Optics & Laser Technology 78 (2016) 81–103

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

[INVITED] State of the art of Brillouin fiber-optic distributed sensing

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ARTICLE INFO

Article history:
Received 8 September 2015
Accepted 9 September 2015
Available online 29 October 2015

Keywords:
Nonlinear optics
Brillouin scattering
Fiber optic distributed sensing
Fiber optic sensing
Fiber sensors

ABSTRACT

Fiber-optic distributed sensing, employing the Brillouin effect, is already a commercially available measurement technique for the accurate estimation of the static strain/temperature fields along tens of kilometers with a spatial resolution of the order of a meter. Furthermore, relentless research efforts are paving the way to even much wider usability of the technique through recently achieved enhanced performance in each of its critical dimensions: measurement range has been extended to hundreds of kilometers; spatial resolution is of the order of a centimeter or less, signal to noise ratio has been significantly improved; fast dynamic events can be captured at kHz's sampling rates; and a much better understanding of the underlying physics has been obtained, along with the formulation of figures of merit, and the preparation and early adoption of appropriate standards and guidelines. This paper describes the basics, as well as the state of the art, of the leading Brillouin interrogation methods, with emphasis on the significant progress made in the last 3 years. It also includes a short introduction to coding, which has proven instrumental in many of the recently obtained performance records.

1. General Introduction

Following the immense impact they had on telecommunications, optical fibers have finally established their advantageous value also in the field of sensing. Almost all physical quantities of interest, such as strain, temperature, magnetic field, electric field, acoustic fields, rotation, humidity and many more (to be called from now on: *measurands*), can be sensed by their direct or indirect effect on the propagation of light in the fiber [1,2]. For example: When a section of a fiber is strained, either by tension or compression, its physical length is obviously changed and, in addition, the averaged refractive index along the section is affected as well. These changes have a *direct* impact on the phase of the optical wave propagating in the fiber, which can then be measured in order to quantify the applied strain. Strain also affects the speed of sound in the fiber, which is another characteristic of the fiber that can be interrogated by the Brillouin effect, see below. Through the Faraday effect, a magnetic field parallel to the fiber longitudinal axis will rotate the State Of Polarization (SOP) of light propagating in the fiber by an angle, which is proportional to the strength of the field, paving the way to electrical current sensors (where the induced magnetic field in a closed loop of optical fiber around a conductor is a measure of the carried electrical current). Bonding a magnetostrictive material to an optical fiber provides an *indirect* measure of the magnetic field, since light propagating in the fiber is not directly affected by the magnetic field itself but rather by the strain induced by the expanding/contracting magnetostrictive intermediary.

Optical fibers are outstanding candidates to serve as sensors due to their unique properties: (i) they can both sense and transmit the sensed information by the same waveguide; (ii) they offer a low-loss link and thus can be used for long range sensing; (iii) they are dielectric and as such are not effected by electromagnetic interference nor generating one; and finally, (ix) they are very thin (~0.1 mm) and low weight, easily embeddable in graphite-fiber based composites, as well as in printed structures, or, alternatively, bonded to the surface of almost any material.

A variety of linear and non-linear optical transduction mechanisms have been studied in the last 30–40 years, dealing with the conversion of all kinds of measurands to local measurable optical effects in the fiber. Many optical-intensity-based point sensors have been developed, including simple optrodes, where special materials are attached to the fiber tip to sense temperature, partial pressure of various gases and other relevant measurands. Also developed and commercialized are highly sensitive interferometric hydrophones, highly accurate current sensors and fiber-optic gyroscropes [3]. Multiplexing many point sensors on the same strand of fiber has always been a laudable goal, culminating in the successful deployments of very large and quite complex arrays of individual interferometric hydrophones and

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http://dx.doi.org/10.1016/j.optlastec.2015.09.013
0030-3992/

accelerometers for sonar and seismic oil exploration and utilization [1,2].

By far the most successful and widely used strain/temperature fiber-optic point sensor today is the fiber Bragg grating (FBG). It is rather easily made by exposing a few millimeters of standard single mode fiber to a periodic pattern of UV illumination (at ~244 nm), which inscribes a permanent refractive index grating along the fiber core. This grating of period Λ selectively reflects light, having a peak reflectivity at a wavelength of $\lambda_B = 2n\Lambda$, where n is the local effective refractive index of the fiber. Strain and/or temperature will shift λ_B by ~[1 picometer (pm) of wavelength]/[1 microstrain (με)] and 10 pm/1 °C (at λ_B~1550nm in standard silica-based single mode fibers). The sensitivity to strain mainly originates from the induced change in Λ, while temperature predominantly affects n, with some dependence also on the fiber coating (*e.g.*, standard acrylic *vs*. high-temperature-tolerant polyimide). Wavelength division technologies (wideband light optical transmitters with wavelength selective receivers, or, alternatively tunable lasers, which scan the available optical bandwidth looking for the FGBs' reflection peaks) make it simple to multiplex a few tens of FBGs with different λ_B's along a strand of fiber, using currently available and quite affordable commercial interrogators. FBGs are highly reliable sensors, capable of handling a huge dynamic range of strain and/or temperature under both static and highly dynamic scenarios.

