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Fiber optic sensor networks

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Abstract

One of the main goals in fiber optic sensor technology is to multiplex together a high number of sensors in the same network in order to share expensive terminal equipment and develop a system including multiple measuring points. Different kind of multiplexing networks for fiber optic sensors will be described and compared here, including networks using optical amplification and lasing multiplexing systems. State of the art in multiplexed and distributed sensor networks is also shown, focused on robust, remote and distributed Brillouin networks.

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1. Introduction

The cost of a single channel fiber optic sensor is relatively high. Fortunately, aggregation of the sensors results in their cost reduction, given that it would be possible to share either the source of light, system of detection, or, preferably, both. Furthermore, the most suitable transmission medium for the signals generated by the fiber sensors is also optical fiber, from which follows that all the advantages of the fiber-based networks are also directly applicable to the fiber optic sensor networks.

Multiplexing is the simultaneous transmission of two or more information channels along a common path. A fiber sensor system includes three main parts or subsystems: the sensing elements or transducers, the optical fiber channel and the optoelectronic unit [1]. Because the last subsystem uses to be the most expensive one, when is possible to multiplex a high number of sensing points in the same optical fiber network using a common optoelectronic unit, the cost per sensing element decreases.

Trends for the network implementation using sensor multiplexing are just as much, or even more widespread than those of the fiber transmission networks.

Multiplexing of optical fiber sensors is a concept that includes three basic tasks [2]

- Launching of optical signals with the correct power level, spectral distribution, polarization and modulation into the network.
- Detection of the portion of optical power codified or modulated by the sensor element, which is sent by means of transmission or reflection.

- Unique identification of the information corresponding to each sensor in the network, by means of proper addressing, polling and decoding.

Because of this, in the realization of the sensor networks it is possible to utilize the following: various modulation techniques of diverse parameters of the optical signal, different network topologies and simple or complex decoding methods of the received signal. And all of these as a function of the type of sensors multiplexed within the same network.

When designing a network, one should take into account the strong relationship that exists between all the factors mentioned above, together with the existing economic conditions; that would give rise to a most appropriate network. The cost of the network depends on many factors, and the dominant cost is usually application specific. In some applications, the cost of the fiber may be dominant, and a multiplexing scheme that provides the highest channel density per fiber will provide the lowest total cost. However, usually the cost of the electro-optics system dominates, and multiplexing approaches that provide the highest channel density per laser may be the lowest cost approach [3].

Thus, the mail goal of most fiber sensor networks, is to connect a number of sensors to a single reading unit. These sensors can be addressed either simultaneously or sequentially by using optical switches. No manual intervention should be necessary.

This paper highlights the main fiber optic sensor networks general concepts and characteristics and seeks to provide a state of the art of modern multiplexing sensor networks.

2. **Fiber optic sensor networks. Basic concepts**

In classifying optical fiber sensor networks, it is necessary to make a first subdivision between them:

- Simple networks. Term which is applicable to the networks in which only one type of sensors is multiplexed.
- Hybrid networks, in which several types of sensors are multiplexed, or through which several types of signals circulate, as may be the case of superposed data and sensors signals in a local area network [4].

Further preliminary subdivisions that must be made in order to clearly define a network, and which is based on the type of sensors used are [5] (Fig.1):

- Transmissive networks, based on transmissive sensors.
- Reflective networks, that use the reflected signal in each sensors and that usually result in fiber saving.

Finally, it is common to distinguish between point multiplexed sensors and distributed sensors, as shown in Fig.2. In the distributed sensors there is only one sensing element, and the objective of the signal processing is to recover the measurand as a function of position along the sensing element. On the other hand the multiplexing of point sensors consists of processing the value of the measurand corresponding to each discrete sensing element.

It must be made clear that both types of sensors may coexist in the same network, resulting again in hybrid networks [6].

As far as the type of optical signal is concerned one can make an initial distinction between networks capable of multiplexing sensors by employing optical signal's phase for the information transmission (interferometric sensors networks), or ones that are based on codifying the intensity of light (by means of some multiplexing technique) which we will call the intensity sensor networks. It is precisely this classification which is utilized in most of the classical texts covering this topic [7], [8].

One can see in Figure 3 different multiplexing formats as a function of optical signal's varying parameter used for data representation.

There exist a number of diverse topologies for making sensors available in a network. They are divided into four basic configurations, shown in figures 4.a and 4.b; where each one in turn can be of a transmissive or reflective type. One important factor to have in mind in fiber optic networks in general and in the sensor ones in particular is the optimized value of the received signal level arriving from each of the sensors. A fiber optic transmission system always has available a range of optical power, such as the existing difference between the maximum level of signal that can be received by a detector without saturating and the corresponding minima for which the system will operate with the acceptable signal to noise ratio. Where in a star topology the choice of the splitting ratio is easy (1/N, where N is the number of sensors to be multiplexed), that of the bus architecture is a delicate subject [8]. In the usual case, where it is desirable that all the couplers have equal splitting ratio, the optimum value would still be 1/N. On the other hand, the signal can be optimized by making each coupler to have a different coupling ratio. This last case, however, is not common and results on an increased cost and complexity of the network.

2.1 Point and distributed sensors

Point sensors are able to perform the measurements of a great variety of physical and chemical parameters. However, there are tens of applications in structural health monitoring were the main parameters to be controlled are temperature and sometimes strain and vibration. For those applications, distributed sensing is a suitable choice when many measurement points are needed along a linear network. Term “distributed” refers to the ability to simultaneously detect scale and location of a measurand anywhere along a continuous length of sensing fiber. This differs from the concept of multi-point sensing, where the measurement is done at specific locations with point sensors, such as fiber Bragg gratings [9].

The use of fiber optic distributed sensing was stimulated by the Optical Time Domain Reflectometry (OTDR) technique, which uses the temporal resolution of light continuously Rayleigh backscattered from an optical pulse propagating in the optical fiber [10]

The Rayleigh scattering appears from the interaction of the light with refractive index fluctuations in the fiber core that appear in spatial scales much shorter than the light wavelength. Optical Time Domain Reflectometry was developed initially as a network diagnostic tool for optical fiber telecommunication systems. The basic arrangement shown in Fig. 5 is used to map attenuation as a function of length along a single fiber cable (bus configuration). The test fiber is illuminated with a short pulse of duration Δt at time t=0. As the light propagates through the fiber it suffers Rayleigh scattering, and a portion of the scattered light is recaptured by the fiber core and guided back towards the detector. If a set of sensors are deployed along the fiber in a serial array, the effect of the measurand of a sensor is to modify the attenuation of the section of fiber within it is incorporated. By using OTDR, the attenuation of each sensor is recovered, from which each sensor of the array is spatially identified and the measurand is derived.

The use of different means of measurement the time delay taken from for light to travel from the source to the detector leads to other time domain techniques, such as the above mentioned OTDR and Optical Frequency Domain Reflectometry (OFDR) or polarization domain reflectometry (POTDR)[11].

Modern and very high resolution Optical Frequency Domain Reflectometry can be used to measure the Rayleigh backscatter from the fiber and thus map the imperfections that cause it. Once this map, or fingerprint, is stored, it can be used in some very interesting applications from distributed fiber-optic sensing to network security and intrusion prevention. It can also be used for quasi-distributed measurements of FGBs sensors arrays (Fig. 6). With this technique, temperature changes can be measured with a resolution of 0.1 ºC and changes in strain with a resolution of 1 μm/m [12].

Non-lineal scattering effects are also used for distributed measurements. Raman scattering is generated by the interaction of the propagating light with molecular vibrations in the medium. Brillouin scattering is generated by interaction of the light with acoustic modes in the medium, which are induced by the light propagation [9].

Figure 7 shows the spectral characteristics of the several types of lineal and non-lineal nature scattered light useful for distributed sensing. The ratio of the Stokes and anti-Stokes wavelengths symmetrical about the optical power in Raman scatter is uniquely related to temperature and after correction for the slight differences in Rayleigh backscatter can be used as a very effective temperature probe. Raman backscatter systems have been commercially available since two decades ago and have found real applications niches such as monitoring tunnels for fire. The sensor is particularly simple to install and provides temperature resolutions of the order of 0.1 to1 ºC within resolution lengths of order of one meter over interrogation lengths extending to several tens of kilometers [13].

Brillouin scatter in contrast is usually used in the frequency domain. The peak offset frequency for Brillouin scattering is measured and is a unique function of the acoustic velocity (and therefore temperature and strain) in the optical fiber. Typically, the temperature and strain coefficients are so that a temperature shift of a degree centigrade gives the same signal as a strain change of a few microstrains [13]. Consequently Brillouin scatter can be used as a strain and temperature monitor where the strain ranges are large enough. Brillouin scatter is nowadays used to interrogate many tens of kilometers of fiber length. Brillouin optical time domain analysis (BOTDA) is one of the most used approaches for this sensing technique. It uses a short pump pulse which is launched into the test fiber at one end, while a continuous wave (CW) probe beam is launched into the fiber at the other. The probe optical frequency is offset from that of the pump by the nominal Brillouin offset frequency. The CW probe light experiences Brillouin gain at the spatial locations along the fiber where the frequency offset is matched to the peak Brillouin gain. The time dependence of the detected CW light thus provides a “profile” of the gain experienced by the light as the pump pulse passes along the fiber [14].

2.2 Modulation format

Two are the most commonly used multiplexing techniques, namely time division multiplexing (TDM), wavelength division multiplexing (WDM) (Fig.8). These techniques, also in combination (or not) with frequency division multiplexing (FDM), coherence division multiplexing (CDM) (Fig. 9) or polarization division multiplexing (PDM) offer a broad scenario of possible solutions which different performance implications, using different architectures for addressing the sensors inside the sensors network.

TDM is the most straight forward technique for multiplexing optical fiber sensors and, in fact, the first one ever employed [10]. It relies on utilization of pulses generated by a single light source which are sent directly into the network. In such a system to each of the emitted pulses a series of associated pulses is being generated at the output, in the amplitude of which and in whose separation resides information to be extracted.

WDM is one of the most utilized multiplexing techniques. Here a different wavelength is associated with a particular sensor in such a way that the information of each one of them traverses the network on different optical subcarrier. Topologies which are typically used in these networks are of a bus or a star configuration, given that they are of the reflective sensor type, or of a dual bus in the transmissive sensor case.

Figure 10 presents a schematic diagram of the reflective bus configuration where a single light source (which may be a tunable laser or a broadband source) generates multiple optical subcarriers (wavelengths) to each one of which, typically, corresponds to a particular sensor. Reflected optical signals from the wavelength selective sensors (typically Fiber Bragg Gratings, FBGs) are collected in the head of the fiber bus for being further delivered to the receiving stage of the network wherein each wavelength is measured.

The availability of low cost FBGs sensors makes this multiplexing technique especially attractive. Together with tunable lasers or broad spectrum emitting sources (LEDs, ELEDs, fibers doped with rare earth elements) this technique has been converted into a preferred one [13].

2.3 Active optical sensors networks

Optical amplification techniques, and particularly, doped fiber amplifiers supposed a revolution for optical fiber systems. Optical amplification is nowadays a mature technology, massively employed in long and medium haul telecommunication networks.

