Designation: F3079 – 14

# Standard Practice for Use of Distributed Optical Fiber Sensing Systems for Monitoring the Impact of Ground Movements During Tunnel and Utility Construction on Existing Underground Utilities[1]

This standard is issued under the fixed designation F3079; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This practice specifically addresses the means and methods for the use of distributed optical fiber sensors for monitoring ground movements during tunnel and utility construction and its impact on existing utilities.

1.2 This practice applies to the process of selecting suitable materials, design, installation, data collection, data processing and reporting of results.

1.3 This practice applies to all utilities that transport water, sewage, oil, gas, chemicals, electric power, communications and mass media content.

1.4 This practice applies to all tunnels that transport and/or store water or sewage.

1.5 This practice also applies to tunnels that carry the utilities in (1.3), water for hydropower, traffic, rail, freight, capsule transport, and those used for storage.

1.6 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E2586 Practice for Calculating and Using Basic Statistics

2.2 *Other Standards:*

IEC 61753-1 Fibre Optic Interconnecting Devices and Passive Components Performance Standard—Part 1: General and Guidance for Performance Standards[3]

IEC 61757-1 Fibre Optic Sensors—Part 1: Generic Specification[3]

COST Action 299 "FIDES" Optical Fibres for New Challenges Facing the Information Society[4]

ITU-T G.652 Characteristics of a Single-mode Optical Fibre and Cable[5]

## 3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *accuracy*—the closeness of the measured value to the true or the ideal value of the parameter being measured. Accuracy represents the difference between the measured result and the true value and is affected by both bias and precision.

3.1.2 *attenuation*—the decrease in power of a signal, or light wave, from interaction with the propagation medium. The decrease usually occurs as a result of absorption, reflection, diffusion, scattering, deflection, dispersion or resistance.

3.1.3 *attenuation budget (also called optical power dynamic range and link budget)*—the maximum cumulative one-way or two-way power loss between the interrogator and the measurement point that allows a measurement with a specified performance.

3.1.4 *bias*—the difference between the measured result after averaging and the 'true' value. The true value can be obtained either by measuring a reference standard maintained by the national standard organizations or by using a traceable measuring instrument.

3.1.5 *bofda*—Brillouin optical frequency domain analysis.

[1] This test method is under the jurisdiction of ASTM Committee F36 on Technology and Underground Utilities and is the direct responsibility of Subcommittee F36.10 on Optical Fiber Systems within Existing Infrastructure.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from International Electrotechnical Commission (IEC), 3, rue de Varembé, P.O. Box 131, CH-1211 Geneva 20, Switzerland, http://www.iec.ch.

[4] For additional information, visit http://www.cost.eu.

[5] Available from International Telecommunication Union (ITU), Place des Nations 1211, Geneva 20, Switzerland, http://www.itu.int.

3.1.6 *bofdr*—Brillouin optical frequency domain reflectometry.

3.1.7 *botda*—Brillouin optical time domain analysis.

3.1.8 *botdr*—Brillouin optical time domain reflectometry.

3.1.9 *characteristic frequency and/or wavelength at reference temperature (Brillouin technologies)*—the wavelength that characterizes the sensor response at reference temperature as monitored by the interrogator. As Brillouin frequency varies with wavelength of the light source, this also changes the temperature and strain coefficients for various sensing fibers. Therefore, the characteristic frequency and the wavelength at a specified reference temperature and at zero strain are usually provided by the producers.

3.1.10 *cladding*—optical transparent material over the core of the fiber optic cable, with a refractive index lower than that of the core, to provide total internal reflectance.

3.1.11 *connector*—coupling device that permits a signal to pass from one optical fiber to another.

3.1.12 *connector insertion loss*—the power loss due to the insertion of a connector between two elements.

3.1.13 *contractor*—usually, the entity in charge of construction of the new tunnel or other infrastructure that may impact the utility.

3.1.14 *core*—the primary light-conducting region of an optical fiber. The refractive index of the core is higher than its cladding, the condition necessary for total internal reflection.

3.1.15 *cross-sensitivity*—the unwanted change of measured result due to the influence of physical factors other than the measured parameters.

