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Tapered No-Core Fibre incorporated with Molybdenum Disulfide-based Refractive Index Sensor

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Abstract. This paper presents the design, fabrication, and sensitivity evaluation of refractive index measurement based on no-core fibre (NCF) based sensor. The NCF sensor undergoes several fabrication processes to enhance sensitivity, including carbon dioxide (CO_2) tapering and molybdenum disulfide (MoS_2) coating. This integration will enable the sensor to exhibit superior sensing responses. Experimental results demonstrated that the coated MoS_2 tapered no-core fibre (TNCF) based refractive index sensor exhibited a significantly higher sensitivity of 113.52992 ± 7.13889 nm/RIU, compared to the sensitivity of coated NCF and bare NCF, which are at 79.73184 ± 5.85083 nm/RIU and 64.9418 ± 4.56332 nm/RIU, respectively. This shows that the TNCF coated with MoS_2 exhibited a higher sensitivity make it a potential candidate for various real-time applications. Professionals in industries related to chemical sensing, environmental monitoring, and industrial process control may benefit from the development of reliable and reusable sensor probes.

Keywords: NCF, TNCF, refractive index, molybdenum disulphide.

1. Introduction

Fibre optics, or optical fibre, is a telecommunications technology that transmits large amounts of information over long distances using thin flexible strands of glass or plastic. It operates on the principle of total internal reflection (TIR), where light signals are guided through the fibre by reflecting off its inner walls, ensuring minimal signal loss [1]. A basic fibre optics system consists of three main components: a light source (typically a laser or LED) that emits modulated light, a fibre optic cable that transmits the light with minimal attenuation, and a detector that converts the light signals back into electrical signals for processing by electronic device.

This paper focuses on the fabrication process of NCF sensors to enhance their sensing capabilities. NCF sensors, made from a single material with a uniform refractive index, function without a central core, allowing for improved interaction between light and the external medium. This design results in exceptional sensitivity to changes in temperature, pressure, and refractive index [2]. Additionally, it simplifies the fabrication process by eliminating complex core manufacturing and chemical treatments used in multi-mode fibre (MMF) production [3]. NCF sensors provide a direct and efficient sensing solution, characterized by multimode interference (MMI), which produces interference patterns applicable in sensing, imaging, and communication [4].

As light propagates through an NCF, it evanescently interacts with the surrounding environment, extending beyond the physical boundary of the fibre and penetrating a short distance into the surrounding medium. This evanescent wave interacts with materials in the environment, inducing changes in its intensity, phase, or wavelength, which can be detected and measured to gather data from the surrounding environment. The extended interaction length within an NCF enhances the sensor's sensitivity with precision, enabling the detection of even the slightest changes in the measured parameter [5].

The performance of NCF can be enhanced by coating optimization. Coating optimization for NCF involves applying specialized coatings to enhance sensor performance. These coatings can boost sensitivity by modifying light interaction, enabling detection of minor changes in the environment [6]. By carefully selecting and designing coatings, the sensitivity of the NCF can be improved for specific sensing applications. Figure 1 depict the SMF-NCF-SMF sensing structure.

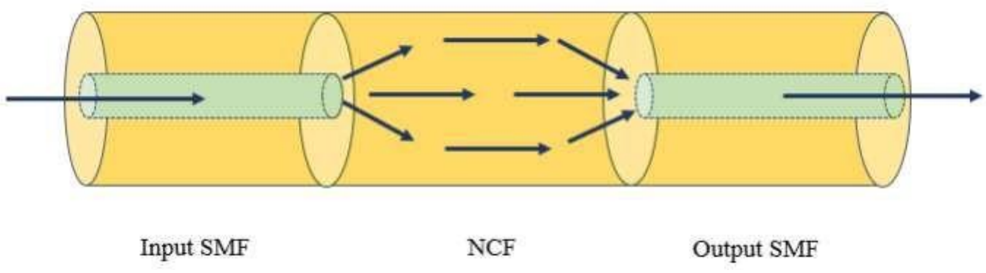

Figure 1 SMF-NCF-SMF sensing structure

Tapering optical fibres is a crucial technique for enhancing the performance of optical sensors. This process involves heating and gently stretching a section of the fibre to create a tapered structure, which improves sensitivity and efficiency by modifying light propagation characteristics. The reduction in fibre diameter allows more light to be confined to the core, facilitating greater interaction with the surrounding medium and enabling effective detection

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of external changes, such as refractive index variations [7]. Traditional tapering methods, including flame torches [8], arc-discharge [9] and chemical etching [10] have limitations in efficiency and uniformity. In contrast, CO_2 laser tapering offers a controlled method for producing clean, symmetrical tapers by focusing a CO_2 laser on a specific fibre section, generating localized heating through infrared light absorption. This technique allows precise control over power, beam diameter, and scanning speed, achieving desired taper dimensions while minimizing external influences [11].