Within the sensor application field there are three main motivations for including optical amplification: to perform distributed sensing based on non-lineal effects reinforced with optical amplification, or to increase the number of point sensors multiplexed in a single network while ensuring good signal quality; or to enable the possibility of remote sensing. Point-sensor multiplexing networks have to deal with the problem of power losses due to the distribution architecture. In this context optical amplification is a possible solution for the problem of poor power budgets, compensating for splitting losses and highly increasing the number of sensors per fiber on the network [15-19]

The optimum configuration of the amplifier employed in a sensor network strongly depends on the system topology, the number of sensors and the multiplexing technique [20-21]. The optical amplifier requirements will be determined by the position within the system. Postamplifiers will typically require high output powers whereas distributed amplification will pursue low noise levels and is well suited for distributed sensing and preamplifiers will require high gain. Star topologies typically employ postamplifiers while bus structures take advantage of the power equalization between the different sensors provided by distributed amplification. Lumped type amplification acting as postamplifier will typically require high output powers while distributed amplification will pursue low. Power amplifiers, also referred as postamplifiers, are placed right after the light source to increase the optical power launched into the network.

When using optical amplification into a sensor network, it is possible to transform the network into a lasing structure. This strategy usually improves the Signal to Noise ratio of the detected signals received from the sensors [1]. Multisensor fiber Bragg grating lasers utilize several fiber Bragg gratings normally at different wavelengths, an amplification section and a mirror (or structure acting as a mirror) to create an in-fiber cavity [22-26]. The utilization of an amplifying medium between the gratings/mirrors, pumped inside or outside the cavity provides gain and thus lasing. The cavity may show single mode or multimode performance depending on the gratings and the cavity length. The utilization of these structures for remote sensing [1] will be also mentioned in section 4.

2.4 Self-referencing

The multiplexing of intensity based sensors has problems with system losses away from the transducer and light source output power fluctuations. To solve this problem, many techniques have been reported in the last 20 years to compensate for these power fluctuations in several kinds of fiber optic sensors such as FBG based sensors or displacement sensors. The self-referencing multiplexing techniques for intensity modulating fiber-optic sensors reduce this problem [27-28]. The technique provides for the multiplexing of a number of sensors and allows transducer caused intensity fluctuations to be determined irrespective of optical losses in other parts of the system or power fluctuations from the laser source. Time division, wavelength normalization [29], spectral splitting [30-31], frequency-based self-referencing methods on differential amplitude [32-35] or using amplitude to phase conversion [36], and others using counter propagating signals [37] or electronic means have been reported to overcome this problem. In the frequency-based self-referencing techniques, the input light is RF modulated and an amplitude ratio measurement are performed at the reception [32-35] or intensity modulations are converted into electrical phase modulation [36, 38-39]. Different interferometric schemes such as Mach-Zehnder, Michelson [33] and ring resonator topologies [32, 34, 35, 40] are considered in the amplitude ratio measurements.

3. Robust networks

Fibers can be broken by human activities or natural events, causing light-path interruption. When this fact happens to an interconnect fiber, only one sensor is isolated. However, failures in the main fibers, which are used to guide all the signals to reduce costs, render the network inoperative [41]. Robustness concept entails the ability of continuous operating despite one or more points of failure on the network [42].

The appropriate scheme of a robust optical fiber sensor network should fulfill three criteria at the same time: firstly, the network must withstand at least one fiber failure at any point; secondly, the network must operate with nominally equal transmission losses for all sensing channels in passing from the transmitter mode to the receiver one, both in normal operation and after recovery from a failure; thirdly, it must be possible to signal the failure and to take the required actions without external resources such as dedicated fibers or radio links.

The ability to operate despite failure will become increasingly important as the use of optical sensor networks grows, and the amount of sensing information to be handled by a sensor network is increasing, especially for these safety and security applications (bridges, dams, nuclear plants, chemical storage sites, etc), where the structure being monitored is of high value (soil pipelines, power transmission lines, and all kind of health monitoring of civil structures) or where the perimeter security is a concern (airports, banks, etc.). Most robust fiber-optic sensor systems have been predesigned for protection against single failures. However, a number of novel topologies with the ability to withstand multiple failures, as well as a mathematical model for these WDM self-healing optical fiber buses have been recently proposed.

Several wireless networks of optical sensors have been also demonstrated to be robust in the presence of noise or changes in the propagation environments [43]. However, the use of fiber-optical sensor networks presents some advantages in comparison with the wireless network: vast bandwidth, electromagnetic interference is not an issue, data privacy is enhanced, and long unamplified transmission ranges are enabled. In addition, these networks offer the intrinsic benefits of the optical fiber, thus, they can be used in combustible, radioactive, or chemically corrosive environments, and even they can be imbedded within the structures [9], [44], [43]. Recently a remote powered by light fiber optic switch for resilient interrogation of FBG sensors arrays was experimentally demonstrated. This fiber optic switch was powered by a photovoltaic power converter illuminated by a Raman laser working at distances up to 50 km [46].

There are, in general, four categories of protection to allow service to be reestablished after a failure: “dedicated” or “shared” protection, each of these has sub-categories called “path” and “line” protection, as a result, dedicated line, dedicated path, shared line and shared path are the four classes. All of them have direct counterparts in telecommunications networks [47].

The manner the sensor unit is connected to the network is, typically, the main difference between dedicated and shared protection. Dedicated protection employs a coupler (see Fig. 11) while shared protection uses a switch (see Fig. 12). As can be seen, dedicated protection offers clear advantages from the point of view of cost, simplicity of automatic protection switching (APS) software, ease of signaling and the ability to withstand multiple failures in some topologies; while shared protection is more suitable when the losses are a limiting factor, and it is worth noticing its ability to offer spatial reuse [48], [49].

In dedicated protection, the signal travels through both working and protection fibers simultaneously. The receiver will accept only one, and the other will be discarded. The criterion of acceptance is usually by default of the signal provided by working fibers. In shared protection, the switch is chosen if the signal travels via working or protection fibers. Only the working fibers are used in normal operation, and only the protection fibers in the event of a cable fail to provide the required redundancy.

On the other hand, path protection and line protection differ in the form of protection. In path protection, each sensor is protected individually by the switch located in the transmission or receiver node which reroutes the information in the event of a failure in the network (see Fig. 13). Conversely, in line protection, the sensors are protected by the nearest switches to the failure, and such switches do not belong to the transmission/receiver node but they are placed in the sensor network itself (see Fig. 14) [50]. Thus, if there is a failure, the network is able to reconfigure the route.

There have been many studies of how to ensure survivability of telecommunications fiber networks and sensor radio networks. However, depending on their topologies, the most representative robust fiber-optic sensor systems can be classified as: ring networks [51], [52], [53], double ladder bus [42],[48],[49],[54],[55], linear fiber laser [56], [57], [58], [59], and mesh sensing systems [52], [60], [61], [62], [63] each one with their own pros and cons. So, the choice of a protection scheme is determined by the performance, cost and final application of the network.

4. High performance networks

Fiber optic sensor networks have emerged as a powerful tool for condition assessment of expensive (including bridges, dams and other civil constructions), large and complicated structures [9], [44].

Thus, optical fiber sensors are used for the monitoring of complicated composite structures because they are capable of measuring strain and temperature over several tens or even hundreds of kilometers by accessing only one end of an optical fiber [64], [65]. There are a number of reported applications to actual structures, for example dams [66], marine vehicles [67], bridges [64], [68], and aircrafts [69]. In addition to this, some of these methods may find applications as useful as tsunami early warning systems [70].

The development of the technology and components used in the optoelectronics units and multiplexing networks for sensors has been helped by the fast growing of the fiberoptic telecommunication technology. High performance tunable lasers, couplers, optical switches, optical amplifiers, filters and detectors are available for sensors multiplexing due to the major market that supposes telecommunications

Even though their market advantages, optical fiber networks for sensors fake three challenges [71]: to ensure **service continuity** in the event of point failure(s) on the network; to enable the possibility of **remote sensing** and the need to **increase the number of sensors** that can be multiplexed on a single network while ensuring good signal quality. The first challenge was previously pointed out, and the two last are thoroughly discussed below.

Due to the noise and loss induced by the Rayleigh scattering and attenuation along the fiber respectively, the maximum transmission distance with a broadband light source without using optical amplification is usually limited up to few tens of km [72], [73]. Because of that, the maximum measurement distance of fiber sensor systems comes out to be a practical issue. A lot of work has been done to increase the measuring distance of the fiber sensor, however most of this proposal makes the setup quite complicated.

For example, Lee at al. proposed a Raman amplifier-based long-distance sensing system using a combined sensing probe of an erbium-doped fiber (EDF) and a FBG, but more than one laser soured was used. In addition, the measurement length was only 50 km for that system [74], [75].

Fu *et al.* demonstrated a 75-km long distance FBG sensor system. However, amplification was needed every 25 km which made the system more complicated and less controllable in practical applications [76]. On the other hand, Saitoh *et al.* demonstrated an ultra-long distance fiber Bragg grating sensor system able to detect changes in the FBG reflection wavelengths even if the FBG was 120 km from the sensing position without using amplification [70] and a 230 km FBG sensor system using a high-speed swept-wavelength light source using EDF amplification [77]. Rao *et al*. proposed a 100-km long-distance FBG sensor system based on a tunable fiber ring laser configuration [78]. Leandro *et al.* presented and demonstrated a technique for remote sensing of FBGs beyond 150 km that combined Raman, Brillouin, and erbium gain in a linear cavity fiber laser [79]. The experimental setup used for this remote interrogation of two FBGs is presented in Figure 15.

Because of the measurement length limitation by the loss and attenuation along the fiber, increasing the pump power seems to be the most effective method to get a longer distance fiber sensor system. However, high noise levels and undesired lasing effects were induced when the pump power was increased to a threshold, which is the main reason why it is hard to get longer distance FBG sensor system. To achieve longer distance measurement, complicated setups with a lot of components are used to reduce the noise effect. In practical usage, however, simple and easily launched long distance sensor systems are desired. As examples of that, Fernandez-Vallejo *et al.* proposed two simple systems based on a wavelength swept laser to scan the reflection spectra of the FBGs; one of those simple systems was able to detect four multiplexed FBGs placed 250 km away using Raman amplification [80] and Bravo *et al.* demonstrated a 253 km ultra-long remote displacement sensor system based on an OTDR and a fiber loop mirror without using any optical amplification [81].

Table 1 summarizes some of the advances in remote sensing systems for optical fiber sensors in chronological order taking into account the most representative characteristics of the systems.