3.1.16 *distributed optical fiber sensor system (DOFSS)*—a system using optical fiber cable as a sensor, without discrete elements such as wound mandrels or fiber Bragg gratings, that is sensitive over its entire length to deliver spatially continuous and resolvable data on the desired measured parameters.

3.1.17 *drift*—a slow change in time of the monitoring characteristics of the measurement system.

3.1.18 *durability*—a quality of a manufactured component of a measurement system or of the entire measurement system measured by how well it withstands a sustained period of specified operation.

3.1.19 *engineer*—the licensed professional engineer designated by the owner/operator of the utility or the tunnel to represent the owner's/operator's interests during the ground movement monitoring process.

3.1.20 *failure criteria of the sensor*—the measurement uncertainty due to overstressing, overheating and other factors leading to results or data that are unreliable.

3.1.21 *gauge length (GL)*—the length of the fiber that contributes to the measured output value of a single channel.

3.1.22 *life expectancy*—a period of time during which the measuring system or its components are expected to operate according to its specifications for defined conditions.

3.1.23 *limiting conditions*—the extreme conditions that a measuring instrument is required to withstand without damage, needing to switch off or degradation of specified characteristics when it is subsequently operated under its rated operating conditions.

3.1.24 *linearity*—the tolerance to which the transfer response characteristics of a measurement system (scale factor) approximates a straight line over the sensor range of the system. For Brillouin sensors, it means that the range of temperature or strain should be within the Brillouin frequency which is linearly proportional to the strain or temperature. For Optical Frequency-Domain Reflectometry (OFDR) systems it means that the wavelength or frequency shift is linearly proportional to temperature or strain over certain length.

3.1.25 *link budget (also called optical power dynamic range or attenuation budget)*—the maximum cumulative one-way or two-way power loss between the interrogator and the measurement point that allows a measurement with a specified performance.

3.1.26 *location accuracy*—the estimated location of a measurement or other system output, such as a detection report, minus the true location of the stimulus that generated the measurement or output.

3.1.27 *measurement range*—a set of values of measured parameters for which the error of a measuring instrument is intended to fall within specified limits.

3.1.28 *measuring spatial resolution*—the minimum distance over which the DOFSS is able to detect the value of the measured parameter, such as strain or temperature, averaged over this minimum distance, within the specified uncertainty.

3.1.29 *measuring time*—the required time interval needed to obtain a measurement within the specified uncertainty, the spatial resolution, and the system range, including any time required for data post-processing.

3.1.30 *noise*—the random variation in the measurement result unrelated to the measured parameter. It primarily affects the precision of measurement.

3.1.31 *operating temperature range of the measurement unit*—the range of temperatures over which, the measurement unit can collect data on the parameters of interest, without losing its capacity for performance and reliability.

3.1.32 *operator*—the firm hired by the owner to perform operation and maintenance of the tunnel or utility.

3.1.33 *optical fiber sensing cable*—cable formed using one or more strands of optical fiber to sense physical parameters and/or transmit data.

3.1.34 *optical fiber sensor*—composed of one or more optical fiber sensing cables and the associated light signal processing equipment as pertinent to DOFSS defined in 3.1.16.

3.1.35 *optical power dynamic range* (also called *link budget* and *attenuation budget)*—the maximum cumulative one-way or two-way power loss between the interrogator and the measurement point that allows measurement with a specified performance.

3.1.36 *owner*—the person(s) or a governing body charged with construction, operation and maintenance of the underground utility or tunnel system.

3.1.37 *precision*—describes how repeatable a measurement result is. Precision is measured by the estimated standard deviation of a specified series of measurements.

3.1.38 *Rayleigh cotdr*—Rayleigh coherent optical time domain reflectometry.

3.1.39 *repeatability*—the closeness of the agreement between the results of successive measurements of the same measured parameter carried out under the same conditions of measurement. This means that for every one hundred repeated strain or temperature measurements, repeatability is the measure of the highest probability associated with either the strain or the temperature.

3.1.40 *report*—the official written work product or project deliverable that contains a description of the scope of work done, data collected and presented in various forms, interpretation of the data, findings and recommendations for further action.

3.1.41 *reproducibility*—the closeness of the agreement between the results of measurements of the same measured parameter carried out under changed conditions of measurement.