2. Methodology

2.1 Preparation of SMF-NCF-SMF Sensor

The sensor fabrication involves multiple phases. The process starts with fibre stripping, the process begins by stripping the protective coating of single mode fibre (SMF) and NCF using a fibre stripper tool. The stripping process begins on NCF of six different lengths, ranging from 2.0 cm to 4.5 cm, with increments of 0.5 cm each. The stripped process exposes the bare fibre underneath.

Fusion splicing is a technique that joins two fibre optic lines, enabling a continuous and efficient transmission of optical signals. The splicer meticulously aligns the two ends of the fibres to achieve accurate alignment and create a secure splice. This alignment process ensures that the fibres are perfectly align before advancing. An electric arc is used to melt the fibre ends and fuse them together. The fusion process creates a durable, high-quality connection between the fibre strands SMF-NCF-SMF sensor.

Journal of Physics: Conference Series **2974** (2025) 012014 doi:10.1088/1742-6596/2974/1/012014

2.2 Preparations of Ethylene Glycol – Water Solution

The quantity of ethylene glycol (EG) employed in each sample differs by 0 % to 100 %, with a steady rise of 20 % in each subsequent sample. The sample preparation process entails combining water and EG solution. The process starts by adding the appropriate amount of water and the specified quantity of EG to a blank glass container, and the solution been stirred gently. The refractive index of six different EG –water solution compositions been measured. Table 1 shows the refractive index of the prepared samples, respectively.

Table 1 Refractive index value for EG: water ratio solutions

Sample	EG: Water Ratio	Refractive Index (RIU)
1	0:100	1.3321
2	20:80	1.3516
3	40:60	1.3734
4	60:40	1.3935
5	80:20	1.4103
6	100:0	1.4279

2.3 Coating of MoS_2 on NCF and TNCF sensor

The NCF and TNCF sensors being coated with 10 ml of MoS_2 samples. MoS_2's high surface-to-volume ratio and diverse active sites, such as sulfur defects, vacancies, and edge sites, make it an ideal candidate for efficient adsorption of molecules. The ultrahigh surface-to-volume ratio of MoS_2 enhances its reactivity and adsorption capabilities, enabling precise capture of molecules and accurate detection and concentration of target analytes. Additionally, MoS_2's high Young's modulus and flexibility help to maintain the coating's stability and integrity, allowing for consistent and accurate detection [12].

Journal of Physics: Conference Series **2974** (2025) 012014 doi:10.1088/1742-6596/2974/1/012014

To prepare the coating for the optical fibre, 0.5 g of MoS_2 powder will be combined with 60 ml of IPA to createa 0.05 molar solution of MoS_2. The mixture will be agitated using a magnetic stirrer for 30 minutes at room temperature. Following this, the solution will be transferred to an ultrasonic bath and subjected to ultrasonic treatment for a duration of two hours, also at room temperature.This precaution is essential to prevent excessive heating, which could potentially degrade eitherthe solvent or the MoS_2 material [13]. This step is critical for achieving a uniform dispersion of the components within the solution.

The liquid solution is poured onto the NCF and TNCF on a small acrylic slide to create a composite coating on the fibre. The coated sample is dried using the drop-cast technique as shown in Figure 2. It is recommended to let the MoS_2 solution on the fibre optic cable dry for 72 hours at room temperature to ensure complete drying.