Table 1. State of the art of remote fiber-optic sensor systems

Year / Ref	Network length	Laser resource/ Amplif. type	Remarks
2005 [82]	50 km	multiwavelength Raman fiber laser	PS-FBG temperature and strain sensors
2007 [70]	120 km	No amplification	Strain sensors
2007 [83]	100km	Rayleigh backscatter	remote fiber dynamic strain sensing system
2008 [77]	230 km	EDFA	Strain sensors
2009 [84]	4 km	EDFA	PS-FBGs detect and identify organic vapours

2010 [72]	100 km	Raman + EDFA	Temperature sensors 30 dB signal noise ratio
2011 [85]	100 km	Raman + EDF	Vibration (from 1Hz to 1000Hz) sensor system
2011 [86]	120 km	BOTDA + bi-directional Raman amplification	2 meter spatial resolution and a strain/temperature accuracy of 45 με/ 2.1ºC
2011 [87]	100 km	hybrid Brillouin + Raman	Temperature sensors; 30 dB OSNR; immunity from the light source power fluctuations
2011 [79]	155 km	Raman + EDFA + Brillouin	sensing temperature changes with a sensitivity of 10 pm/ºC
2011 [80]	200km 250 km	Raman	Temperature sensors Two simple systems
2011 [81]	253 km	No amplification	Displacement sensor system based on a fiber loop mirror
2011 [88]	100 km	Brillouin	Temperature and strain sensor system; 50 m spatial resolution
2011 [89]	50km	Dual-wavelength Raman fiber laser	Simultaneous measurement of bending and temperature
2012 [90]	150 km	Raman + EDFA	Temperature and vibration sensor system
2012 [64]	30 km	Optical pulse correlation	Temperature and strain sensor system; suppression of instability
2012 [91]	50 km	EDFA and an Optical time domain reflectometry (OTDR)	Displacement sensors based on microbenders
2012 [92]	171 km	No amplification Based on self-heterodyne detection	Remote FBG sensors system based on the self-heterodyne detection. Two temperature sensors (11pm/ºC)
2013 [93]	75 km	Raman + EDFA	Ladder structure
2013 [94]	200km	Raman + EDFA	200 km remote lasers for FBGs multiplexing

As it was previously pointed out the need to increase the number of sensors that can be multiplexed on a single network while ensuring good signal quality is one of the major challenges of the optical fiber networks for sensors. Systems employing large number of arrays of FBGs have performed successfully in numerous field trials and applications involving a wide variety of structures. Figure 16 shows the amplified TWD/WDM array topology demonstrated in [95].

The largest interferometric fiber-optic sensor array reported to date consisted of a time and wavelength-division multiplexed architecture combining up to 256 sensors onto a single fiber pair [96]. Time division multiplexing has been revealed to have low crosstalk and high sensitivity for multiplexing a high number of sensors [97], [98]. In a TDM scheme, the maximum number of sensors per fiber pair is limited by the distribution losses.

Nevertheless, compensation of splitting loss as well as the fiber loss can be achieved by incorporating EDFAs in the array. For example, high-gain pre- and post-amplifiers were used in a 64-element interferometric sensor by researchers from the Naval Research Laboratory (NRL) [99]]. A better solution has been developed in which an amplifier is placed in front of each distribution coupler on both buses in the TDM scheme [100]. A system was demonstrated that consisted of a ten-rung ladder structure using multiple low-gain amplifiers to overcome the branching loss in each ladder rung. This method allows 200 sensors to be addressed by only one fiber pair with a minimum detectable signal of 5.7 μrad/√Hz [101]. However, due to nonlinear effects, and the optical duty cycle or interrogation rate of each sensor it is increasingly difficult to support more sensors beyond a total number of about 300 in a TDM scheme [97].

Compared with the TDM architecture, the combination of WDM with a TDM architecture is significantly more efficient, both in terms of number of channels per fiber and number of channels per laser [96], [101]. This architecture has demonstrated high performance from sensors in an optically efficient arrangement with low component numbers, and can theoretically be extended to interrogate at least 192 [98] to 256 [96] sensors through two fibers while achieving a low-phase resolution limited by the optical amplifier noise. Nevertheless, the optical power levels received for signals significantly decreases with increasing array size.

Recently this technique has been extended to a novel architecture considered to be the best approach to support high resolution. Liao *et al.* show the viability to up to 4096 sensors using only commercial available components through one pair of telemetry fibers [95].

A number of interrogation systems can be used to sense distributed sensors and point sensors simultaneously so the number of sensors that can be allocated in one fiber is increasing day by day. In addition to this, the capability of distributed sensing has led to real advantages in mayor application areas such as oil and gas industry, infrastructure monitoring, security, seismic measurement, reservoir pressure, flow and temperature monitoring, among others [102], [103]. As an example of these applications Nakstad *et al.* has developed a novel, high-performance large-scale fiber optic Ocean Bottom seismic Cable (OBC) system, based on combined wavelength- and time-multiplexing of FBGs based interferometric sensors. A large-scale manufacturing system has been developed to handle the manufacturing of several systems per year- each system having at least 2000 sensor stations [104].

As it was previously pointed out, distributed optical fiber sensors are attracting an increasing interest due to their wide range of potential industrial applications in strategic sectors such as energy [105], defense, security [106], or transportation. As mentioned before, fiber sensors based on Brillouin optical time-domain analysis (BOTDA) exploits the dependence of the Brillouin frequency shift parameter on temperature and strain [107], [108], [109], so these distributed Brillouin sensors are able to measure with highly accurate structures over long single mode fibers exceeding several tens of kilometers [71]. That is the reason why monitoring civil structures to which optical fibers can be attached with highly accurate distributed measurement over long single mode fiber can be measured [110], [111]. These distributed optical fiber sensors have been applied to the power grids, railways, bridges, tunnels, roads, constructions, water supply systems, dams, oil and gas pipelines and other facilities, and can be also integrated with wireless networks [112].

One of the main drawbacks of this technique is that the measurement range of these systems has a trade-off between the measurement range and the spatial resolution [71]. Consequently, present research in BOTDA sensors has two different varieties: long-range BOTDA sensors, which are able to perform measurements in tens of kilometers with meter resolutions, or high-resolution sensors with centimeters spatial resolution, but for relatively short-distances fibers. Moreover, if these schemes were for remote sensing, this measurement range should be divided by a two factor (because stimulated Brillouin scattering only occurs when incident pump light is contradirectional to the signal), limiting their use in certain applications in which the distance to monitor is too long. The performance of distributed sensors is listed in following tables. Table 1 and 2 summarize the state of the art of distributed optical fiber sensors based on Brillouin technique for long-range BOTDA sensors and high-resolution sensors respectively.

Distributed sensors can be realized in the time domain using optical pulse to determine the spatial resolution as 10–90% changing signal [113]. In addition to this, there are three types of OTDR sensors based on Rayleigh [114], Brillouin [115] and Raman [116] scattering. These sensors can also be realized in the frequency domain, so called OFDR based on Rayleigh scattering [117] and Raman scattering of the power ratio of Stokes and anti-Stokes [118]. The Raman technology is based on frequency modulation of an electrical optical modulator’s baseband signal, the detection of Stokes and anti-Stokes ratio then gives a temperature relation, due to the small tuning range of the modulator; this technology yields a spatial resolution of 1 m [119] over 1 km length using direct detection without getting phase information.

Among Rayleigh, Raman and Brillouin scattering based sensors, Brillouin sensors have shown the best performance in terms of sensing length, over 150 km with spatial resolution of 2 m and temperature resolution of 1.5 °C [120] with Er-doped fiber amplifier, and high spatial resolution of a few centimeters. The limitations of sensing length result from fiber losses over the long sensing length, which can be compensated by either Raman scattering amplification or EDFAs [121].

Among three different kinds of scattered light in optical fiber, Rayleigh scattering is the strongest, Brillouin scattering is 15–20 dB weaker, and Raman is the weakest [113]. However, when a laser with a 50 kHz linewidth is used as a phase OTDR source, the spectral width of the Rayleigh scattering is the same as that of the laser, while the Brillouin spectrum width is 30 MHz, and the Raman scattering width is ~THz. One can integrate the optical energy over the spectrum for Brillouin and Raman scattering to improve SNR, while for Rayleigh scattering this is not possible due to the narrow linewidth. Because of Brillouin and Raman gain, the sensing length can be improved significantly.

With high spatial resolution (1 mm) the frequency domain distributed sensor is much more cost effective than OTDR, as the broadband electronics and digitizer requirements have made OTDR based systems very expensive. This is especially true for Brillouin grating type sensors, which requires three lasers to be locked together and PMF to be employed as the sensing fiber which makes such systems complicated and expensive. The advantage of Brillouin scattering based distributed sensors versus Rayleigh scattering based sensor systems are: (1) they measure the Brillouin frequency change, which is an absolute change, rather than the intensity or phase change; and (2) OFDR can only detect relative changes from one of the reference fiber conditions. It uses a correlation function to locate temperature or strain changes between two events. It means that large temperature or strain gradients will not be detected, as the temperature or strain induced wavelength shift can be larger than the wavelength peak itself [113].

Table 2. State of the art of long-range BOTDA sensors

Year/Reference	Technique	Distance	Resolution	Accuracy
2012 / [122]	Brillouin	2km	2cm	2ºC
2012 / [108]	Brillouin +Raman	25 km	3m	4ºC
2012 / [123]	Brillouin + Raman	100km	2m	1.2ºC
2012 / [124]	Brillouin +Raman	100km	0.5m	2.9 ºC
2010 / [125]	Brillouin + EDFA	50km	1m	2.2ºC / 44 με
2010 / [126]	Brillouin + EDFA	2km	2m	± 2MHz
2012 / [127]	Brillouin + EDFA	100 km	7m	100με
2012 / [128]	Brillouin + Raman bidirectional	120 km	1m	1.3ºC / 26 με
2005 / [129]	Brillouin + Raman	100km 150km	50m	0.8ºC 5.2ºC
2011 / [130]	Brillouin + Raman	120 km	2.3m	2.6ºC / 52 με
2011 / [131]	Brillouin (BOTDA)	50 km	5m	± 1.6 MHz

Table 3. State of the art of high-resolution BOTDA sensors

Year / Ref	Technique	Distance	Resolution	Accuracy	Others
2013/[109]	Brillouin + Rayleigh Backscatter	92m	50cm	±1.2ºC ±15 με	It uses the DPP-BOTDA approach
2012/[132]	BOTDA	50m	1cm	± 1.33ºC	Enhanced SNR to the BOTDA systems
2012/[133]	Brillouin + Phase shift	160m	1m	± 20 με	It uses Brillouin phase-shift instead of the conventional Brillouin gain
2012/[134]	Brillouin + correlation domain	500m	17cm	---	The apodization of the laser has the effect of improving the

	technique				spatial resolution
2009/[135]	Brillouin + correlation domain reflectometry	3cm	13mm	±100 με	One-end-access high-speed distributed strain sensing with high spatial resolution
2006/[136]	Brillouin + optical correlation domain analysis	3mm	1.6mm	±60 με	A novel beat lock-in detection scheme is used
2012/[137]	Brillouin + Raman scatterings	500m	50 cm	0.5 MGy 100% hydrogen concentration in atmosphere	It is shown that 1.3 μm working wavelength is in favour of hazardous environment monitoring
2012/[138]	Brillouin	Several hundred meters	2m	± 0.21 MHz/%H_2	Distributed hydrogen sensing into long-range structures, (such as radioactive waste repositories)
2012/[139]	Brillouin (BOFDA)	210m	3cm	± 0.84 MHz	It has potentialities for mm-scale spatial resolution and long sensing ranges
2012/[140]	Stimulated Brillouin scattering	42 cm	<1cm	~ ±200 με	Distributed fiber sensing based on dynamic Brillouin grating in optical fibers
2012/[141]	Brillouin LIDAR approach	100m	1m	±0.1°C	Remote measurements of sound speed (and temperature) in the ocean

5. Conclusions

This paper reviewed fiber-optic sensors multiplexing main techniques and some recent developments in optical fiber based sensing networks. Main characteristics of new multi-point and distributed networks were addressed. Finally, it was summarized the current trends in robust multiplexing of fiber sensors, and the main records and performance of distributed and remote sensing fiber optic networks.