3.1.42 *resolution*—the smallest change in the measured parameter that can be indicated by the measurement system. Not to be confused with precision. This is often called the "quantization interval" of the measurement system.

3.1.43 *responsivity*—the change in the response (output signal) of a complete measurement system to the corresponding change in the stimulus (input signal).

3.1.44 *scale factor*—the inverse of the ratio of a change in the stimulus to corresponding measured change.

3.1.45 *scale factor at reference conditions*—the ratio of the measured input parameter's engineering units to the output parameter's units.

3.1.46 *sensor range*—the range between the smallest and the largest allowable value of the measured parameter.

3.1.47 *spatial resolution*—the minimum distance between two step transitions of the measured parameter in time domain that can be independently observed with a specified performance.

3.1.48 *spatial sampling interval (dx)*—The spatial distance along the fiber between two adjacent outputs of the DOFSS. This is usually controlled by the high-rate temporal sampling interval of the optical detector, dt, and the speed of light in the fiber, cf, using dx = dt*cf/2. The spatial sampling interval shall be at least one-half of the spatial resolution.

3.1.49 *system distance range*—the length of fiber over which the measurement can be performed within the stated precision, or the system can achieve its stated performance (for example, probability of detection, location accuracy...).

3.1.50 *tester*—the person or the entity responsible for carrying out the evaluation of the impact of tunneling or utility construction.

3.1.51 *total internal reflection*—reflection that occurs in a medium when the incidence angle of a light ray striking a boundary of the medium is greater than the critical angle and the entire energy of the ray is reflected back into the medium.

3.1.52 *true value*—the result of a measurement that would be obtained by a perfect measurement with no precision or bias error.

3.1.53 *updating time*—the time interval between updates of the measured value of all channels of the DOFSS. This is the same as the temporal sampling interval for systems other than multi-channel or those that provide data incrementally.

3.1.54 *warm-up time*—the duration from the time power is turned on until the system performs in accordance with all specifications.

3.1.55 *wavelength*—the length of a wave measured from any point on a wave to the corresponding point on the next cycle of the wave.

3.1.56 *wavelength of operation*—the range of wavelengths of optical radiation the sensor uses to provide the required data.

Note 1—Every effort has been made in the above definitions to be consistent with those defined in Cost Action 299 and IEC 61757-1.

## 4. Summary of Practice

4.1 Distributed optical fiber sensing technology has many advantages over current methods using discrete "point" sensors for monitoring ground movements around underground utilities and tunnels. The advantages include, but are not limited to:

4.1.1 Their distributed nature means that there are no monitoring gaps, as compared to conventional point sensors, provided the distributed optical fiber sensing cable is installed over the whole length, area or volume of interest;

4.1.2 A single optical fiber sensing cable can provide tens of thousands of continuously distributed measurement points;

4.1.3 No electricity used within the optical fiber sensing cable; thus, it is immune to electromagnetic interference and does not cause electromagnetic interference (EMI), other than that generated by the electro-optical equipment—which can be shielded and controlled;

4.1.4 They are generally safe in explosive environments;

4.1.5 They can be made robust to chemical exposure through proper design and materials selection for the protective outermost sheath of the cable;

4.1.6 Cost-effective due to the ability to collect data over long distances from a single electro-optical interrogator unit; cable lengths for a single system of 60 miles (100 km) are achievable.

4.2 Successful broader adoption of this technology depends on the proper selection of most appropriate materials, design, installation, data collection, interpretation and reporting user interface design.

4.3 This practice offers the minimum standards on the essential aspects of this technology.

4.4 There are many different technologies that fall within the classification of DOFSS that can be used for measuring ground movement during tunneling or utility construction and its impact on existing utilities. The focus in this practice, however, is solely on the most widely used Brillouin scattering technologies (BOTDR / BOTDA).

4.5 The user of this practice needs to be cognizant that a companion standard covers the standard practice for leak detection in pipelines using Rayleigh Coherent Optical Time Domain Reflectometry (COTDR). That standard describes the complementary technology to Brillouin DOFSS in far more detail. Rayleigh COTDR can also be used for very precise detection of short-term ground movements. It is most applicable, however, to short-term strain events because Rayleigh methods cannot measure very low frequency strain in the presence of the background thermal variation in most environments. This practice's focus is primarily on the most widely used Brillouin technology for measuring long-term strains. The users of this practice may refer to companion standards for specific guidance on the use of other forms of optical fiber sensing technologies to meet the needs of similar or other applications.

