Review and Progress in Distributed Fiber Sensing

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Abstract: Optical fibers have crucially contributed to promote the concept of distributed sensing with a large impact. The different types of fiber optics distributed sensing techniques are reviewed and their performances and limits are presented.

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1. Introduction

The concept of distributed measurement was soon applied to optical fibers through the technique of Optical Time-Domain Reflectometry (OTDR), mostly to evaluate loss and detect faults along a fiber. It was also one of the first application in which a phenomenon – Rayleigh scattering - seen as a penalty for the normal use of fibers – loss in propagation - was exploited for sensing purpose. This approach has turned out to be the general rule for the development of distributed fiber sensing configuration.

In the late 80's many different sensor configurations were proposed, mostly based on the inelastic Raman and Brillouin scatterings in optical fibers. These configurations were steadily improved during the 90's to make them more accurate, with a longer range and a faster acquisition, more compact and more stable for field applications and eventually cheaper. But this is quite recently that potential users could really grab the interest of distributed sensing and the market has shown these past few years a promising steady growth, stimulating the outcome of new actors in the research and the associated business.

The concept of distributed sensing is simple: the sensing element has a linear geometry and the sensing system provides for any position along the sensing element a value of the quantity to be measured, e.g. temperature. This way such a sensor can substitute for thousands of point sensors, the sensing element having the 2 functions of converting the measured quantity into a modulation of the signal and of transmitting the signal before and after modulation to the processing unit. It is evident that the optical fiber is an excellent candidate to be such a sensing element, the main difficulty being to identify the right phenomenon activated by the measured quantity that will give the proper modulation on the signal.

The fields of application for distributed sensors are situations that require to be informed continuously on a quantity over an extended distance. Installing point sensors in such situations would mean a huge bundle of connections and a large multiplexing system for processing. Distributed sensors only require 1 or 2 connections and a single processing unit. This unit is normally much more complex since it must handle and process rapidly a large quantity of information using a consequently scaled storage and displaying capability. As a general rule distributed sensors turns more effective in situations where more than 100 point sensors would be required. In addition they are particularly suited in applications matching the thread-like geometry of the fiber in which a continuous distribution of the measurand must be acquired, as shown in Fig. 1. This is a quite revolutionary approach in sensing, for which a single system can fully inform about a long structure (1D), a wide area (2D) or an entire construction (3D).

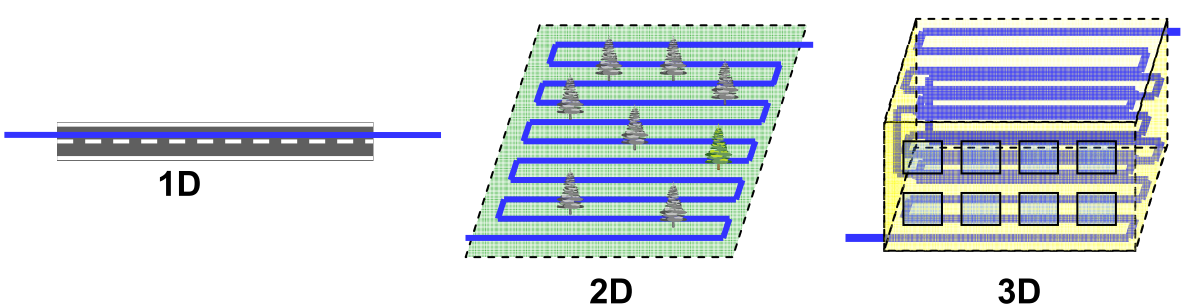

Fig. 1 Distributed fiber sensors are well suited to monitor long 1D structure like a road or a pipe, but also can be installed to survey a large 2D area like a surface or a slope, or even an entire 3D structure like a tank or a building.

2. Principles of distributed fiber sensors

A distributed sensing system provides for each measured point a couple of values: the position *and* the magnitude of the measured quantity. Normally its performances are evaluated by three characteristics: the accuracy on the measured quantity, the range for the position and the spatial resolution. These 3 characteristics are normally interdependent and one must be specified while the other 2 are fixed. A related important quantity is the number of resolved points *N* that gives the distributive power of the sensor and is simply given by the range divided by the spatial resolution. In recent distributed fiber systems *N* widely exceeds 10'000.

The distributed fiber sensors can be separated into 2 classes, according to the mechanism used to convert the magnitude of the measured quantity into a modulation of the light that is position-dependent.

I. **Linear type of interaction or backscattering**: Light spontaneously scattered back into the fiber can be assimilated to a continuous distributed reflection along the fiber. This is the principle used for the OTDR technique based on the elastic Rayleigh scattering, but it has also been successfully implemented using the 2 inelastic Raman and Brillouin scatterings. The amount of scattered light must carry the information about the measured quantity.

