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Design and Fabrication of Multi-Cladding Special Fiber-Based Optical Sensors: A Study on Resonant Wavelength Power Transmission

Mohammad Ismail¹, Dr. Rajeev Kumar Singh²

Research Scholar, Department of Physics, Bhagwant University, Ajmer (Raj.), India¹

Assistant Professor, R K College, Madhubani, Bihar, India²

ABSTRACT: Fiber-optic temperature sensors are increasingly being explored for their advantages of rapid response, high sensitivity and immunity to electromagnetic interference. In this study, a novel fiber-optic temperature sensor based on a multi-cladding special fiber is designed and fabricated using the modified chemical vapor deposition (MCVD) technique. The proposed sensor incorporates a four-layer cylindrical structure, with the special fiber spliced between two single-mode fibers (SMF–special fiber–SMF) through fusion splicing. Thermal annealing of the silicone-coated fiber at 100 °C for 10 hours further enhanced its stability. Experimental investigations were performed using a superluminescent diode (SLED, 1550 nm) as the light source and an optical spectrum analyzer (OSA) for spectral characterization, while a temperature-controlled chamber enabled precise tuning of the sensing range.

KEYWORDS: Optical Fiber; Sensor; Fabrication; Transmission.

I. INTRODUCTION

Fiber optic sensor technology has been under development for four decades, leading to the creation of diverse devices such as fiber optic gyroscopes, temperature, pressure and vibration sensors, as well as chemical probes. Fiber optic sensors have many benefits, including enhanced sensitivity relative to current methods and geometric adaptability, allowing for arbitrary form configurations. Fiber optic sensors, being dielectric devices, are suitable for high voltage, high temperature, or corrosive conditions. Moreover, these sensors are compatible with communication systems and provide the capability for remote sensing. Recent investigations in the subject have concentrated on the creation of novel materials exhibiting non-linear optical characteristics for significant potential applications in photonics. Examples of these materials include conjugated semiconducting polymers that integrate optical and electrical features of semiconductors. Furthermore, these conducting polymers exhibit photoluminescent and electroluminescent characteristics, making them appealing for optoelectronic applications. The study and development of fiber-optic sensor devices has broadened their applicability across several technical sectors, including medicine, chemistry and telecommunications. Optical fiber sensors have been engineered to quantify an extensive range of physical characteristics, including chemical variations, strain, electric and magnetic fields, temperature, pressure, rotation, displacement, radiation, flow, liquid level, vibrations, light intensity and color. Fiber-optic sensors are devices capable of functioning in extreme settings where traditional electrical and electronic sensors encounter challenges. Optical fiber sensors are dielectric devices that are typically chemically inert. They do not need electric lines for operation and are technically suitable for functioning in hostile media or corrosive situations for remote sensing applications. The fundamental components of an optical fiber sensor are an optical source, a transducer and a receiver. Lasers, diodes and/or LEDs often serve as the optical source in these sensing apparatuses. Optical fibers (single or multimode), doped fibers and/or bulk materials serve as the transducer (sensor core). A photodetector is used at the sensor system's output to identify changes in the optical signal resulting from physical perturbations in the system. In optical fiber sensor systems, the modifiable optical characteristics include amplitude, phase, color (spectral signal) and state of polarization. Therefore, in view of this, this paper focuses on design and fabrication of a novel fiber-optic temperature sensor based on a multi-cladding special fiber using the modified chemical vapor deposition (MCVD) technique.

Design and Fabrication of the Multi-Cladding Special Fiber-Based Optical Sensors: -

Fiber-optic temperature sensors have garnered significant interest across various domains due to their widely recognised benefits, including rapid reaction time, heightened sensitivity, resistance to electromagnetic interference. Numerous fibre temperature sensors variants with distinct architectures and concepts have been devised. This work presents and showcases a novel fibre temperature sensor that utilises a multi-cladding special fibre. The core and inner cladding of the fibre are composed are formed using the typical modified chemical vapour deposition (MCVD) approach. The exhibited resonant spectrum exhibits a high degree of sensitivity to variations in the refractive index of the fibre coating. Figure 1 represents the refractive index (RI) profile of the proposed multi-cladding special optical fiber, showing how the refractive index varies radially from the fiber's center outward. This step-index refractive index profile with alternating high and low indices is referred to as RI splitting. It allows controlled resonance coupling and high sensitivity in sensing applications (such as temperature measurement in your study). The central high-index core (n_1) combined with multiple cladding layers (n_2 , n_3 , n_4) makes the fiber highly responsive to external perturbations, giving it an advantage over conventional single-cladding fibers.