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LEGENDS

Fig. 1: Serial multiplexed sensors (a) reflective arrangement (b) transmissive arrangement

Fig. 2: Multiplexed and distributed sensors

Fig.3: Multiplexing formats for sensor networks

Fig.4.a: Multiplexing Topologies for fiber optic sensors: Bus, ladder, star

Fig.4.b: Multiplexing Topologies for fiber optic sensors: Tree, mesh

Fig.5: OTDR multiplexing

Fig.6: OFDR multiplexing

Fig.7: Linear and non-linear scattering effects for distributed measuring

Fig.8: TDM (a) and WDM (b) multiplexing bus sensor networks for point sensors

Fig.9: CDM multiplexing bus sensor network for multiplexing point interferometers

Fig.10: WDM multiplexing bus sensor network for FBG sensors

Fig. 11: Dedicated protection

Fig. 12: Shared protection

Fig. 13: Path protection

Fig. 14: Line protection

Fig. 15: Experimental setup used for remote sensing of fiber Bragg gratings beyond 150 km demonstrated in ref [79].

Fig. 16: Amplified TDM/WDM array topology shown in ref [95].

Table 1. State of the art of remote fiber-optic sensor systems

Table 2. State of the art of long-range BOTDA sensors

Table 3. State of the art of high-resolution BOTDA sensors

t1

Year / Ref	**Network length**	**Laser resource/ Amplif. type**	**Remarks**
2005 [82]	50 km	multiwavelength Raman fiber laser	PS-FBG temperature and strain sensors
2007 [70]	120 km	No amplification	Strain sensors
2007 [83]	100km	Rayleigh backscatter	remote fiber dynamic strain sensing system
2008 [77]	230 km	EDFA	Strain sensors
2009 [84]	4 km	EDFA	PS-FBGs detect and identify organic vapours
2010 [72]	100 km	Raman + EDFA	Temperature sensors 30 dB signal noise ratio
2011 [85]	100 km	Raman + EDF	Vibration (from 1Hz to 1000Hz) sensor system
2011 [86]	120 km	BOTDA + bi-directional Raman amplification	2 meter spatial resolution and a strain/temperature accuracy of 45 $\mu\varepsilon$/ 2.1ºC
2011 [87]	100 km	hybrid Brillouin + Raman	Temperature sensors; 30 dB OSNR; immunity from the light source power fluctuations
2011 [79]	155 km	Raman + EDFA + Brillouin	sensing temperature changes with a sensitivity of 10 pm/ºC
2011 [80]	200km 250 km	Raman	Temperature sensors Two simple systems
2011 [81]	253 km	No amplification	Displacement sensor system based on a fiber loop mirror
2011 [88]	100 km	Brillouin	Temperature and strain sensor system; 50 m spatial resolution
2011 [89]	50km	Dual-wavelength Raman fiber laser	Simultaneous measurement of bending and temperature
2012 [90]	150 km	Raman + EDFA	Temperature and vibration sensor system
2012 [64]	30 km	Optical pulse correlation	Temperature and strain sensor system; suppression of instability
2012 [91]	50 km	EDFA and an Optical time domain reflectometry (OTDR)	Displacement sensors based on microbenders
2012 [92]	171 km	No amplification Based on self-heterodyne detection	Remote FBG sensors system based on the self-heterodyne detection. Two temperature sensors (11pm/ºC)
2013 [93]	75 km	Raman + EDFA	Ladder structure
2013 [94]	200km	Raman + EDFA	200 km remote lasers for FBGs multiplexing

t2

Year/Reference	**Technique**	**Distance**	**Resolution**	**Accuracy**
2012 / [122]	Brillouin	2km	2cm	2ºC
2012 / [108]	Brillouin +Raman	25 km	3m	4ºC
2012 / [123]	Brillouin + Raman	100km	2m	1.2ºC
2012 / [124]	Brillouin +Raman	100km	0.5m	2.9 ºC
2010 / [125]	Brillouin + EDFA	50km	1m	2.2ºC / 44 με
2010 / [126]	Brillouin + EDFA	2km	2m	± 2MHz
2012 / [127]	Brillouin + EDFA	100 km	7m	100με
2012 / [128]	Brillouin + Raman bidirectional	120 km	1m	1.3ºC / 26 με
2005 / [129]	Brillouin + Raman	100km 150km	50m	0.8ºC 5.2ºC
2011 / [130]	Brillouin + Raman	120 km	2.3m	2.6ºC / 52 με
2011 / [131]	Brillouin (BOTDA)	50 km	5m	± 1.6 MHz

t3

Year / Ref	Technique	Distance	Resolution	Accuracy	Others
2013/[109]	Brillouin + Rayleigh Backscatter	92m	50cm	±1.2ºC ±15 με	It uses the DPP-BOTDA approach
2012/[132]	BOTDA	50m	1cm	± 1.33ºC	Enhanced SNR to the BOTDA systems
2012/[133]	Brillouin + Phase shift	160m	1m	± 20 με	It uses Brillouin phase-shift instead of the conventional Brillouin gain
2012/[134]	Brillouin + correlation domain technique	500m	17cm	---	The apodization of the laser has the effect of improving the spatial resolution
2009/[135]	Brillouin + correlation domain reflectometry	3cm	13mm	±100 με	One-end-access high-speed distributed strain sensing with high spatial resolution
2006/[136]	Brillouin + optical correlation domain analysis	3mm	1.6mm	±60 με	A novel beat lock-in detection scheme is used
2012/[137]	Brillouin + Raman scatterings	500m	50 cm	0.5 MGy 100% hydrogen concentration in atmosphere	It is shown that 1.3 μm working wavelength is in favour of hazardous environment monitoring
2012/[138]	Brillouin	Several hundred meters	2m	± 0.21 MHz/%H_2	Distributed hydrogen sensing into long-range structures, (such as radioactive waste repositories)
2012/[139]	Brillouin (BOFDA)	210m	3cm	± 0.84 MHz	It has potentialities for mm-scale spatial resolution and long sensing ranges
2012/[140]	Stimulated Brillouin scattering	42 cm	<1cm	~ ±200 με	Distributed fiber sensing based on dynamic Brillouin grating in optical fibers
2012/[141]	Brillouin LIDAR approach	100m	1m	±0.1°C	Remote measurements of sound speed (and temperature) in the ocean

Figure1

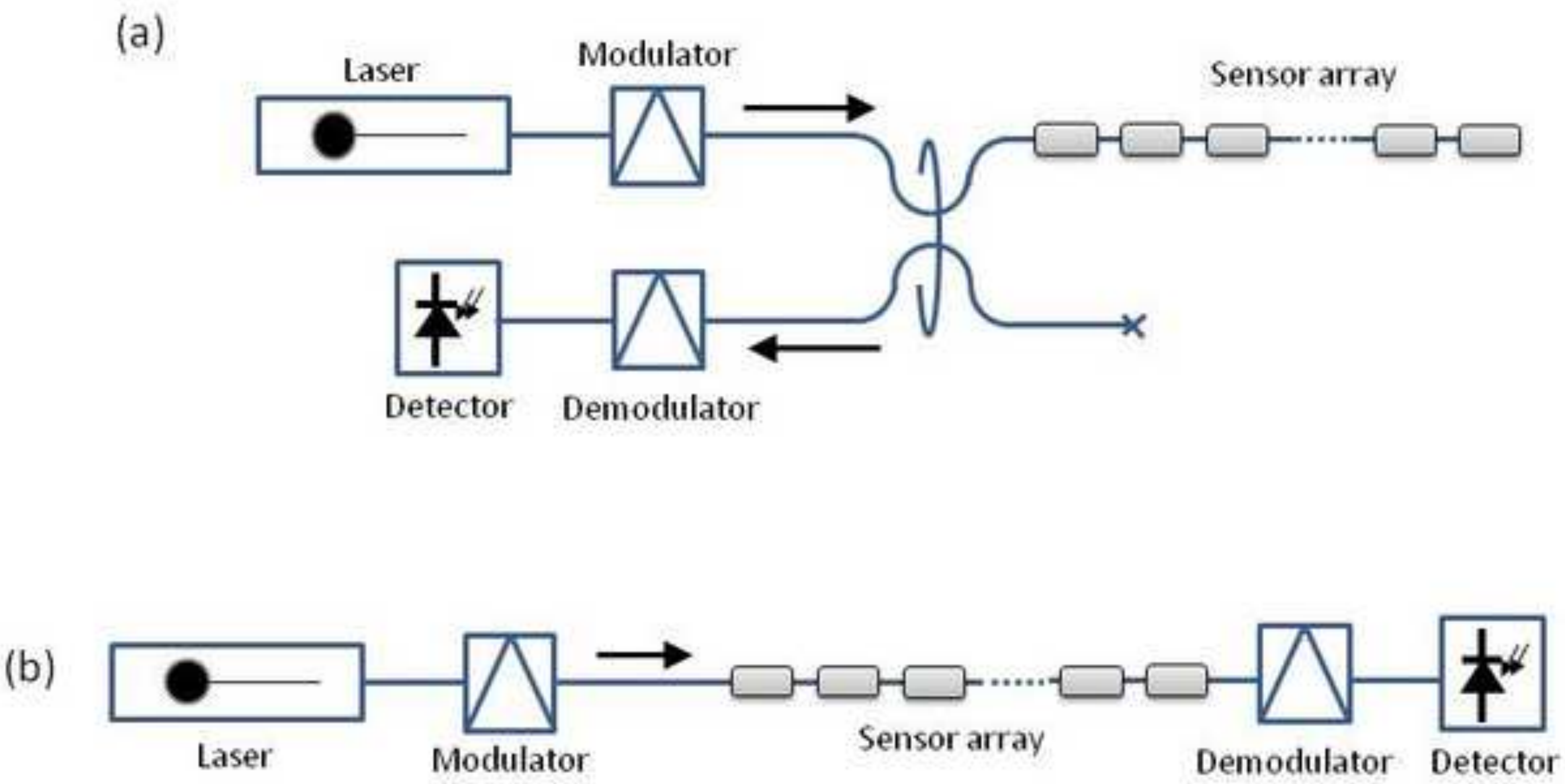

(a)
Laser
Modulator
Sensor array
Detector
Demodulator
(b)
Laser
Modulator
Sensor array
Demodulator
Detector

