Journal of Contemporary Issues in Business and Government Vol. 28, No. 01, 2022
https://cibgp.com/

P-ISSN: 2204-1990; E-ISSN: 1323-6903
DOI: 10.47750/cibg.2022.28.01.043

ANALYSIS ON APPLICATIONS OF OPTICCAL FIBER ON BRILLOUIN SCATTERING PHENOMENA

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ABSTRACT
It has been demonstrated that Raman distributed optical fibre sensing is a mature and versatile scheme that provides a great deal of flexibility and effectiveness for the distributed temperature measurement of a wide range of engineering applications. This is an advantage that Raman distributed optical fibre sensing has over other established techniques. Over the course of the last few decades, this technology has undergone a period of rapid development and has found widespread use in fields ranging from industrial manufacture to scientific research. On the other hand, classical Raman distributed optical fibre sensing suffers from the following four conceptual or technical limitations: (i) The accuracy of the system's temperature measurement is hindered by a difference in the Raman optical attenuation, a low signal-to-noise ratio (SNR) of the system, and a fixed error in the Raman demodulation equation. ii) There is an incompatibility between the sensing distance and the spatial resolution. (iii) The SNR of the system and the measurement time of the system are in direct opposition to one another. (iv) Dual-parameter detection cannot be carried out using Raman distributed optical fibre sensing. This article presents a review of recent developments in performance enhancements and typical applications of Raman distributed optical fibre sensing. These developments are based on the theoretical and technical bottlenecks described above. The performance and accuracy of these systems can be improved by integrating the technology of this optical system with other knowledge-based technologies, such as demodulation technology, for example.

1. INTRODUCTION
An optical fibre is made up of a great number of glass components, the exact number of which can vary anywhere from a few to as much as a few hundred. Cladding is the name given to the layer of glass that surrounds and protects the core of glass fibres that make up the fibre optic cable. In addition to this, the cladding has a tube that is known as a buffer tube protecting it. The strand possesses one additional layer of protection, which is known as the jacket layer.

1. **Core-** It is a thin piece of glass located near the center of the fiber on which the light is transmitted
2. **Cladding-** A glass core surrounds a material on the outside called the outer material. During normal operation, the outer material reflects light back into the core.
3. **Buffer Coating-** Fibers are protected by a plastic coating that prevents damage from the elements.

1.1 How does an Optical Fiber work?
The operation of optical fibres can be explained by the concept of total internal reflection. Since light rays move in straight lines, it is challenging for them to transport large amounts of information because of the nature of their movement. This is a problem. As a consequence of this, making use of this benefit will be extremely challenging in the absence of a very long wire that is devoid of any bends. In order to eliminate this type of distortion, optical cables are constructed in such a way that each individual light beam is curved inward. Light rays travel the length of the optical fibers, reflecting off the inside walls as they travel and transmitting data from one end to the other. Depending on the purity of the material, lights do degrade over greater distances; however, this

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degradation occurs at a rate that is significantly lower than when using metal cables. The following is a list of the components that can be found in fibre optic relay systems:

1. **Transmitter-**Light signals are produced and encoded in order to be transmitted.
2. **Optical Fiber-**Light pulses (signals) are transmitted through this medium.
3. **Optical Receiver-**The receiver receives the transmitted light pulses (signals) and decodes them into usable signals.
4. **Optical Regenerator-**Data transmission over long distances requires this.

1.2 The Types of Optical Fibers

Optical fibers come in various types based on their refractive indices, materials, and light propagation modes.

According to refractive index, the classification is as follows:

Step Index Fibers: They are characterized by a core covered with a cladding that has a uniform refractive index.

Graded Index Fibers: Increasing distances from the fiber axis cause the refractive index of the optical fiber to decrease.

As a result of the materials used, it can be classified as follows:

- **Plastic Optical Fibers:** Plastic optical fibers have a polymethylmethacrylate core material.
- **Glass Fibers:** They are made of very fine glass fibers.

The following is a classification of light based on its propagation mode:

- Single-mode fibers are used to transmit signals over long distances.
- Multimode fibers are used for short-distance signal transmission.

There are four types of optic fibers depending on their mode of propagation and refractive index, which are as follows:

- Step index-single mode fibers
- Graded index-Single mode fibers
- Step index-Multimode fibers
- Graded index-Multimode fibers

2. COMPONENTS FUNDAMENTAL TO OPTICAL FIBRE

The three primary components of an optical fibre are illustrated in Figure 1. These components are the core, which is responsible for transmitting light, the cladding, which surrounds the core with a lower refractive index and contains light, and the coating, which shields the fragile fibre that is contained within.