4.6 The DOFSS technologies discussed in Section 6 of this practice measure the longitudinal strains along the optical fiber sensing cables to assess the impact of new tunnelling and utility works on existing tunnels or utilities. The conversion of the strain measurements to displacement measurements require processing of the strain data with appropriate assumptions for the boundary conditions. Therefore the resulting indirect displacement measurements are expected to yield an estimate of the in-situ displacements. As a result, the measured ground movements referred to in the text of this practice shall be used bearing this in mind. Better accuracy may be achieved, however, when procedures discussed in 9.3 and 9.5 of the practice are used.

## 5. Significance and Use

5.1 This practice is intended to assist engineers, contractors and owner/operators of underground utilities and tunnels with the successful implementation of distributed optical fiber sensing for monitoring ground movements prior to construction for site planning and during utility and tunnel construction and operation and the impact of such ground movements on existing utilities.

5.2 Before the installation of distributed optical fiber sensing begins, the contractor shall secure written explicit authorization from the owner/operator of the new tunnel/utility and the existing utilities allowing an evaluation to be conducted for the feasibility of distributed optical fiber sensing for monitoring ground movements for the intended purpose and to have access to certain locations of the structure and the surrounding ground. It may also be necessary for the installer to have written explicit authorization from applicable jurisdictional agencies such as the Department of Transportation, the Army Corps of Engineers, the Department of Environmental Protection and other.

5.3 Engineers, contractors, and owners/operators shall also be cognizant of how the use of distributed optical fiber sensing for monitoring ground movements around utilities and tunnels might interfere with the use of certain equipment or tools near the installed optical fiber sensing cable in some special situations. For example, repair activities may have to temporarily remove, relocate, or avoid the optical fiber cable.

5.4 Engineers, contractors, and owners/operators should be cognizant of how installation techniques and optical fiber (OF) cable location and protection can affect the performance of DOFSS.

## 6. Instrumentation Objective, Design and Layout

6.1 *Brief Overview*—The effect of Brillouin scattering is the most widely used form of DOFSS technology which provides a monitoring technique to measure strain and temperature along the intended optical fiber route as shown in the schematic view in Fig. 1. The optical cable itself plays the role of hundreds of thousands of sensors of multiple parameters of interest for long distances. Usual telecommunication optical fiber cables are designed to protect the optical fibers from the surrounding environment. In a strain sensing cable, however, the environment causing stimuli must be efficiently transferred to the optical fiber core that transmits light or the medium in which we can measure the effects of Brillouin scattering.