II. **Nonlinear type of interaction or wave coupling through a parametric process**: Two counterpropagating waves are coupled through a nonlinear parametric process, resulting in an energy transfer from one wave called pump into the other one called probe. The strength of the interaction must depend on the quantity to be measured, so that the local coupling efficiency will directly be function of the measured quantity and will modulate the probe wave accordingly.

To create a position-dependent modulation of the light two techniques are currently used:

A. **Time-domain coding**: The activating signal is a light pulse that is during propagation either continuously back-reflected through a scattering process (case I) or locally coupled to a CW probe wave (case II). The local modulation amplitude is found from the time delay on the backscattered signal or the probe CW wave after the pulse launching time. The spatial resolution is normally given by the pulse width. The longer the pulse, the higher the backscattered signal or coupled signal, but the worse the spatial resolution, so that a trade-off has to be made between measurand accuracy and spatial resolution. In addition a fine spatial resolution requires short pulses and thus a wideband detection showing a higher noise level. This coding is the most straightforward and can be applied to any type of distributed sensing configuration using any kind of interaction.

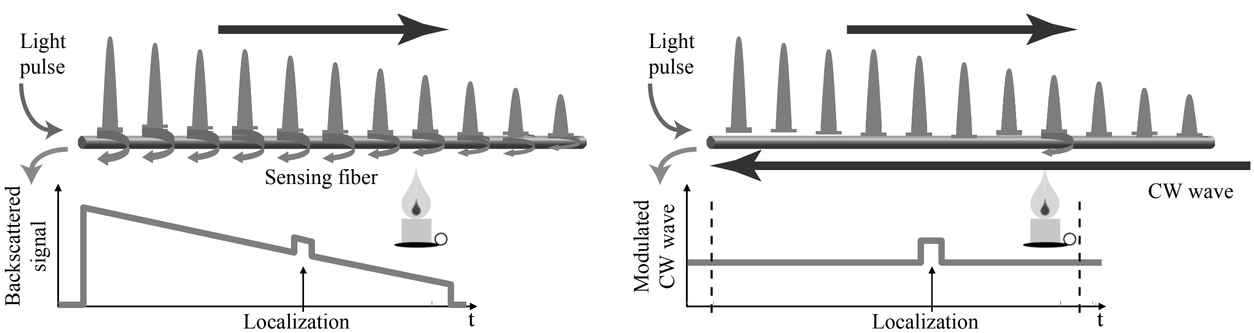

Fig. 2 Principle of the time-domain coding to retrieve the local magnitude of the interaction, in which a pulse of light activates locally the process (Case I, left: linear through continuous scattering; Case II, right: nonlinear through local coupling to a CW wave). The hot spot locally changes the magnitude of the process efficiency that is observed like a modulation of the measured signal in the time domain.

B. **Frequency-domain coding**: In this case the activating signal is a CW wave whose frequency is linearly swept in time. The reflected signal will thus return to the fiber input with a frequency shift proportional to the round-trip time. When mixed with the same signal, but locally reflected in the instrument, the beat note shows a frequency that is proportional to the reflection distance along the fiber. For fully distributed reflections the beat signal will contain a continuous distribution of frequencies that can be separated by performing a simple Fourier transform. The amplitude of the local interaction can then be found by mapping each frequency with a position along the fiber. The advantage of the frequency-domain coding is the possibility to achieve excellent spatial resolution while maintaining a moderate detection bandwidth. The spatial resolution is function of the frequency sweep rate and the frequency step that is simply the inverse of the recording time duration. Millimeter spatial resolutions can be obtained, that remain unreachable using the time domain technique.

The main limitation of the frequency-domain coding results from the interferometric mixing to generate the beat note. This requires that the 2 mixed signals are mutually coherent, so that the coherence length of the signal must be larger than twice the optical length of the sensor. For long ranges it requires high coherence sources with a kHz linewidth. In addition the polarizations of the mixed signals must match, that is practically impossible in a real situations (random birefringence along the fiber), so that a polarization diversity detection scheme must be implemented.

For the same reason the frequency-domain coding cannot be used when the spectrum of the light is significantly broadened by the interaction. This is the case of inelastic spontaneous scatterings, for which this coding cannot be used.

It must be mentioned the special case of the frequency correlation coding that can be applied only to the nonlinear interactions (case II), in which the frequency difference between the 2 counterpropagating waves is constant only at one position in the fiber. In a parametric process like stimulated Brillouin scattering the efficiency is sharply better for a constant frequency difference and the interaction can be made local this way. This is practically achieved by counterpropagating two identically sinusoidally frequency-modulated signals.