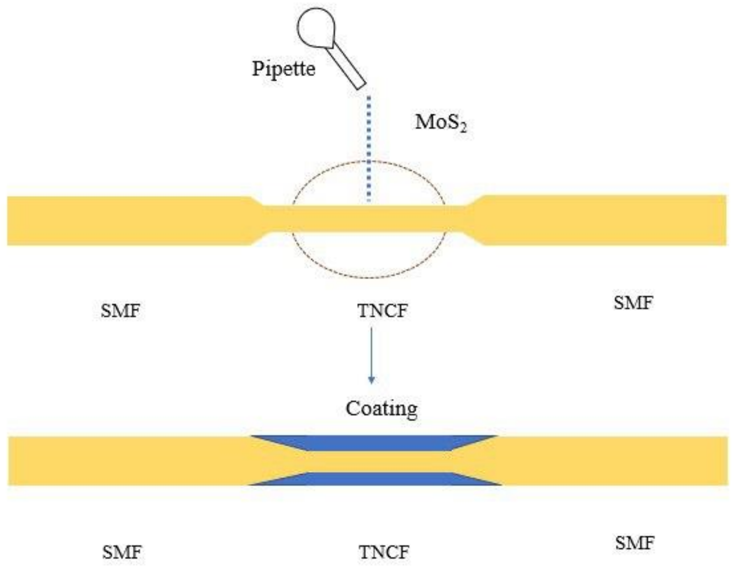

Figure 2 TNCF coating process

2.4 Tapering process by CO_2 laser

The bare NCF is cleansed with IPA to eliminate any undesired dirt or impurities prior to tapering. The power of a CO_2 laser is defined as the amount of laser energy emitted per unit of time, typically measured in watts (W). The optical fibre absorbs energy from the CO_2 laser, converting it into heat, which softens the fibre material. This thermal energy enables precise control over the diameter and shape of the fibre during the tapering process. The CO_2 laser was utilized to perform the tapering process on the NCF, resulting in a reduction in its diameter. This reduction in diameter is expected to enhance the sensitivity of the sensor.

The power in this experiment is set to 24 W to achieve an optimal reduced waist diameter. Very thin fibers tend to experience increased bend losses, which restrict their flexibility and practicality in bending applications. Additionally, these thin fibers can be fragile and more prone to breakage, compromising their durability and reliability. In contrast, thicker fibers may encounter heightened intermodal dispersion and mode coupling, which can lead to a degradation in signal quality.

Figure 3 shows a schematic diagram of the tapering process system, highlighting the main steps involved. Two exact stepper motors pulled the fibre for a length of 5 mm during the heating phase, operating at a speed of 700 rpm, respectively. The diameters of the TNCF weremeasured using the AmScope microscope. Figure 4 illustrates the diameters of the TNCF. TheTNCF will also be coated with 10 ml of MoS_2 solution to serve as a sensor to detect changes in the refractive index of an EG-water solution.