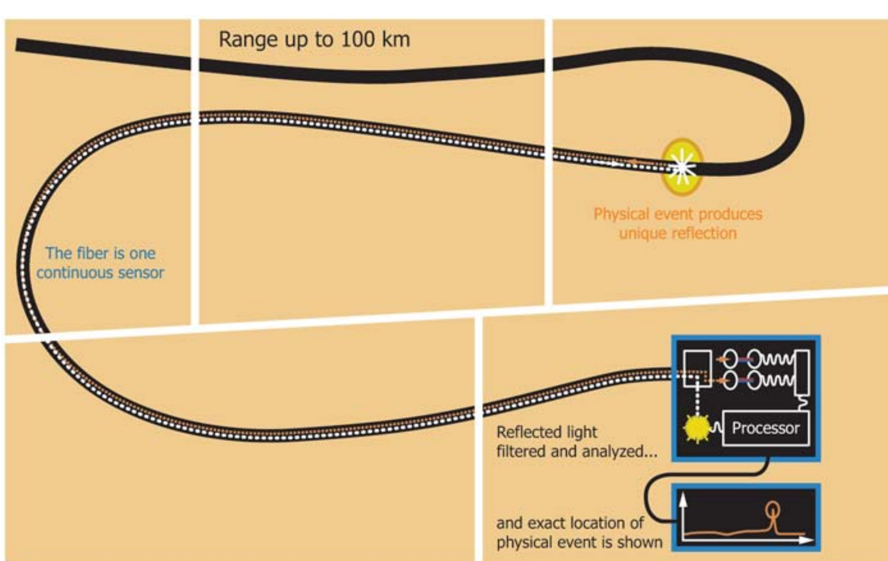



FIG. 1 Typical Layout of a DOFSS

Typical optical fiber sensing cable designs are shown in Figs. 2-4. When light travels through a transparent media such as glass, most of it goes through the core of the fiber, while a small fraction is back scattered due to the perturbation following the principle of total internal reflection illustrated in Fig. 5. Different components of the back scattered light can be identified, including the Brillouin scattering components, such as the peaks shown in Fig. 6; these are carefully analyzed and used to measure temperature or strain along the fiber. In this technology, two laser beams are injected into an optical fiber core from both its ends, as shown for BOTDA in Fig. 7. One is called the pump signal, being a pulse-modulated (for BOTDA systems) or a sinusoidally modulated (for BOFDA systems) laser beam of a unique wave profile; the other one is the continuous (CW) probe laser, sometimes referred to as the Stokes laser. The interaction of these two laser beams produces an acoustic wave through the phenomenon called "electrostriction." The pump signal is backscattered by the phonons, and the energy is transferred between the pump signal and the CW probe light. The Brillouin Loss Spectrum (BLS) or Brillouin Gain Spectrum (BGS), as the function of frequency difference between the two laser beams, is measured by scanning the frequency of the CW probe light. The value of the strain or the temperature can be estimated using the shift of the peak frequency of BLS/BGS (Brillouin frequency), whilst its position calculated from the light round-trip time as shown on the right one-half of Fig. 7. Similar set up for the BOTDR technology is shown in Fig. 8. Therefore, an appropriate interrogator, like the one shown in Fig. 9, with a graphic user interface shown in Fig. 10, and the software, for example shown in Fig. 11, can acquire and keep track of the position and the magnitude of the strain or temperature at hundreds of thousands of locations along the route of the optical fiber, essentially in real time. Typical results from such BOTDA and BOFDA are shown for strains in Fig. 12 and Fig. 13, respectively.

6.2 *Effect of Brillouin Scatter Facilitating Temperature and Strain Measurements*—Brillouin scatter is extremely sensitive to any changes in temperature and the deformation or the strain experienced by the optical fiber. In this regard, most environmental stimuli the optical fiber is exposed to can be correlated to temperature and strain, and measurements can be made on the effects of such environmental stimuli on the serviceability of a buried pipeline or the ground responding to the impact of tunneling or new utility construction. The frequency shift, $\nu_B$, can be calculated using:

$$\nu_B = \{2\ n\ V\ a\} / \lambda o \quad (1)$$

where:

$n$ = the effective refractive index of the propagating mode,
$Va$ = the acoustic wave velocity in the optical fiber, and
$\lambda o$ = the vacuum wavelength of the incident light.

It is clear that the Brillouin frequency shift is affected by the acoustic wave velocity, which can be expressed using the theory of elasticity, for homogenous, isotropic, linearly elastic solids as:

$$V a = \{K / \rho\}^{0.5} \quad (2)$$

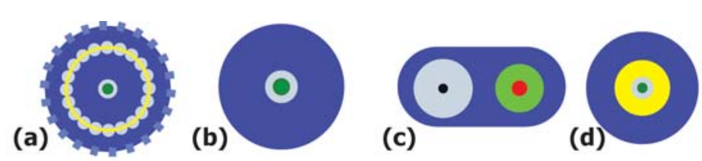
where:

$K$ = the bulk modulus, and
$\rho$ = the density of the optical fiber.

The density of the optical fiber is dependent on temperature; therefore, the Brillouin peak shifts when plotted as a function of the difference in the frequency between the laser pump and the signal varying with temperature as shown in Fig. 14. Similarly, any deformation or strain in the optical fiber affects the density of the optical fiber as shown in Fig. 15. In summary, the temperature and the strain induced in the optical fiber can be measured using the effects of Brillouin scattering.