Figure2

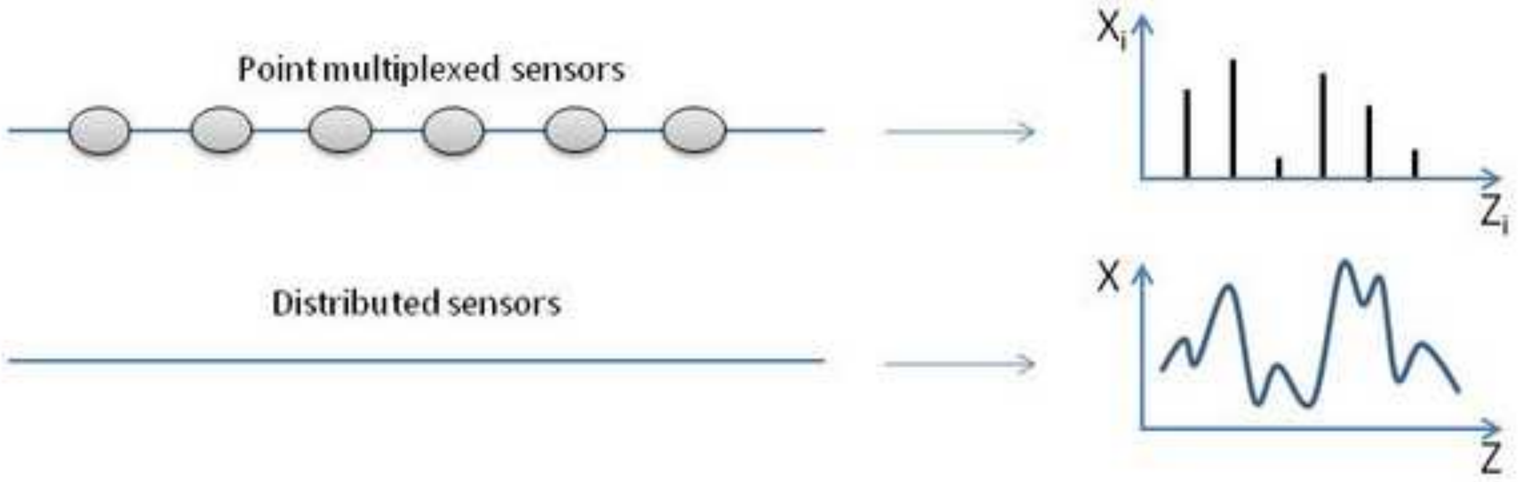


Figure3

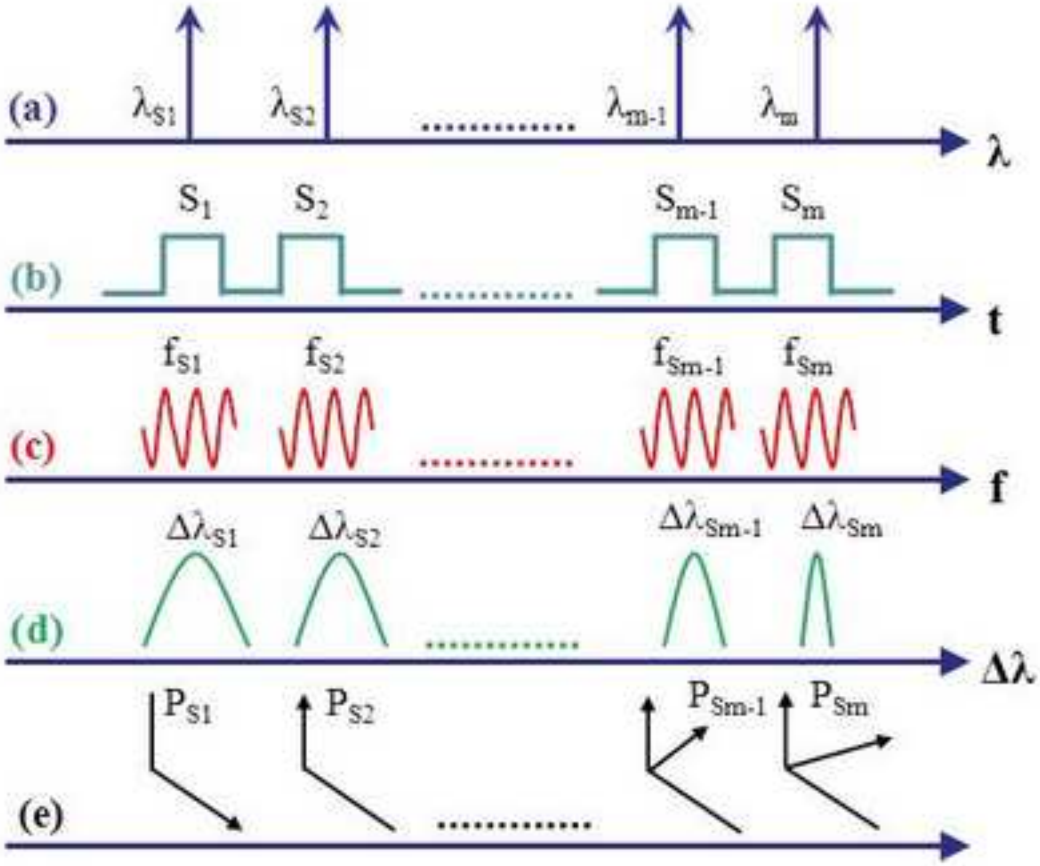

(a)
λS1
λS2
λm-1
λm
λ
(b)
S1
S2
Sm-1
Sm
t
(c)
fS1
fS2
fSm-1
fSm
f
(d)
ΔλS1
ΔλS2
ΔλSm-1
ΔλSm
Δλ
(e)
PS1
PS2
PSm-1
PSm

Figure4a

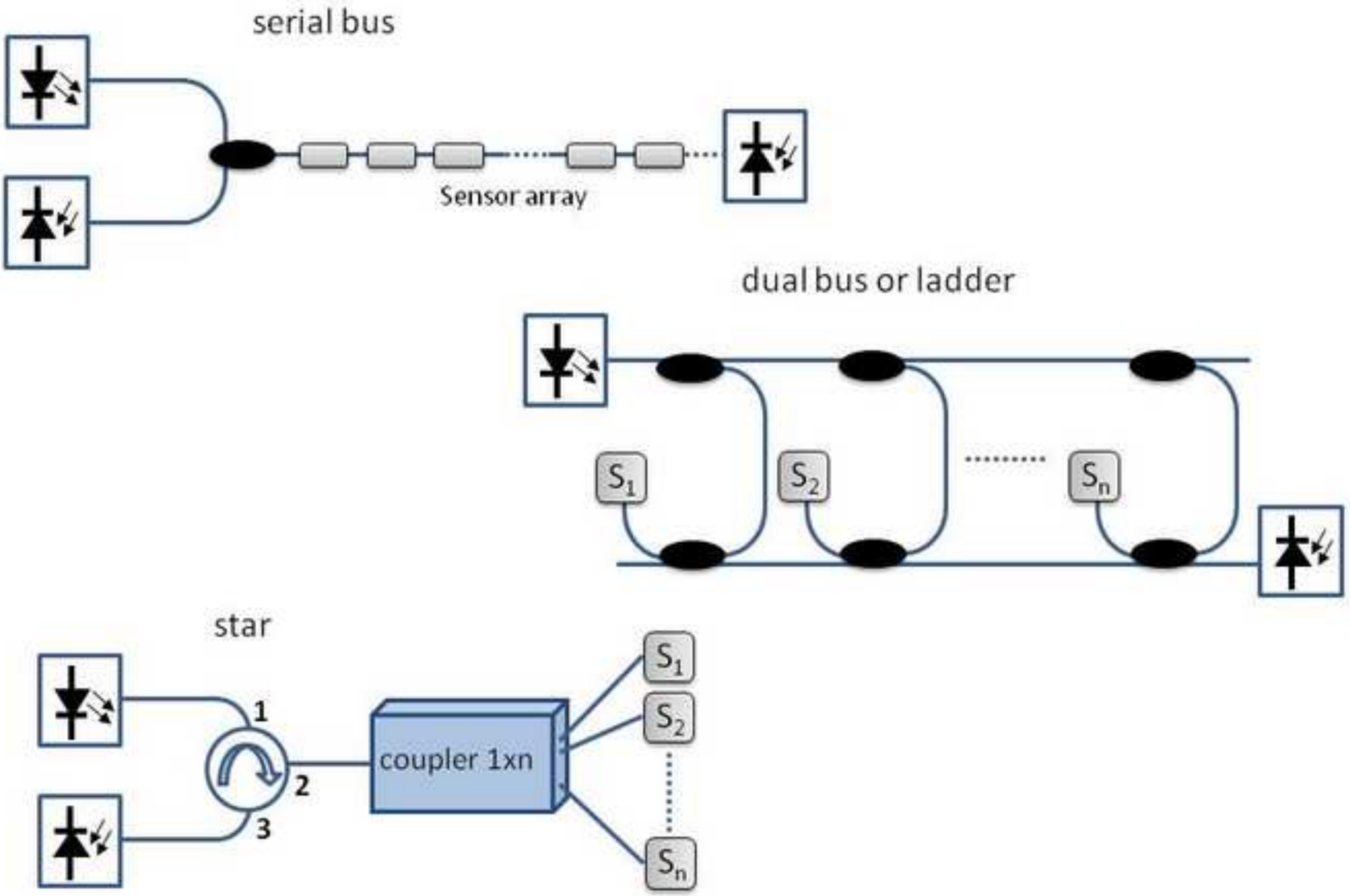

serial bus
Sensor array
dual bus or ladder
S_1
S_2
S_n
star
1
2
3
coupler 1xn
S_1
S_2
S_n