Fig. 1. Components of optical fiber.

2.1. Core

The core of an optical fibre is the most microscopic part of the fibre and is responsible for the transmission of light. The core can alternatively be made of glass or plastic, two more viable materials. Glass composed of silicon dioxide (SiO_2) is used for the core. Five kilometres distant from

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the stuff, we have no trouble seeing anything. In order to raise the Refractive index, the reformation process makes use of several dopants, such as Germania, phosphorus pentoxide, and alumina. Cores are available in a wide range of diameters, each of which corresponds to a certain use. Simply said, the size of the core might range anywhere from 200 to 3.7 metres. The typical diameter is 9 nm in size. The communication cores range from 50 to 62.5 metres in length. In addition to single-mode and multi-mode optical fibres, there is also multi-mode optical fibre available [13]. A single mode of light travels all the way to the centre of the 8 to 10 microns, where it travels at a certain frequency. Either 50 or 62.5 microns is used for the core size of multi-mode cables.

The light is transmitted through the optical fiber's core, which is the smallest part of the fibre. Even while glass makes up the majority of optical fibre cores, there are also those that are constructed of plastic. The ultra-pure silicon dioxide (SiO2) glass that is used in the core is so transparent that one could look through five kilometres of it and believe they were looking through a window. This glass was chosen for its use in the core.

During the manufacturing process, dopants such as Germania, phosphorous pentoxide, or alumina may be utilised in order to increase the refractive index in accordance with predetermined parameters.

Optical fibre cores are available in a wide range of diameters, making them adaptable to a wide variety of uses.

2.2. Cladding

The layer that is furthest away from the core is called the cladding. The cladding encases the core of the optical fibre and brings the refractive index down, making it possible for the fibre to perform its job. Cladding and core are made from the same silicon dioxide-based material and are permanently fused together when using glass cladding as the cladding material. During the manufacturing process, different quantities of dopants are added to the core and the cladding. This ensures that the core and the cladding continue to have a refractive index difference that is 1 percent greater than one another.

The core of a typical fibre optic cable has a refractive index of 1.49 at 1300 nm, while the cladding has a refractive index of 1.47. On the other hand, the values for these variables change depending on the wavelength. The core of the same fibre will have a variable refractive index when viewed through a spectrum of wavelengths [14]. In the same way that the core is created in conventional diameters, the cladding is as well. Glass cladding used to be manufactured separately from core and cladding, but since then, SiO2 has been permanently blended in the form of a liquid. This is necessary for optical fibre to function properly because the cladding's refractive index must be lower than the core's. By fusing the core and the cladding together, we are able to achieve a change in refractive index of 1%. Depending on the frequency, the core of a 1300 nm wavelength has a refractive index of 1.49, while the cladding has a refractive index of 1.47 [15]. Additionally available is cladding with a slandered diameter. The normal width of cladding is between 125 and 140 millimetres. Cores with thicknesses of 9 microns, 50 microns, and 62.5 microns can be supported by cladding with a thickness of up to 140 microns. Cores with thicknesses of up to 100 microns can also be supported by cladding with a thickness of up to 140 microns.

3. PRINCIPLES AND LIMITATIONS

3.1 Principles

Raman scattering is a type of optical scattering in which the interaction of a pulsed light with molecular motion changes the frequency of the incoming light as it travels through the sensing fiber56. Raman optical fibre sensing is based on the principle of Raman scattering. The pulsed light will either absorb or emit optical phonons from or to the sensing fiber, and as a result, it will either get converted into an anti-Stokes light that has a high frequency or a Stokes light that has a lower frequency, depending on which state it is in. Both the anti-Stokes and the Stokes Raman photons can be represented by the following equations, (1) and (2), respectively:

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$$hv_s = h\left(v_o - \Delta v\right) \quad (1)$$

$$hv_{as} = h\left(v_o + \Delta v\right) \quad (2)$$

where vs and vas are the frequencies of the Raman Stokes signal and the anti-Stokes signal, respectively; h is the constant associated with the Planck constant; and vo is the frequency of the incoming signal when it first occurred.