3. Rayleigh loss distributed sensing

This is the simplest configuration in which the local loss is measured using a conventional OTDR (time-domain coding) or OFDR (frequency-domain coding) is used. The problem is this case is to implement a transducing mechanism that converts the quantity to be measured into an excess loss for the light propagating in the fiber. This requires the development of special cable in which a micro-mechanical deformation is applied to the fiber when the measured quantity varies [1]. These types of sensors have demonstrated their ability to detect chemical and humidity using special fiber coating. If they are really cost-effective, the main problem remains the linearity and the reversibility of the transducing mechanism.

4. Raman distributed sensing

Dakin *et al* proposed in 1985 for the first time to use a non-elastic scattering for distributed sensing [2]. The spontaneous scattering process is generated by thermally-activated acoustic waves and their phonon population follows a Bose-Einstein distribution. This makes the scattering cross-section temperature-dependent and the spontaneous Raman scattering suitable for temperature distributed sensing.

Information about temperature is retrieved from the comparison between the intensities backscattered into the Stokes (downshifted optical frequency) and the Anti-Stokes (upshifted optical frequency) waves. In the Anti-Stokes process the scattering annihilates a phonon and the cross-section is proportional to the average phonon number $\overline{n}$ that is given by the Bose-Einstein statistics $\overline{n} = 1/[\exp(h\Delta\nu/kT) - 1]$. For a Stokes process the scattering creates a phonon and the commutation rules of the quantum annihilation-creation operators make the cross section proportional to $\overline{n}+1 = \exp(h\Delta\nu/kT)/[\exp(h\Delta\nu/kT) - 1]$.

The information about the temperature is found by measuring the powers scattered at the Stokes and Anti-Stokes wavelengths and by simply evaluating the ratio between these 2 powers that exponentially depends on temperature:

$$\frac{P_{Stokes}}{P_{Anti-Stokes}} \sim \exp(h\Delta\nu/kT) \qquad (1)$$

A simple one-point calibration must then be carried out at one temperature. The basic experimental configuration of such a sensor is sketched in Fig.3.

The technology of the Raman distributed sensor is now very mature and commercial instruments are very cost-effective. The sensitivity of the instrument is directly proportional to the collected power in the Stokes and Anti-Stokes scattered waves. To maximize the light that is spontaneously scattered requires the use of multimode fibers. The range of Raman sensors is normally limited to 10 km, through the cumulated effects of loss and intermodal dispersion that limits the position accuracy. A typical performance is a 1 K temperature accuracy with a 1 m spatial

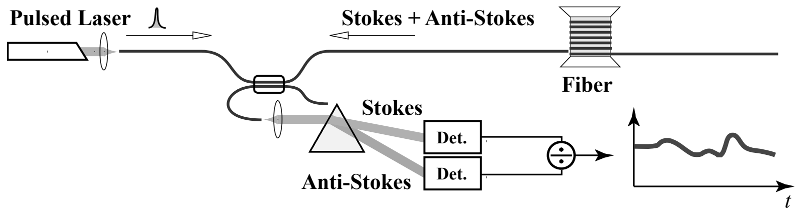

Fig. 3 Diagram of the experimental configuration of a Raman distributed fiber sensor. The light pulse is spontaneously backscattered while propagating along the fiber and the Stokes and Anti-Stokes are detected separately after a spectral filtering.

resolution at a distance of 10 km, obtained after a 5 minutes averaging. These figures can be substantially improved if the experimental conditions are alleviated (shorter range, worse spatial resolution, etc…).

Raman distributed sensors remains definitely very attractive for short range and fast temperature sensing, like for instance for fire detection in a tunnel. The main drawbacks of this technology are the severe performance penalty when using single-mode fibers that would be cheaper and less sensitive to loss and dispersion, and the sensitivity to wavelength-dependent losses, regarding the large wavelength difference between the Stokes and Anti-Stokes scattered waves. A wavelength-dependent loss causes an erroneous evaluation of temperature for distant points and this problem can only be worked out by performing a bidirectional measurement (2 successive measurements from each fiber end).