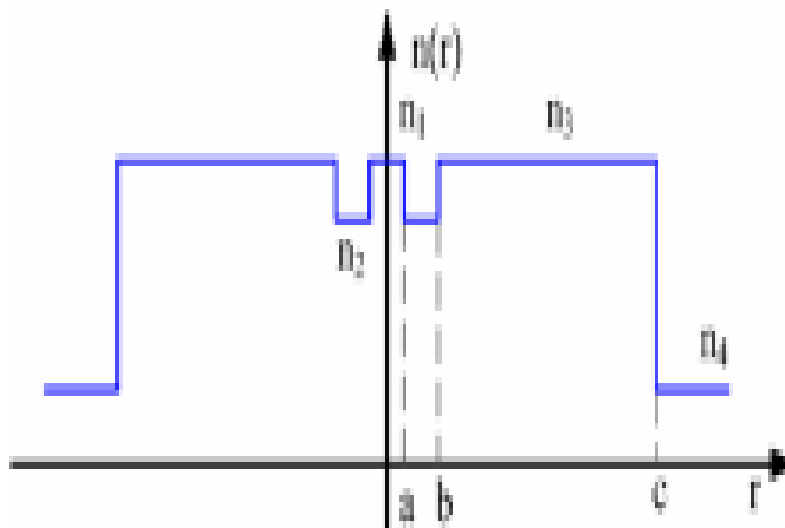


Fig 1: RI splitting of the distinct fiber

The use of the special fibre for temperature sensing involved the splicing of a segment of the special fibre into a standard single mode fibre. This process was carried out using a fusion splicer (FITELE S177), resulting in the formation of a structure consisting of SM fiber-special fiber-SM fibre, as depicted in Figure. In addition, the silicone-coated special fibre underwent thermal annealing at a temperature of 100°C for a duration of 10 hours. The light wave is received by one SM fibre at one end and subsequently collected by the second SM fibre from the core of the special fibre at the other end. By employing this method, one may examine and analyse the resonance spectrum of the unique fibre and its temperature sensing properties. Figure 2 shows the procedure of fabrication. The fabrication of the unique fiber with cladding-mode resonant properties was carried out using the modified chemical vapor deposition (MCVD) process. In this method, a high-purity fused silica tube of 20 mm diameter and 2 mm wall thickness served as the substrate. The deposition of the fluorine-doped layer was achieved using O_2 , Freon, and $SiCl_4$ as reactants, followed by the coating of a pure silica layer using O_2 and $SiCl_4$ at a deposition temperature of around 1500 °C. After deposition, the supporting tube was collapsed into a solid preform at approximately 2000 °C, which was then mounted on a drawing tower and subsequently drawn into fiber at a temperature of about 1800 °C. The refractive index profile of the fabricated fiber around the core and inner cladding regions was examined using an optical fiber analyzer (EXFO NR9200).