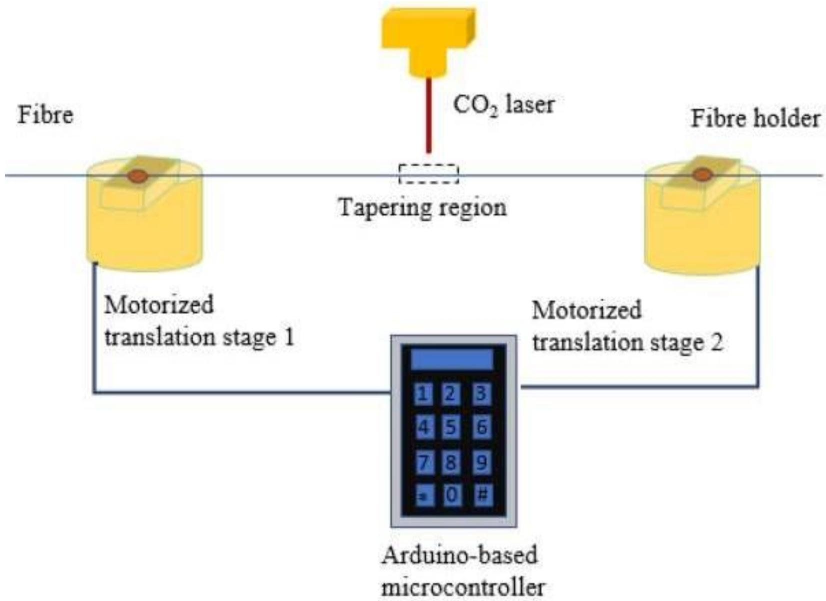

Figure 3 Taper process of NCF by using a CO_2 laser

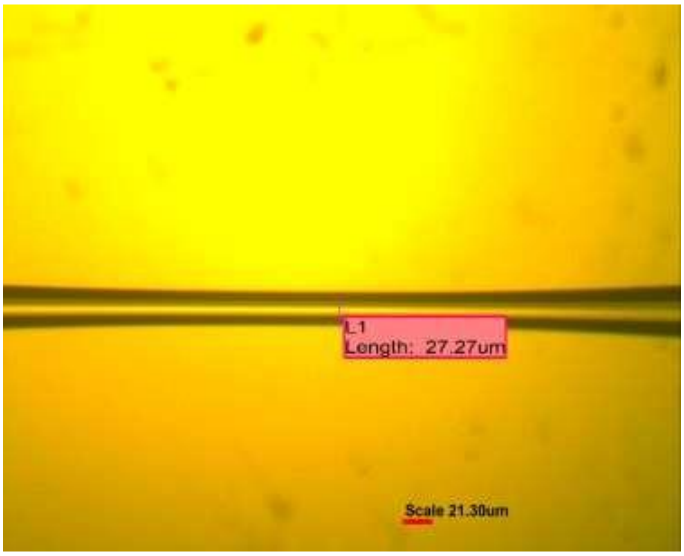

Figure 4 Diameter size of NCF: power 24 W

2.5 Experimental Setup

The experimental setup shown in Figure 5 was used to study on the fibre's reaction to various external refractive indices. The stripped fibres were connected to a Halogen-Tungsten white light source using FC-FC fibre connectors. The NCF, coated NCF and coated TNCF, functioning as the sensing element, was positioned on a glass slide and applied with EG-water solutions. The opposite side of the optical cable was linked to a CCS 200 compact spectrophotometer. The Thorlabs optical spectrum analyzer (OSA) software was used to record the optical spectra of EG-water solutions.

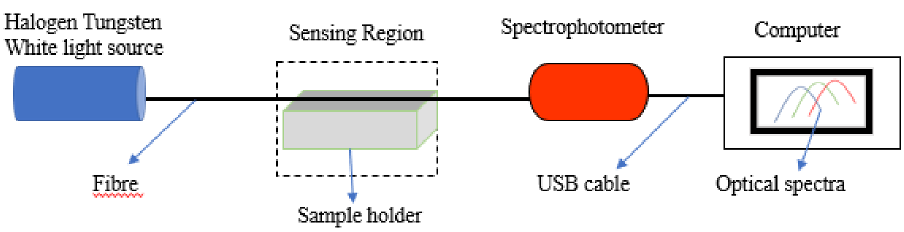

Figure 5 Experimental setup

3. Results and discussions

3.1 Optimization of NCFs lengths

The study utilized various lengths of NCF as the sensing region, ranging from 2.0 cm to 4.5 cm, with increments of 0.5 cm respectively. The SMF-NCF-SMF sensor was employed to detect variations in the sample's refractive index. Preliminary measurements were conducted to determine the optimal length of the NCF. The measurements required detecting alterations in the refractive index of the EG-water solution.

The sensor's mean sensitivity was analyzed and tabulated in Table 2. Data analysis shows that the 3.0 cm NCF length has the highest average sensitivity of 62.28 nm/RIU compared to others. The results indicate that the sensor equipped with a 3.0 cm NCF is better at detecting and reacting to variations in refractive index than sensors with other NCF lengths.

Table 2 Sensitivity of NCF at different sensor lengths

NCF length (± 0.1) cm	Sensitivity (nm/RIU)			
	1st Measurement	2nd Measurement	3rd Measurement	Mean
2.0	56.46	54.14	56.57	55.72
2.5	49.30	44.25	48.05	47.20
3.0	62.45	59.44	64.94	62.28
3.5	58.85	56.68	59.98	58.50
4.0	59.60	58.04	56.12	57.92
4.5	59.01	58.05	54.94	57.33

Figure 6 illustrates the relationship between the wavelength shift and the refractive index change of the sample, utilizing a 3.0 cm length of NCF as the sensing region. The graph depicts how the wavelength shifts vary in response to changes in the refractive index of an EG-water solution, ranging from 1.33 to 1.43, respectively.