Figure4b

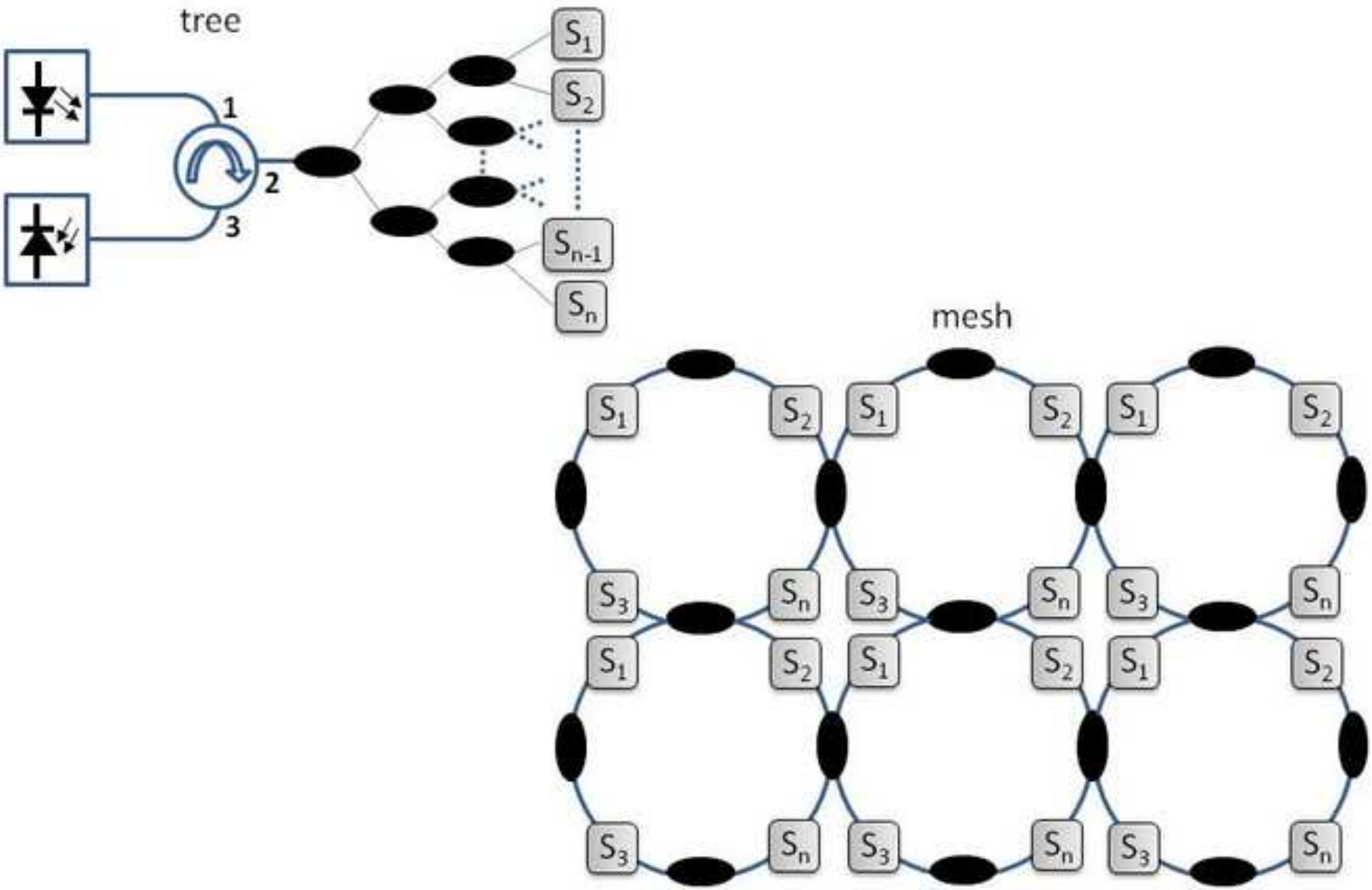


Figure5

Click here to download high resolution image

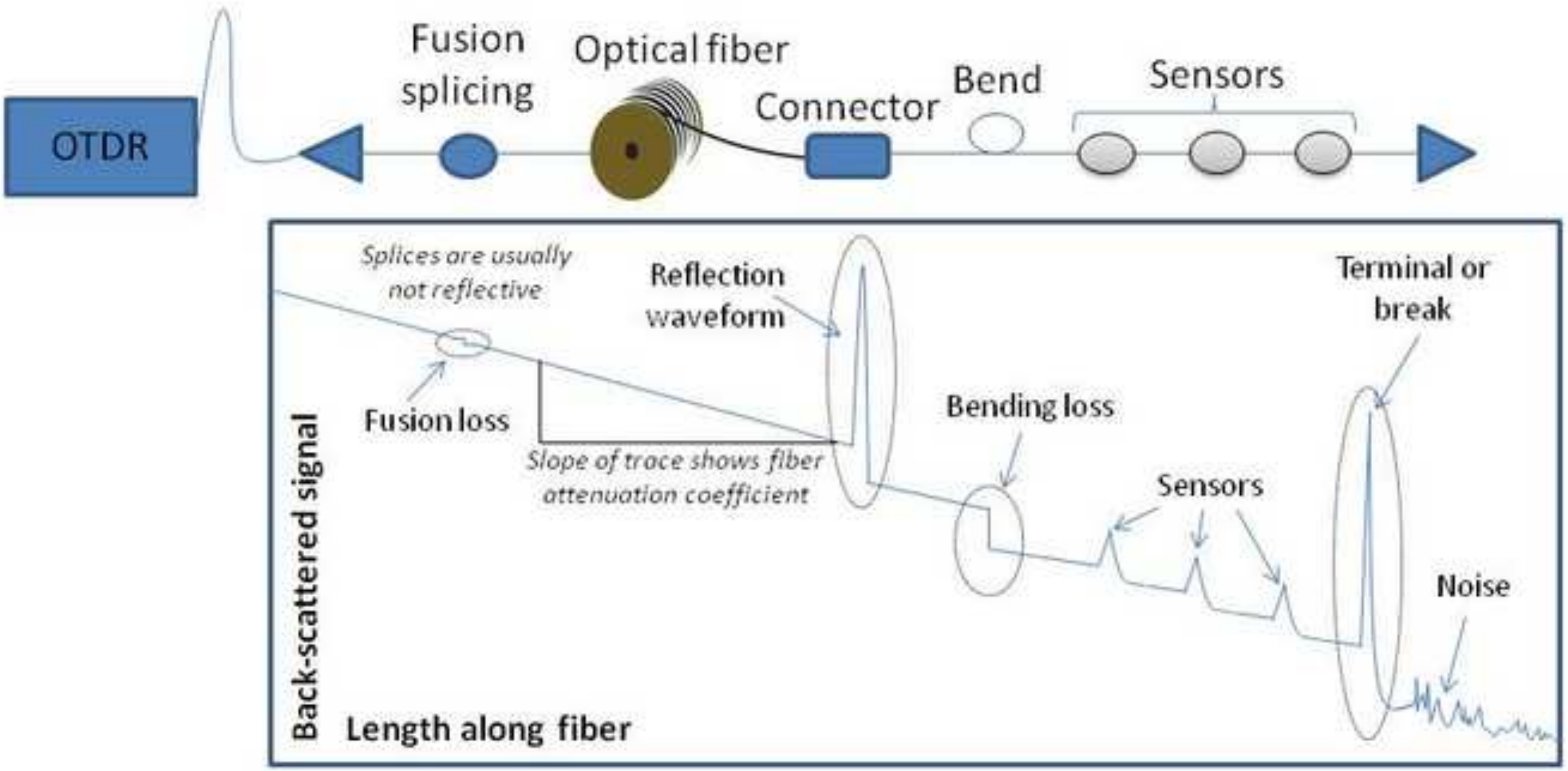


Figure6

Click here to download high resolution image

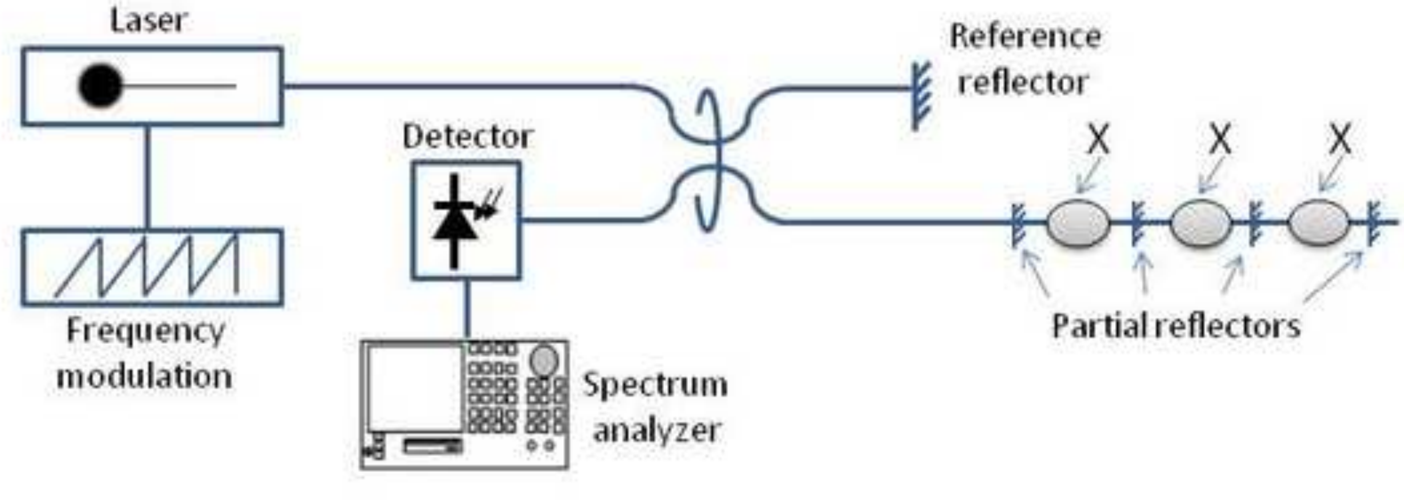


Figure7

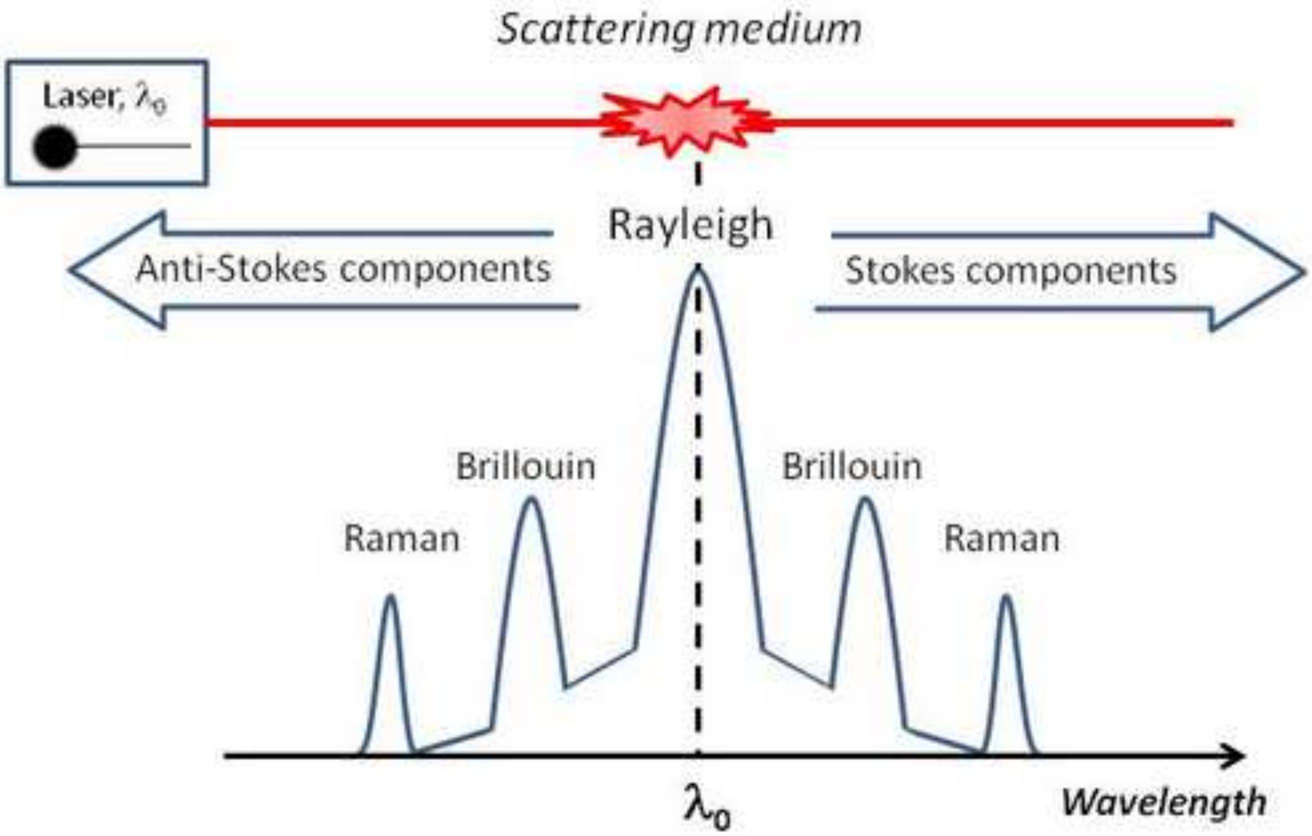

Scattering medium
Laser, λ_0
Rayleigh
Anti-Stokes components
Stokes components
Brillouin
Brillouin
Raman
Raman
λ_0
Wavelength