At the moment, the techniques for temperature demodulation can be broadly categorised into two groups: the dual-channel demodulation approach and the single-channel demodulation method. Both of these categories are subdivided further into numerous subtypes. The single-channel demodulation technique relies solely on the Raman anti-Stokes signal in order to carry out the self-demodulation process, whereas the dual-channel demodulation technique makes use of the signal ratio that compares the intensity of the Raman Stokes signal to the intensity of the Raman anti-Stokes signal in order to detect the distributed temperature data. A pulsed laser with a wavelength of 1550 nanometers (nm), a Raman filter (or a wavelength division multiplexer with settings of 1550 nanometers, 1450 nanometers, and 1650 nanometers), an avalanche photodetector (APD), an amplifier, a data acquisition card (DAC), and a computer are the components that make up the dual-channel demodulation scheme. This is illustrated in Fig. 1(a). A spontaneous Raman scattering happens at all locations along the sensor fibre when a pulsed laser is inadvertently linked to the optical fibre. The backscattered signals that arrive at the Raman filter can be separated into an anti-Stokes signal (1450 nm) and a Stokes signal (1650 nm). After that, these two optical signals pass through the avalanche photodetector and then into the amplifier, where they undergo photoelectric conversion and then are amplified, respectively. In the final step, the digital signal is sent to the computer for processing in the form of temperature demodulation. This step is accomplished by passing the signal through the data acquisition card. The temperature variation information that is dispersed along the fibre may be accurately retrieved using the dual-channel demodulation approach, as shown in Figure 2(b), which exposes this information. On the other hand, the single-channel demodulation approach utilises the Raman anti-Stokes light to resolve the distributed temperature information along the optical fiber, and the experimental equipment that corresponds to this method is represented in Figure 2 below (c). Figure 2 presents a visual representation of the outcomes of the dual-channel demodulation approach (d). In contrast to the dual-channel demodulation system, the single-channel demodulation system consists of nothing more than an amplifier and an analogue phase detector (APD).

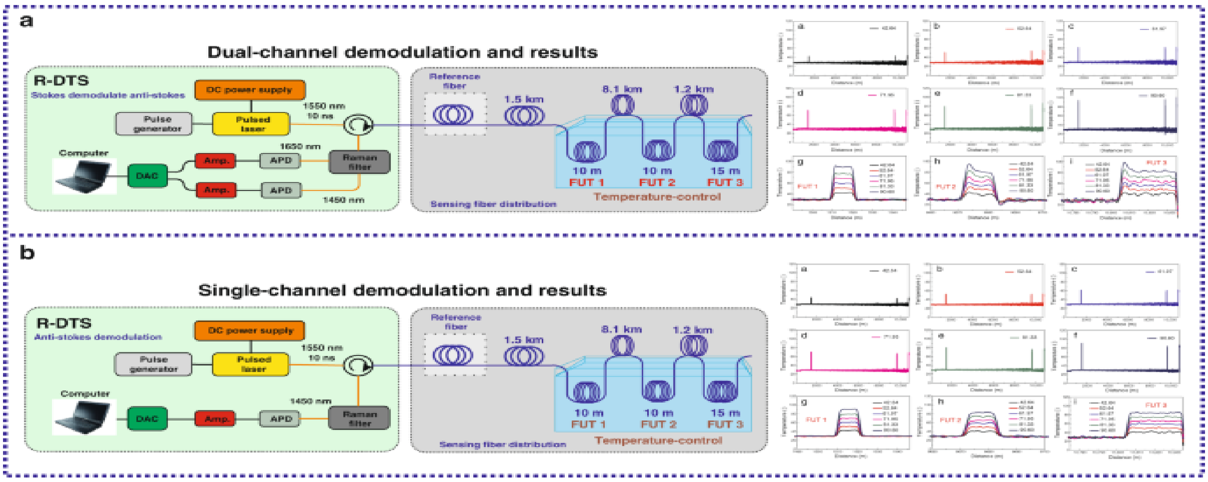

Fig. 2: Experimental setup and results of the Raman distributed optical fiber sensor.

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a Experimental setup and typical results of the dual-channel demodulation principle. **b** Experimental setup and typical results of the single-channel demodulation principle.

