaded Fiber Optic Sensors." *Optics Letters*, 46(5), 1126-1129.
- [9] Liu, Y., et al. (2021). "Longitudinal Stress-Induced Performance Degradation of Fiber Optic Sensors: Mechanisms and Mitigation Techniques." *Journal of Lightwave Technology*, 39(11), 3614-3621.
- [10] Wang, S., & Liu, S. (2022). "Analysis of Longitudinal Strain Effects in Multimode Fiber Optic Sensors." *Sensors and Actuators A: Physical*, 328, 112756.
- [11] He, Y., et al. (2023). "Experimental Study on the Effect of Longitudinal Stress on the Performance of Cascade Fiber Optic Sensors." *Optical Fiber Technology*, 74, 102802.
- [12] Batool M. Saloom, Anwaar A. Al-Dergazly, (2024)"Numerical simulation of optimization the NCF dimension based on spectral response in optic filter", journal of *Optics* , 74, 102802.
- [13] Kim, H. et al. "Cascaded Optical Fiber Structures for Enhanced Sensing Applications." *Optics Communications*, 2021.