Figure8

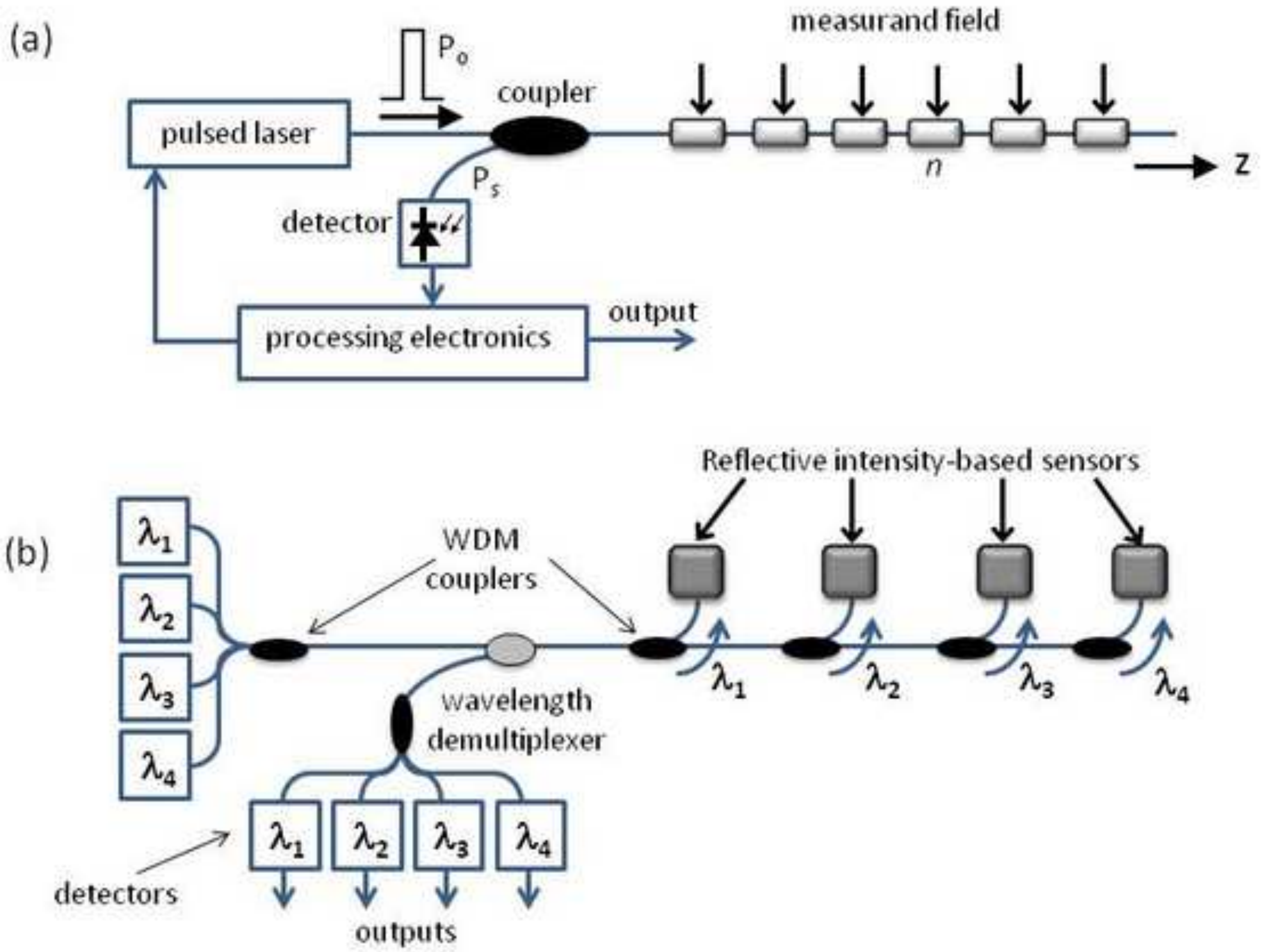

(a)
P₀
measurand field
coupler
pulsed laser
Pₛ
n
z
detector
output
processing electronics
(b)
λ₁
λ₂
λ₃
λ₄
WDM
couplers
Reflective intensity-based sensors
λ₁
λ₂
λ₃
λ₄
wavelength
demultiplexer
λ₁
λ₂
λ₃
λ₄
detectors
outputs

Figure9

Click here to download high resolution image

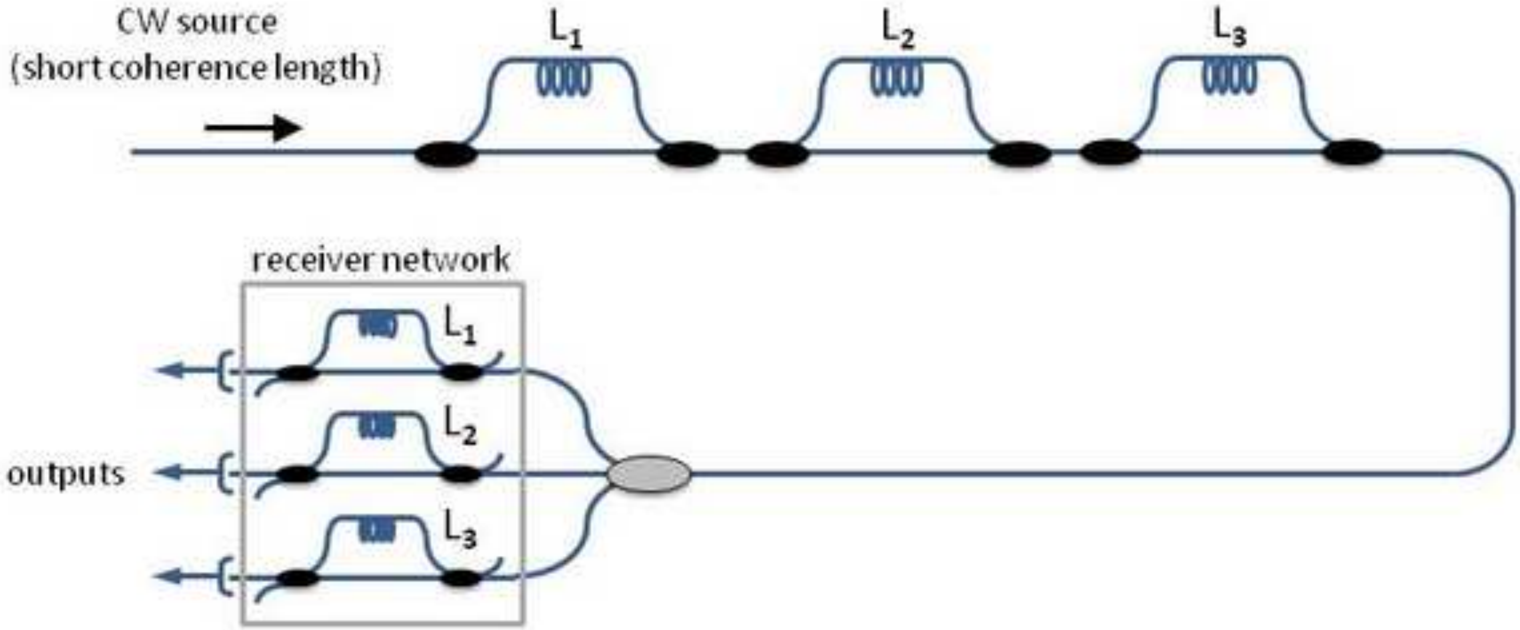


Figure10

Click here to download high resolution image

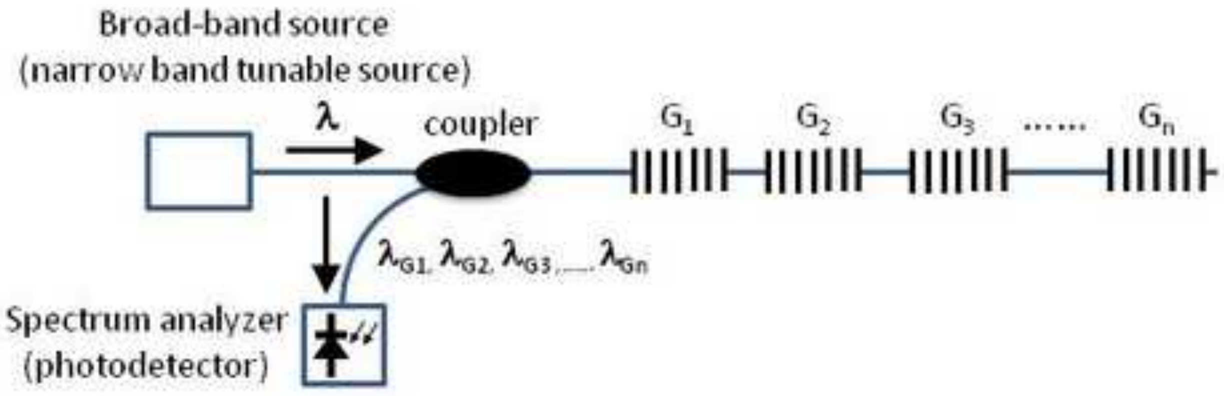


Figure11

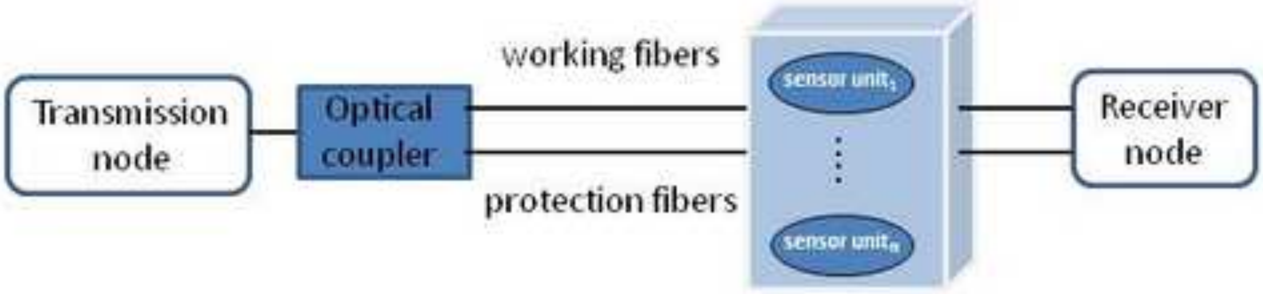

Transmission node
Optical coupler
working fibers
protection fibers
sensor unit$_1$
sensor unit$_n$
Receiver node