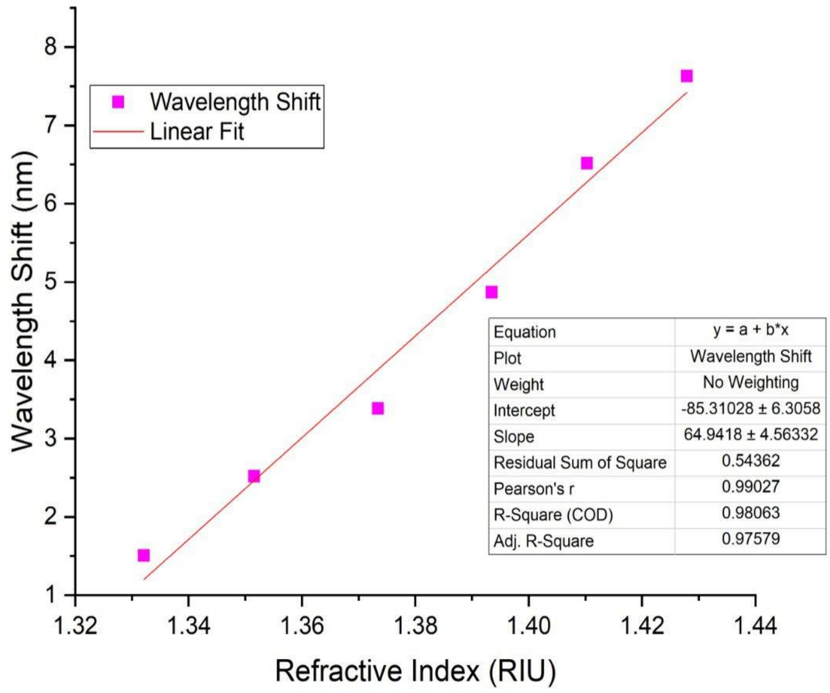

Figure 6 Sensitivity value obtained from 3.0 cm of NCF

Due to its high sensitivity, the 3.0 cm NCF is chosen for coating and tapering process. This comparison will assess the potential enhancement in the sensor system's abilities for refractive index detection.

3.2 Ethylene Glycol – Water Solution Detection by Coated NCF and TNCF

The 3.0 cm NCF and TNCF, coated with 10 ml of MoS_2, were designated as the sensing regions and subjected to tests for detecting various refractive indices of an EG-water solution. These measurements were compared against the uncoated NCF, which served as a baseline for evaluating the sensitivity of the coated NCF and TNCF. The sensitivity values for the coated NCF and coated TNCF are illustrated in Figures 7 and 8, respectively, with measured values of 79.73184 ± 5.85083 nm/RIU and 113.52992 ± 7.13889 nm/RIU. These values weredetermined based on the wavelength shift corresponding to changes in the refractive index of the EG-water solution.