5. Brillouin distributed sensing

The possibility to use the other inelastic scattering – Brillouin scattering - for sensing purposes was proposed in the late 80's [3][4]. The mechanism used in this type of sensor is not based on an intensity measurement, but on the frequency positioning of the Brillouin scattered wave. It makes the measurement very immune to any loss effects. This wave is spectrally shifted with respect to the pump wave by a frequency usually called *Brillouin frequency* $\nu_B = 2nV_a / \lambda_o$, where n is the fiber effective refractive index, λ_o the vacuum wavelength of the pump wave and V_a the acoustic velocity in the fiber core. This acoustic velocity turns out to essentially depend on temperature and the material density. By determining the central frequency of the Brillouin scattered wave, this gives a measurement of the Brillouin frequency ν_B and any change in the acoustic velocity V_a can be monitored this way. Since the scattered light spreads over a narrow spectrum (25 MHz at λ_o =1550 nm) the determination of the central frequency is accurate and small changes of the acoustic velocity can be observed, as illustrated in Fig.4 for different temperatures. Temperature changes smaller than 1 K can be routinely observed this way. But the acoustic velocity is also very sensitive to very small changes of the material density that can be induced by deforming the fiber. Interestingly such a deformation can be obtained by applying a longitudinal strain on the fiber. This way the fiber can be used as a strain gauge for structure monitoring. The dependence of the Brillouin frequency on temperature and strain has been evaluated accurately [5].

Brillouin distributed sensors have been developed following both the linear backscattering approach and the nonlinear parametric coupling exposed in section 2. The Brillouin sensor has turned out to be very attractive on one

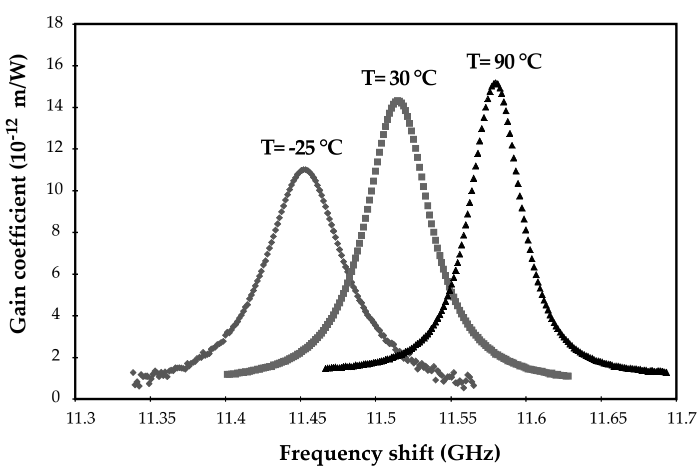

Fig. 4 Brillouin gain spectra measured at different temperatures, showing the temperature dependence of the Brillouin shift as a function of temperature. An identical behavior is observed when the fiber experiences strains [5].

hand for long range measurement since it uniquely uses single mode fibers and its cross-section is 100X larger than Raman scattering, and on the other hand for distributed strain measurement.

The linear approach was historically developed later [6] than the nonlinear coupling, but it is here presented first for a logical reason. The system is identical to a Raman distributed sensor, except the spectral filtering is realized by mixing the backscattered signal with either an optical local oscillator before detection or a microwave local oscillator after detection. This way one frequency component of the backscattered signal can be analyzed at a time with a high spectral resolution and the amplitude of this frequency component can be retrieved in the time domain to get position-dependent information. The local scattered spectrum can be reconstructed by successively incrementing the frequency of the local oscillator. It must be pointed out that the scattered wave usually experiences a small amplification by stimulating a Brillouin parametric amplification, so that it is not a purely linear process.

The nonlinear parametric coupling approach was the first proposed configuration [3][4]. In this case two optical waves must be generated with a very accurate frequency difference, so that the stimulated flavor of the Brillouin scattering can be used. In this situation these 2 waves propagating in opposite directions generates through electrostriction an acoustic wave corresponding to their beat frequency. This acoustic wave, that is the idler in the parametric process, triggers in turn the coupling from the higher frequency wave to the lower frequency wave. The process is highly efficient when the beat frequency is identical to the Brillouin frequency ν_B. The position-dependent information is obtained by pulsing one of the optical waves and by observing the local coupling on the counterpropagating CW wave.

The main difficulty in this second approach is to generate two optical waves with an accurate frequency difference that must be stable to better than 1 MHz. The first proposed configurations used 2 distinct lasers that were locked together using their beat note and a closed-loop servo control. Later it was proposed to use a single laser and to generate the proper frequencies using the sidebands of an electro-optic integrated modulator [7]. This improved greatly the stability and portability of the system and made possible the first field measurements.

The 2 approaches offer pros and cons and the choice has to be made according to the target application. Both approaches can achieve a 30 km range with a 1 m spatial resolution. The first approach (linear) offers the key advantage to require the access to only one fiber end, but must detect much weaker signal and long range measurements with good spatial resolution require very long averaging in the hour range. The second approach (nonlinear) must access both fiber ends and the sensor can no longer be used over its full length if the fiber breaks accidentally at any position. On the other hand the detected signal is much more intense and a full range with best spatial resolution measurement can be completed in a matter of minutes. This second approach also offers the possibility to regenerate the signal to extend the range over 100 km. It must be pointed out that this approach is also very sensitive to depletion of one of the interacting wave and this can bias the spectral distribution measurement at distant positions.