Figure12

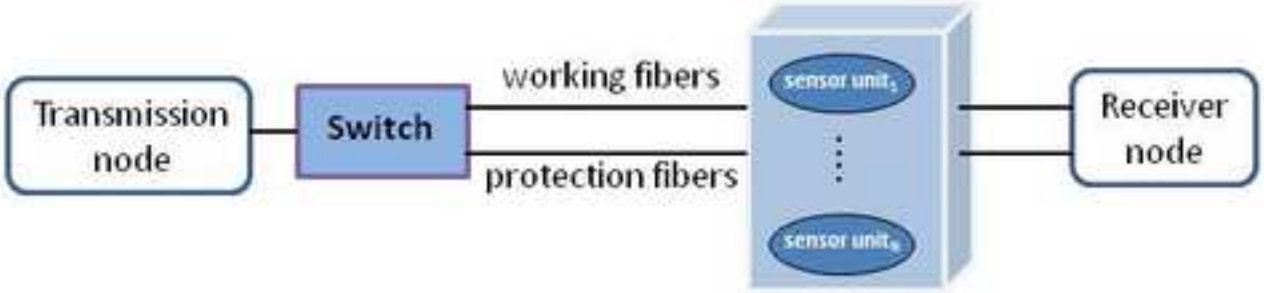

Transmission node
Switch
working fibers
protection fibers
sensor unit$_1$
sensor unit$_N$
Receiver node

Figure13

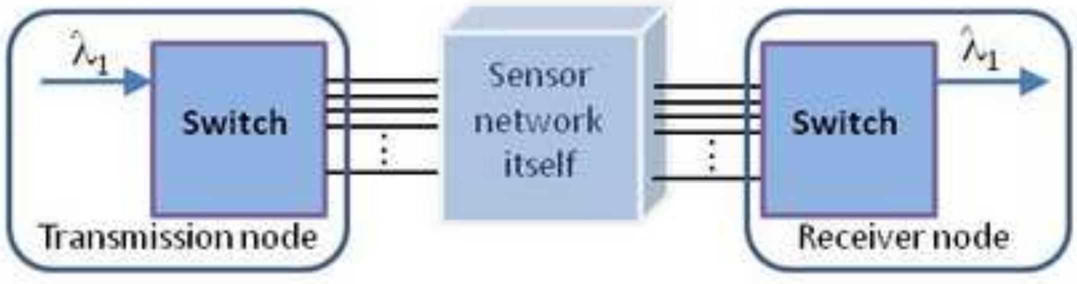
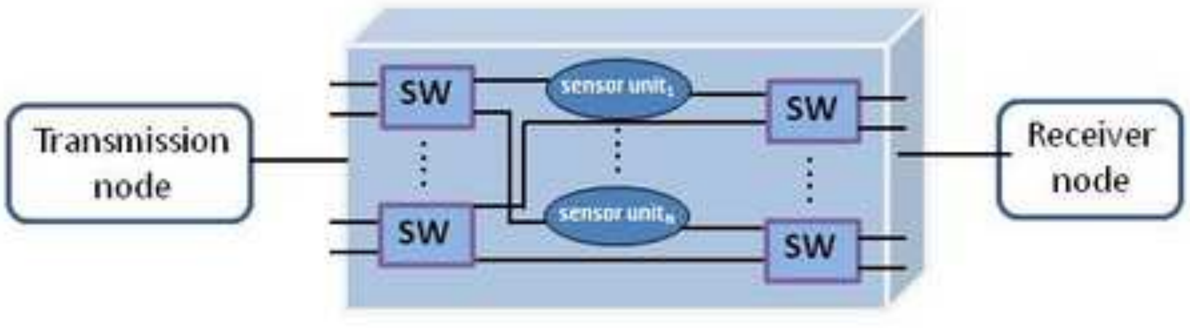

λ_1
Switch
Transmission node
Sensor network itself
Switch
λ_1
Receiver node

Figure14


Transmission node
SW
SW
SW
SW
sensor unit$_1$
sensor unit$_N$
Receiver node

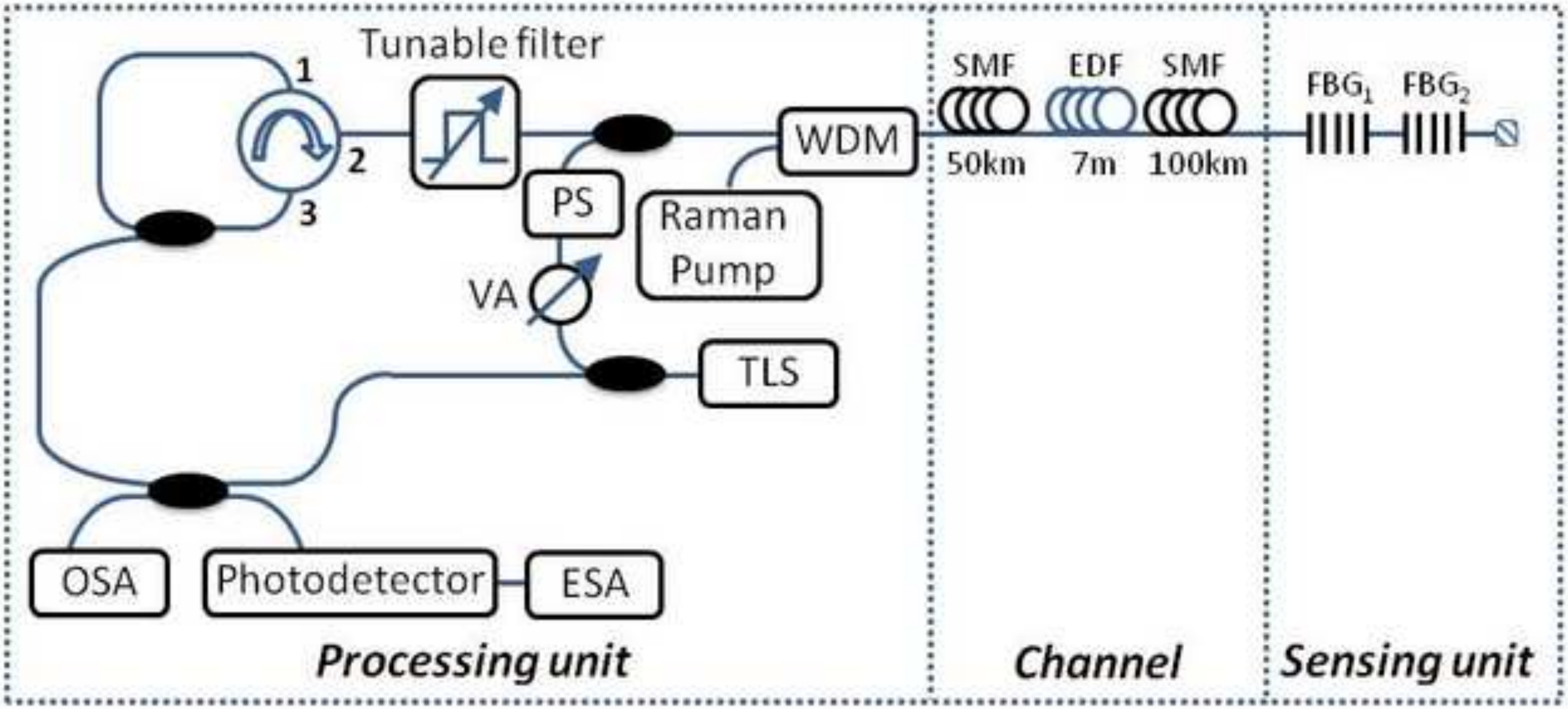
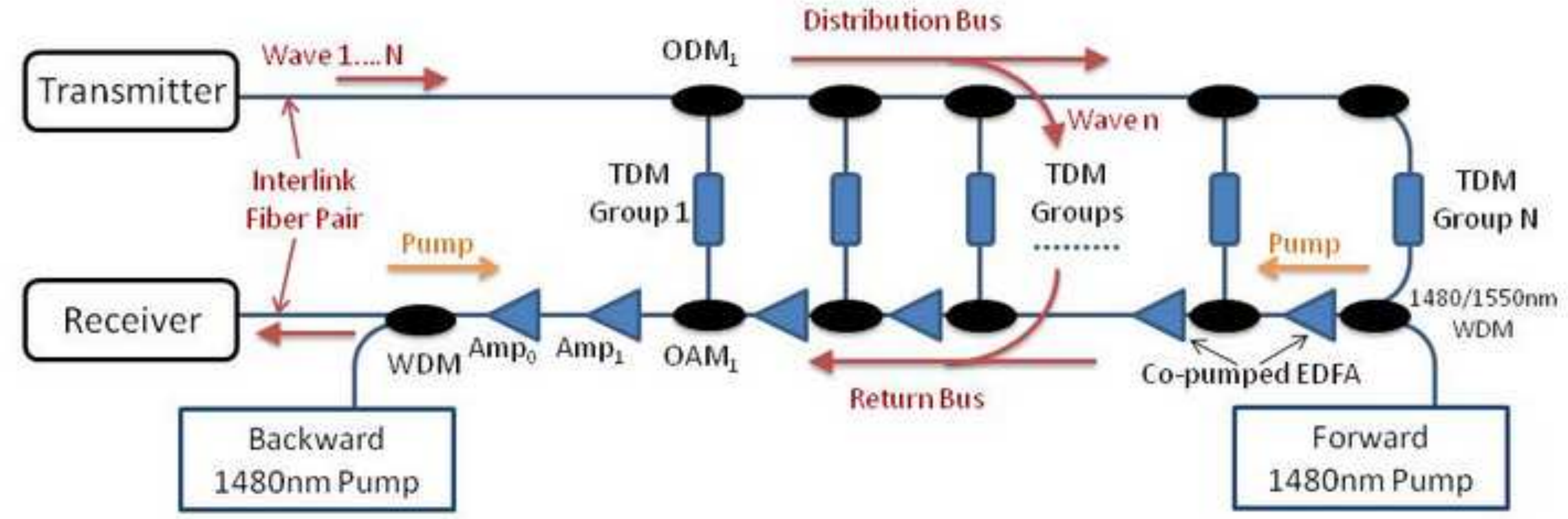

Tunable filter
1
2
3
PS
WDM
Raman Pump
VA
TLS
OSA
Photodetector
ESA
Processing unit
SMF
EDF
SMF
50km
7m
100km
Channel
FBG$_1$
FBG$_2$
Sensing unit

Figure16


Distribution Bus
Wave 1....N
ODM₁
Transmitter
Wave n
Interlink
Fiber Pair
TDM
Group 1
TDM
Groups
....
TDM
Group N
Pump
Pump
1480/1550nm
WDM
Receiver
WDM
Amp₀
Amp₁
OAM₁
Co-pumped EDFA
Return Bus
Backward
1480nm Pump
Forward
1480nm Pump

***Highlights (for review)**

- We present the state of the art in multiplexed and distributed sensor networks
- We have been focused on robust, remote and distributed Brillouin networks
- Different kind of multiplexing networks for fiber optic sensors are shown