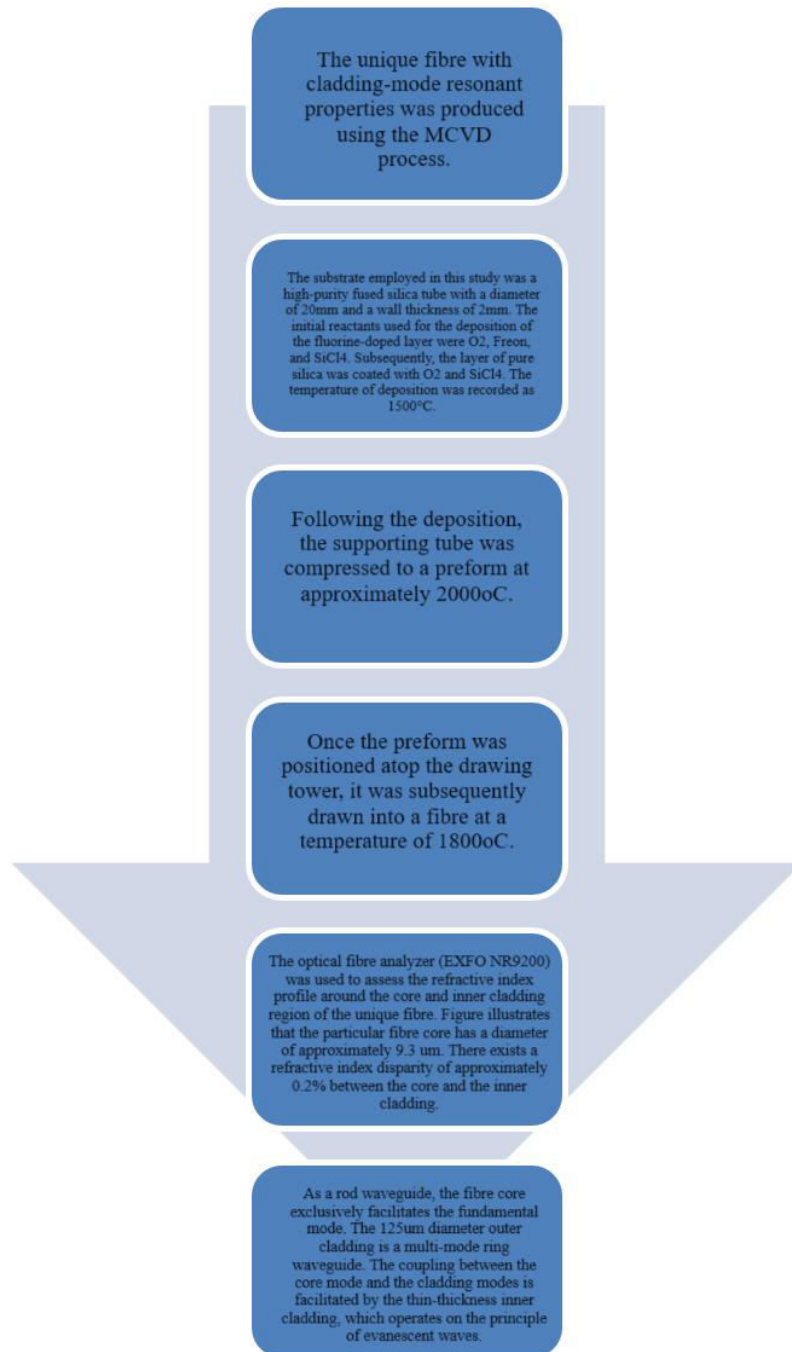


Fig 2: Representation of Procedure

Figure 3 illustrates the refractive index (RI) profile of the fabricated multi-cladding special fiber, highlighting the variation of refractive index across the fiber cross-section as a function of position. The horizontal axis represents the radial position in micrometers (µm), while the vertical axes denote the refractive index difference (left) and absolute refractive index (right). The profile clearly shows distinct regions corresponding to the alternating core and cladding layers. At the center, the core exhibits a higher refractive index, followed by dips corresponding to the inner cladding

with a slightly lower refractive index. The subsequent rise represents the outer cladding, while the final fall indicates the transition to the outermost protective layer or surrounding medium. The observed periodic variation demonstrates the successful implementation of refractive index modulation during the fabrication process, resulting in a structured multi-cladding fiber. This controlled RI distribution is critical for enabling strong mode coupling between the core and cladding modes, thereby enhancing the resonance properties and overall sensitivity of the fiber sensor.