4. MECHANISMS OF MEASUREMENT IN DOFS BASED ON BRILLOUIN AND RAMAN SCATTERING IN TIME DOMAIN

In this section, we will describe how each of the three scattering phenomena that were covered in the section before this one can be used in a sensing scheme for distributed measurement of a particular physical parameter in an optical fibre in time domain. This will be done so that the parameter can be measured in a distributed manner. In DOFS that is based on the time domain, the common method for probing the sensing fibre is a brief flash of laser light. Because the speed of light in the fibre is known, the relative time delay of the backscattering signal from a reference instant is used to locate the response from each specific point along the fibre. This allows for the construction of a spatial trace of the backscattering signal, which will then be further processed in order to extract a particular parameter at any location that is desired.

4.1 Raman Distributed Temperature Sensing (RDTS)

The fact that the intensity of the anti-Stokes scattering optical fibres is dependent on the ambient temperature in the neighbourhood of the fibre makes it possible to measure temperature in a distributed manner using SpRS. This property of anti-Stokes scattering optical fibres makes distributed temperature measurement using SpRS possible. The ratio between the two is denoted by the symbol and can be calculated using the following formula:

$$R(z) = \frac{I_{AS}}{I_S} = \left(\frac{\lambda_S}{\lambda_{AS}}\right)^4 e^{-\Delta E / k_B T} = \left(\frac{\lambda_S}{\lambda_{AS}}\right)^4 e^{-\hbar\Omega_R / k_B T}$$

where Ω_R is the Raman frequency shift and $\Delta E = -\hbar\,\Omega_R$ is the energy difference between the incident and scattered light. The dependence of the ratio between the Stokes and anti-Stokes components on temperature comes from the population levels of the excited vibrational modes of the glass in thermodynamic equilibrium. The anti-Stokes process requires a pre-existing optical phonon, which is more likely to occur at higher temperatures. Specifically, the phonons in the different vibrational energy states follow Boltzman's distribution with temperature and the ratio of the anti-Stokes to Stokes intensities scales exponentially with temperature.

The use of SpRS for measurement of distributed temperature in time domain is known as Raman Distributed Temperature Sensing (RDTS), and its basic schematic is shown in Figure 3. Light from a pulsed laser is sent into the sensing fiber through a circulator and Raman filter with output at the Stokes and anti-Stokes lights is used to separate the two components of the backscattered light, which are detected using Avalanche Photodiodes (APDs), amplified using the Trans-impendence Amplifiers (TIAs) and acquired for further processing.

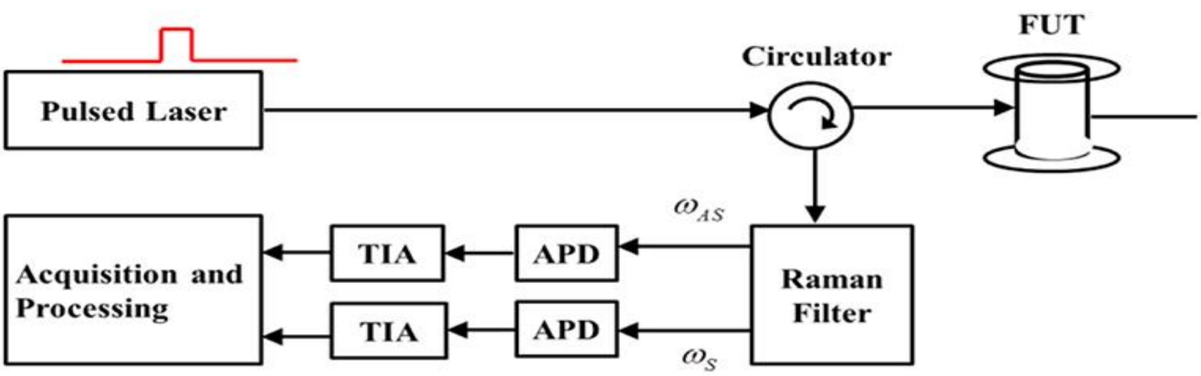

FIGURE 3. Schematic of a basic RDTS.