6.3 *Instrumentation Objective*—The instrumentation objective has to be clearly stated by the involved parties in terms of what problem is going to be solved (for example, detection of ground movements, quantification of axial elongation or shortening, bending, shear, stresses, strains in the utility pipes). The objective shall also include the definition of the time frame of the monitoring-during a limited time period such as when there is nearby construction, a specific season or the lifetime of the structure. The objective shall also include a clear statement on how the resulting data will be used and who will be responsible for data management and analysis. If the system is






(a) Robust, armored fiber optic strain sensing cable with metallic armoring wires and structured outer sheath for enhanced adhesion.
(b) Flexible, mini armored fiber optic strain sensing cable with hermetic metal tube.
(c) Strain sensing cable with one tight-buffer strain fiber and one integrated temperature compensation fiber in loose-tube configuration.
(d) Small, lightweight, high sensitive, metal free tight-buffer fiber optic strain sensing cable.

**FIG. 2 Components of Various Optical Fiber Sensing Cables**

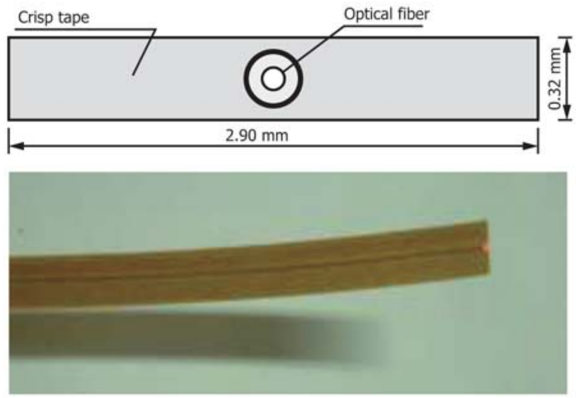



FIG. 3 Components of an Optical Fiber Strain Sensing Cable

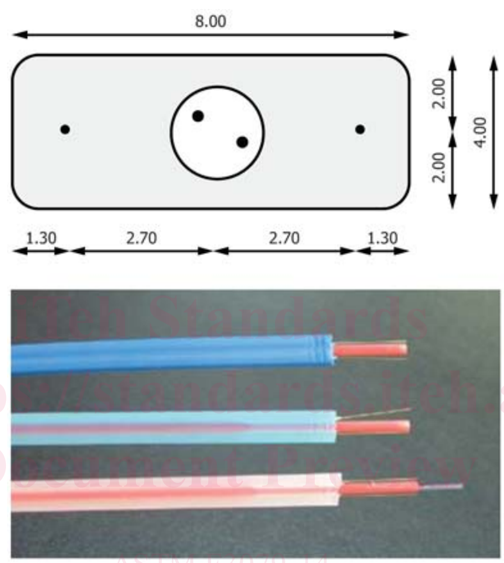



FIG. 4 Components of an Optical Fiber Strain and Temperature Sensing Cable



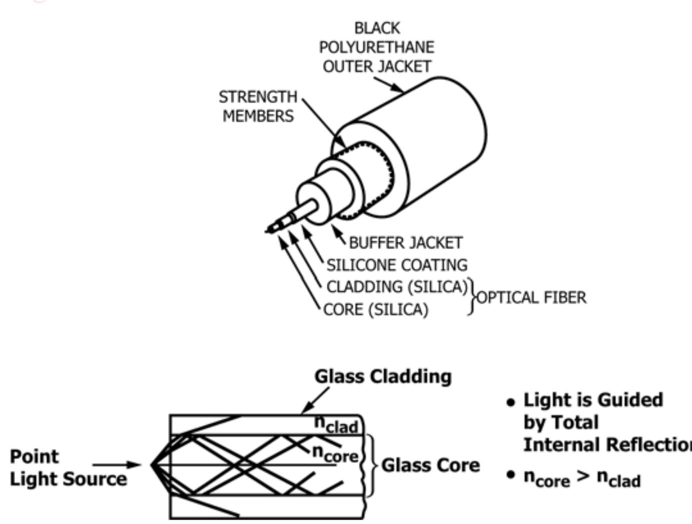



FIG. 5 Principle of Total Internal Reflection

used to generate alerts, a clear response plan to all types of possible alerts also shall be prepared.

6.4 *Instrumentation Design*—The instrumentation has to be designed in a way so that the objective can be achieved by the