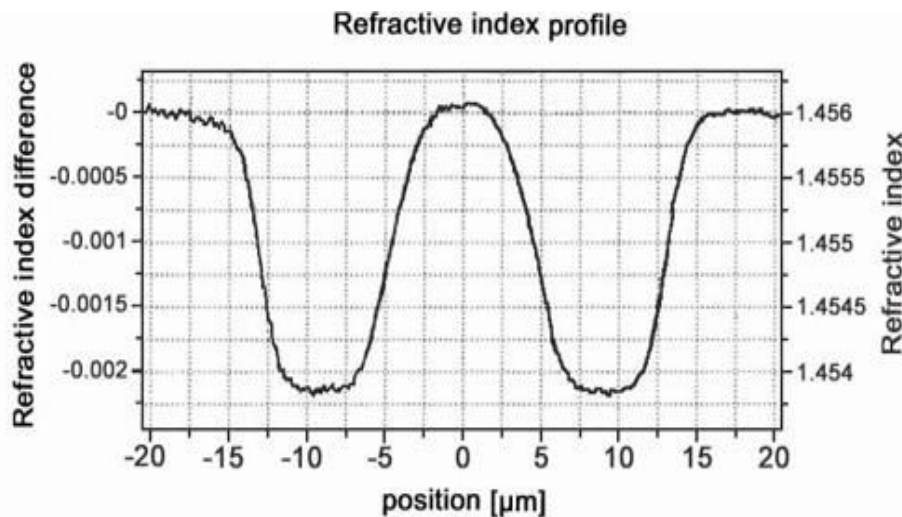


Fig 3: RI Profile

Figure 4 depicts the experimental configuration used to examine the temperature sensing properties. The resonant spectrum was recorded using a superluminescent diode (SLED, SL3200-C42) with a wavelength of 1550nm and an optical spectrum analyzer (OSA and O AQ-6315A). The temperature was adjusted using a temperature-controlled chamber (ESL-04KA). The spliced special fibre had a length of approximately 14mm. In order to mitigate the influence of fibre bending or strain on temperature measurement outcomes, the sensor fibre was suspended in a vertical orientation while being subjected to a load.

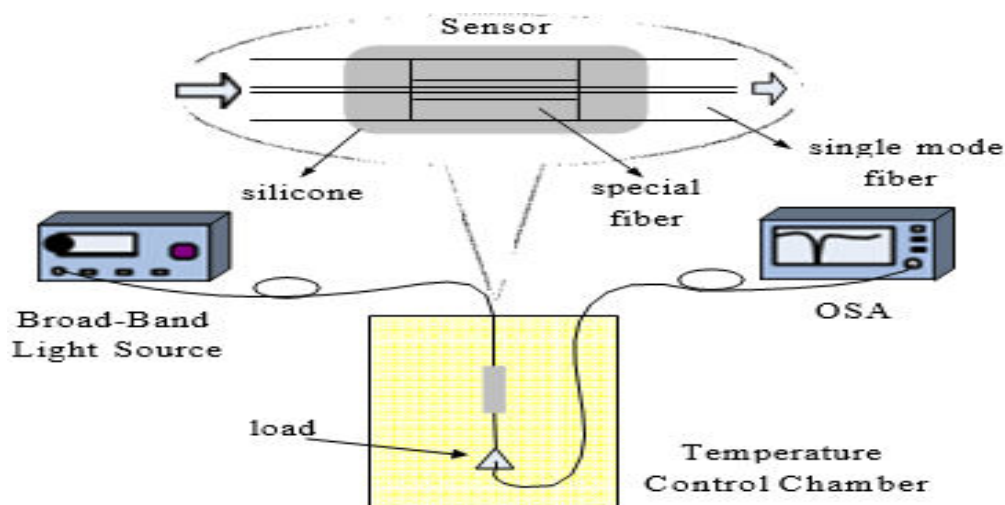


Fig 4: Testing Applicability

An experimental investigation was conducted to examine the relationship between temperature and the resonant spectrum, covering a temperature range of -20°C to $+80^{\circ}\text{C}$. The data presented in Figure 5 demonstrates that when temperature rises, there is a noticeable shift in the centre wavelength of the spectrum towards shorter wavelengths. Furthermore, the overall wavelength shift reaches a maximum value of 21.17nm. The refractive index of the silicone covering material drops with increasing temperature due to its negative thermo-optic coefficient. It can be observed that the resonant wavelength, which satisfies the phase-matching criterion, undergoes a shift towards shorter wavelengths. The experimental curve depicted in Figure 5 illustrates the relationship between the resonant wavelength and temperature. In order to examine the reproducibility, the spectra were subjected to testing across a temperature range spanning from 80°C to -20°C . The sensor exhibits excellent repeatability, as depicted in Figure, when compared to the response observed during the temperature increase process.