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4.2 Improvement of temperature measurement accuracy

The key sensing index of the system is temperature measurement accuracy, which indicates the deviation of the measured temperature from the actual temperature value. This deviation is denoted by the term "temperature measurement error." It is possible to figure out using either the standard deviation of the recorded temperature or the uncertainty of the reading. The following are the primary factors that contribute to an error in the system's temperature readings: (1) the optical attenuation difference between the Raman Stokes anti-Stokes signals; (2) the limitation of signal-to-noise ratio; (3) the demodulation deviation of the Raman transmission equation; and (4) the principle of optical time domain reflection causes the temperature signal in the spatial scale of the pulse width to be compressed into a point, and then the temperature signal detected at this point serves as the final reading. In this particular instance, researchers came up with a number of innovative temperature demodulation algorithms and demonstrated their effectiveness in improving the temperature accuracy. This section provides a more in-depth explanation and analysis of the research progress that has been made in relation to the enhancement of the system's accuracy in terms of temperature measurement.

5. COMPENSATION FOR DIFFERENCE IN THE RAMAN OPTICAL ATTENUATION

In the traditional method of demodulation, the information regarding the ambient temperature was demodulated by using the intensity ratio of the Raman Stokes data and the anti-Stokes data. However, when excited by light with a wavelength of 1550 nm, the Stokes and anti-Stokes signals produced by the Raman spectrometer have a wavelength difference of approximately 200 nm. In typical single-mode fibers, the attenuation of incident light at 1550 nm is 0.2 decibels per kilometer, while the attenuation of light at 1310 nm is 0.4 decibels per kilometer. As a result, when this intensity ratio is directly used for temperature demodulation, a measurement error will invariably be introduced. This is also the primary reason why early systems were unable to surpass a sensing error of 1.0 km, which was one of the reasons why early systems failed to meet their goals. To compensate for this measurement error and improve the accuracy of the temperature reading, some more sophisticated methods have been demonstrated so far.

5.1 Dual laser pumping

As shown in Fig. 4(a1), Suh and Lee used two optical pulse sources of different wavelengths to generate the Raman backscattering signals. Thus, we can obtain two signals with the same wavelength, thereby, achieving a consistency of the Raman optical attenuation coefficient. In the proposed scheme, the wavelength difference between the main laser and the secondary laser is twice the Raman frequency shift. In the experiment, the pulsed signals generated by the main laser and the auxiliary laser are alternately input through the optical switch, and thus, the anti-Stokes backscattered signal from the main laser and the Stokes backscattered signal from the auxiliary laser of the same waveband can be obtained, as shown in Fig. 4(a2). This method can eliminate the fiber dispersion effect introduced by the wavelength difference generated by a single laser, thereby, optimizing the temperature measurement accuracy performance. Therefore, it offers a higher measurement precision in Raman distributed optical fiber sensing. However, the above proposed method requires the main and secondary laser to possess a stable wavelength, resulting in an extra expense (secondary laser).

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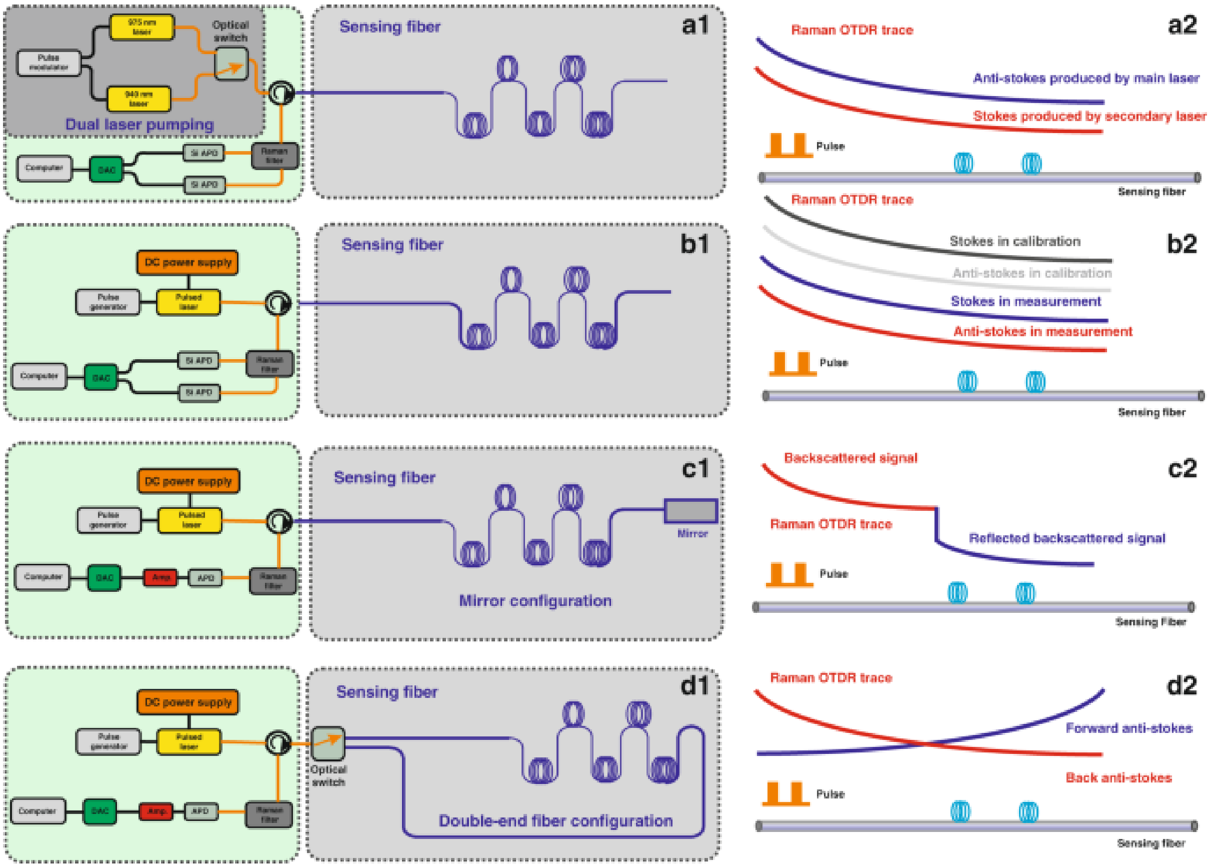