Efforts have been recently pushed on the improvement of the range and of the spatial resolution. Range over 100 km has been demonstrated by amplifying the signal in the fiber [8]. For spatial resolution the limited 25 MHz spectral width of the Brillouin spectrum has been considered for a long time to be an absolute physical limit to the spatial resolution, limiting the minimum pulse width to some 10 ns, or equivalently to a spatial resolution of 1 m. Two very smart solutions were proposed in the past few years to overcome this limit.

The first solution proposes to generate frequency-dithered signals that propagate in opposite directions [9]. If the dithering frequencies are identical, it can be demonstrated that the frequency difference between the 2 waves is constant only at periodic definite locations along the fiber. At these points the stimulated Brillouin interaction is very efficient and can be this way extremely localized. The position of the interaction point can be scanned along the fiber by varying the dithering frequency. Centimeter spatial resolution was demonstrated using this scheme [10].

The second solution proposes to avoid the spectral spreading of the Brillouin spectrum due to the broadband pulse signal by generating the acoustic idler wave using CW waves and by diffracting a weak pulse signal on this acoustic wave [11]. This solution combines the advantage of an ideally narrow Brillouin gain spectrum together with the high spatial resolution of very short pulses. Spatial resolutions down to 10 cm have been demonstrated using this scheme.

6. Coherent Rayleigh distributed sensing

A very innovative type of distributed sensor was recently proposed by Soller *et al* that is based on a special feature of Rayleigh scattering [12]. The silica material in the fiber is highly disordered and this causes scattering centers to be randomly distributed along the fiber. Scattering process can thus be seen as random point reflections and these reflected waves superpose to build up the backscattered wave. In a normal OTDR technique a broadband source is normally used, so that these different reflections add incoherently to give a smooth response. If a coherent wave is used the backscattered wave shows significant intensity fluctuations resulting from the mixing of these random reflections. These random intensity fluctuations are steady and can be exactly replicated if the measurement is later repeated under similar conditions; this is like a fingerprint of the fiber. This feature is detrimental in a normal OTDR loss measurement, since it brings uncertainty in the backscattered intensity and is assimilated to noise. As often in sensing technique this feature can be used to efficiently evaluate environmental change along the fiber.

When the optical length in the fiber is locally varied as a result of temperature or strain change the interference pattern resulting from the random reflections is modified at the position of the change. By slightly shifting the light wavelength the original pattern can be again obtained and the amount of optical length change is exactly proportional to the wavelength change. Actually the wavelength does not need to be changed and the equivalent wavelength shift can be calculated by performing a spectral and a correlation analysis of the original and modified local intensity fluctuation patterns.

This scheme can be applied using a time-domain or a frequency-domain coding. Exceptional performances were obtained by this very original configuration in the frequency-domain approach [13]: 0.1 K temperature resolution is obtained for a 1 cm spatial resolution and 1 K for a 2 mm spatial resolution. The range of the instrument is limited by the coherence of the source and its sweeping capabilities; it currently extends to a few kilometers. Data are acquired and processed in a matter of seconds. A typical measurement is shown in Fig.5.

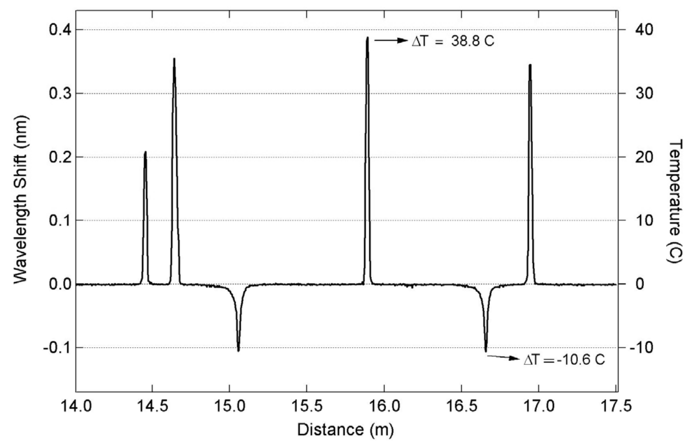

Fig. 5. Distributed temperature measurements using the coherent Rayleigh OFDR technique, showing four “hot” spots and two “cold” spots. Courtesy of Luna Technologies [13]

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