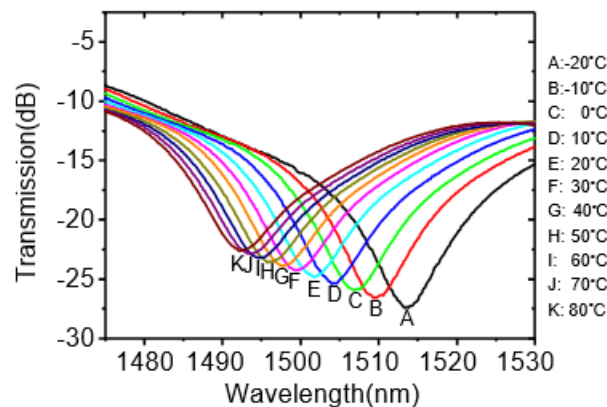


Fig 5: Optical Spectra

The experimental findings depicted in Figure 6 demonstrate the variability of optical power transmission at the resonant wavelength. The transmission at the resonant wavelength exhibits a monotonically increasing trend from -27dB to -22.5dB. The experiment conducted allows for the observation of the fluctuation in transmission at the resonant wavelength, as depicted in Figure. The monotone relationship suggests that the length of the spliced special fibre directly affects its performance in the over coupling region, specifically the $\square\square\square\square\square\square\square\square\square\square$. The concept of monotone response holds significant importance in the context of signal detecting processes within practical applications. Therefore, this work presents a unique fiber-optic temperature sensor that utilises a construction consisting of SM fiber-special fiber-SM fibre. The experimental findings indicate a significant temperature sensitivity. The resonant wavelength shift was tested over a temperature range of -20°C to 80°C , resulting in a total shift of 21.17nm. This shift is significantly more than that observed in traditional FBGs sensors.

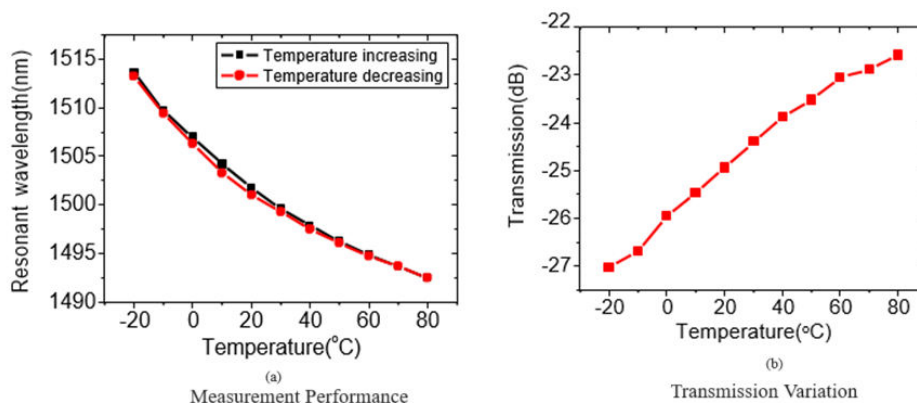


Fig 6: Graphs Showing Variation in Measured Properties

II. CONCLUSION

The present study successfully demonstrates the design, fabrication and characterization of a novel multi-cladding special fiber-based temperature sensor. The fabricated structure, exhibited strong sensitivity to refractive index changes and excellent performance under thermal variations. Experimental observations revealed a significant resonant wavelength shift of 21.17 nm within the temperature range of -20°C to $+80^{\circ}\text{C}$. Furthermore, the monotonic increase in optical power transmission at the resonant wavelength, ranging from -27 dB to -22.5 dB , highlights the effective role of fiber length and coupling conditions in determining sensor performance. The sensor also demonstrated high repeatability during thermal cycling, establishing its stability and reliability for practical use. These findings indicate that the proposed multi-cladding special fiber sensor provides enhanced temperature sensitivity, superior optical transmission characteristics and robust reproducibility, making it a promising alternative to existing fiber-optic sensing technologies.

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