Fig. 4: Advanced compensation schemes for attenuation difference proposed by researchers. **a1** Dual laser pumping scheme. **a2** Raman OTDR traces based on dual laser pumping. **b1** Optical attenuation calibration scheme and (**b2**) Raman OTDR traces based on the optical attenuation calibration scheme of the entire sensing fiber. **c1** End reflection self-calibration scheme. **c2** Raman OTDR traces based on the end reflection self-calibration. **d1** Double-end loop demodulation scheme. **d2** Raman OTDR traces based on double-end loop demodulation.

Advantages of Using Optical Fiber

Although Optical fiber is preferred for many reasons, out of all a few five main reasons are listed herein:-

- **Lower Transmission Losses-** In optical fibers, total internal reflection takes place which leads to low loss of data. Large spacing between the repeaters is also possible when the possibility of data loss is lower. Optical fiber can be used for long-distance communication and the transmission Losses can take place up to 0.2 decibel/km. Negligible transmission Losses in optical fibers are due to material absorption, linear and non-linear scattering, and Fiber bend losses.
- **Huge Bandwidth Potential-** Light rays are used as wave carriers. The light rays have a very high frequency. The optical fibers provide a very large bandwidth due to this high-frequency carrier since as the carrier frequency increases, the bandwidth also increases. The bandwidth ranges about 10^{14} Hertz.
- **High Flexibility, thin, small-sized, and moderate weight-** The diameter of the optical fibers are very small and occupies very little space. These are light-weighted and easy to transport and store. Optical fibers can be used in populated areas so that the fibers can reduce congestion by occupying less space.

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- **Electrical Isolation-** Optical fibers are made of silica which is insulators. The light rays travel inside the insulating material. Hence, there are fewer chances of electrical shocks, short circuits, and sparking hazards.
- **Signal Security-** Hacking of signals is not possible. So if someone tries to steal the signals, they can be detected easily. Hence, this system is mostly used in banking, military, and secret missions.
- **Cost-effective-** It is available at a lower cost compared to the other modes of communication and the encryption process is also easier.
- **Less power Consumption-** It absorbs less power compared to other modes of communication as it transmits light which is the fastest mode of transmission.

CONCLUSION

In this paper, we have given a review on recent progresses in terms of the performance enhancement and applications of the Raman distributed optical fiber sensors. This work is concentrated on a retrospect of four aspects of Raman distributed optical fiber sensing, namely, the temperature accuracy, spatial resolution, sensing distance and multi-parameter measurements. Specific engineering applications of the sensing system such as, fire monitoring, pipeline leak detection, fault detection in power systems and structures such as dams have also been discussed and detailed. In summary, this review aims to clarify the current challenges, theoretical limitations and corresponding solutions of Raman distributed optical fiber sensing, and intends to provide some schemes to break through its limitations for practical applications.

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