But FBGs must be imprinted on the fiber, significantly increasing its cost. Also, as mentioned above, most commercially available interrogators can handle only a fairly small number of FBGs, setting a limit on the number of sensing points, as well as on their density along the fiber. Still quite expensive, draw tower gratings (DTGs), comprising *thousands* of densely written FBGs, all of *same inscribed-* λ_B, have recently become commercially available. However they require special interrogators.

Security applications from border fences to the protection of oil and gas pipes against leaks and theft, as well as the need to monitor the health of structures, such as airplanes, train tracks, dams, bridges, buildings etc., can tremendously benefit from *distributed* sensing using *standard* fibers, where, without any special preparations, the whole length of the fiber serves as a sensor, assuming it is also possible to selectively read the measurand of interest at an arbitrary point along the fiber with a sufficient spatial resolution and sensitivity [4].

Currently available, as well as under-development distributed fiber-optic sensors provide amazing capabilities, unmatched by any other sensing mechanism. Embedded optical fibers, distributedly interrogating the local strain all along their length, can serve as the material/structure nerve system, and as such can tell the end user how the material/structure "feels" strain-wise. A crack, early detected by such a distributed sensor in a supporting concrete beam of a bridge, or the identification of a developing delamination in a critical composite-made part of an airplane, while in-flight, can save many human lives. Such systems may eventually lower the cost of ownership by moving from scheduled-based to condition-based maintenance and may also help in guaranteeing the airworthiness of unmanned piloted vehicles (UAVs) for civil licensing and other purposes. Recent applications of distributed strain sensing include 3D shape sensing and distributed acoustic sensing (DAS) [5–8]. Distributed temperature sensing using the Raman effect [9], has definitely come of age with many applications and affordable interrogators.

The vast majority of distributed fiber-optic sensing technologies rely on one or more of the Rayleigh, Raman and Brillouin scattering effects, which are schematically described in Fig. 1 and its caption. The sensing information is extracted by using an appropriate interrogator, which transmits optical radiation into the fiber and then collects the backscattered radiation, originating from one (or more) of the three physical effects shown in the figure. Dedicated processing is then used to infer the relevant measurand at every resolution cell along the fiber. Localization is achieved, either by pulsing the probing light, like in a radar (OTDR – Optical Time Domain Reflectometry), or through scanning of the probing optical frequency (OFDR – Optical Frequency Domain Reflectometry), or through correlation techniques using codes of varying level of sophistication (OCDR – Optical Correlation Domain Reflectometry). Advanced configurations may also require feeding light to the remote edge of the fiber.

This paper reviews recent developments in the field of distributed fiber-optic sensing using the Brillouin effect. Its structure is described in the following section.

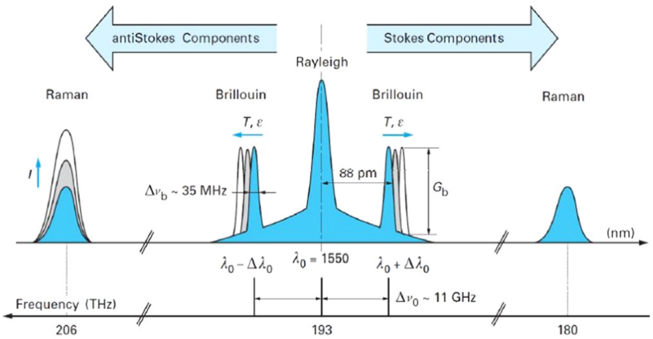

Fig. 1. The three scattering effects in silica (SiO_2) optical fibers, most frequently used for distributed sensing. When light is injected into the fiber, say at wavelength 1550 nm, part of it is backscattered elastically (*i.e.*, without change of wavelength) by the randomly arranged silica molecules, resulting in Rayleigh scattering. Due to the inelastic Raman effect [9,10], the incident wave interacts with vibrational and rotational levels of silica, giving rise to the scattering of Stokes and anti-Stokes radiations, characterized by a frequency shift of ~13 THz from that of the incident wave. The intensity ratio of those portions of these two signals, which are backscattered is used to infer the temperature. The also-inelastic Brillouin effect, which is dealt below in detail, involves the interaction of the incident light with acoustic phonons. Again, Stokes and anti-Stokes are backscattered and their frequency deviation (~11 GHz for standard single-mode optical fibers at ~1550 nm) from the incident wave signals is sensitive not only to temperature but also to strain (after [11]).

2. The Brillouin effect in optical fibers

2.1. Introduction

Brillouin-based fiber-optic distributed sensing [12–16] is a promising technology for the monitoring of many types of structural and environmental changes, already commercially implemented and widely used for the protection of pipelines against leaks, for the inspection of long electrical cables against local heating, for a variety of geotechnical applications and more [2,17]. Sensors based on this technology use the Brillouin nonlinear process [10,17], where acoustic phonons scatter a forward propagating optical wave (called 'pump') into a backward propagating wave (called 'probe'). The backscattered light has a characteristic frequency shift (from that of the pump), called the Brillouin Frequency Shift (BFS) and represented by ν_B, which is a function of the local temperature and mechanical stress. For standard single-mode fibers using wavelengths around 1550 nm the near-room-temperature sensitivities of ν_B are 1 MHz per degree °C and 50 MHz per 1000 με, *i.e.*, 50 MHz per 0.1% elongation/contraction of the fiber. Thus, using appropriate interrogation techniques (and there are a few), the BFS can provide information on the surrounding temperature and strain distributions along the optical fiber. While intensively researched for more than two decades (see