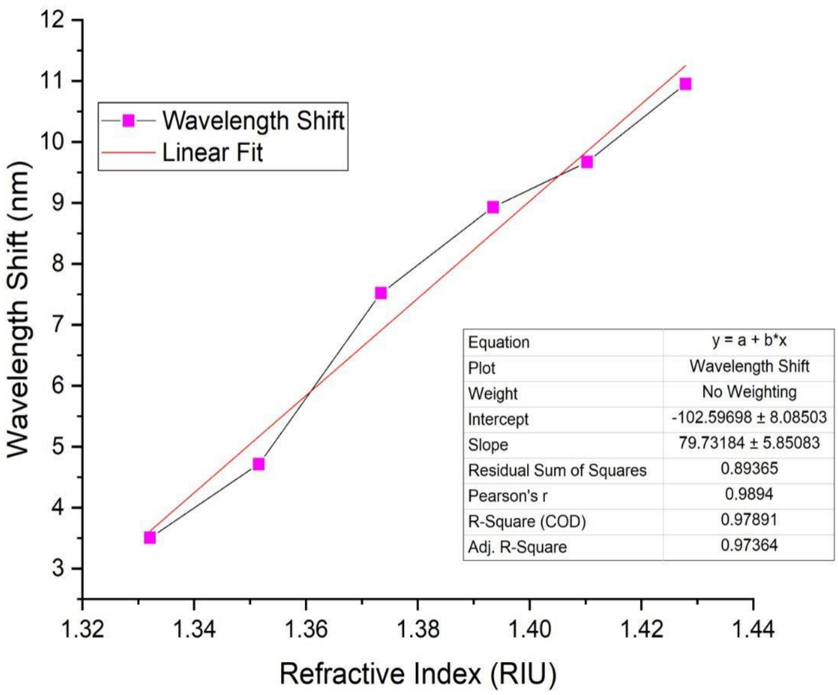

Figure 7 Sensitivity value of coated NCF

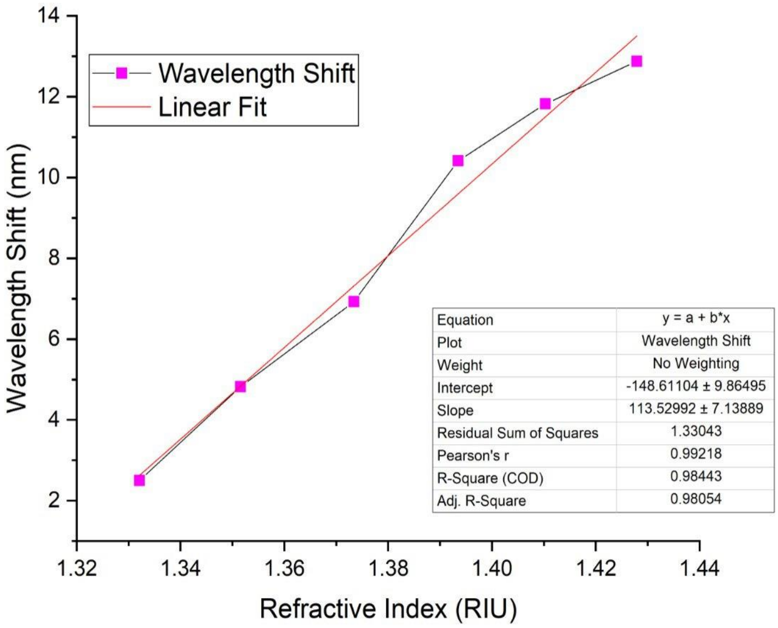

Figure 8 Sensitivity value of coated TNCF

The results indicate that the coated TNCF exhibits greater sensitivity compared to both theuncoated NCF and the coated NCF. This finding supports the hypothesis that the sensitivity of the sensor improves as the NCF undergoes fabrication processes such as coating and tapering. The enhancement in sensitivity can be attributed to the increased generation of evanescent waves within the sensor, which modifies the interaction of light with the surrounding mediumdue to tapering.

Additionally, the coating enhances adhesion to the substrate, ensuring the sensor's structural integrity during operation. It also modifies the refractive index at the sensor's surface, further improving the interaction between light and the surrounding medium, which contributes to the overall increase in sensitivity. Table 3 illustrates a comparison the sensitivity between naked NCF, coated NCF and coated TNCF.

Table 3 Sensitivity of NCF, coated NCF and coated TNCF

	NCF	Coated NCF	Coated TNCF
Sensitivity (± 0.00001 nm/RIU)	64.94180	79.73184	113.52992

4. Conclusion

The findings indicate that a length of 3 cm is the most effective for achieving the desired sensitivity level in detecting changes in refractive index, with an average sensitivity of 62.28 nm/RIU. This suggests that this specific length optimally maximizes the interaction between the evanescent field and the sample. While a longer length may provide a larger interaction area, it does not necessarily lead to increased sensitivity beyond a certain threshold. Therefore, the 3.0 cm NCF will be selected for subsequent coating and tapering processes.

The coated TNCF demonstrates superior sensitivity compared to both the bare NCF and the coated NCF, with a sensitivity measurement of 113.52992 ± 7.13889 nm/RIU. This observation aligns with the literature, which suggests that the fabrication of the fiber synergistically enhances the sensor's performance. Tapering increases the evanescent field, while the coating offers additional advantages, such as protection against environmental factors and improved interaction with target substances. The combination of these effects results in a highly sensitive sensor capable of detecting subtle changes in the refractive index of the surrounding medium, thereby establishing it as a valuable tool for various applications in sensing technology.

5. Acknowledgement

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