

Introduction to Fiber Optic Sensing

A guide to understanding the fiber optic
sensing landscape



SENSURON
ENGINEERING AT THE SPEED OF LIGHT

Table of Contents

Understanding the Fiber Optic Sensing Landscape	3
Types of Interferometers Used in Fiber Optic Sensors	5
Scattering Based Fiber Optic Sensors	7
Raman.....	7
Rayleigh.....	8
Brillouin	8
Fiber Bragg Grating Based Sensors	8
Fiber Bragg Gratings	8
Demodulation Techniques	10
Wavelength Division Multiplexing	10
Optical Frequency Domain Reflectometry.....	11
Multi-Sensing Platforms	12
Final Thoughts	13
Additional Resources	13

Fiber optic sensing is becoming pervasive across multiple industries including manufacturing, medical, aerospace, automotive, civil and energy. Within the market, there are dozens of types of technology, each with their own capabilities. Navigating the fiber optic sensing landscape can be challenging due to the variety of technologies. This guide is intended to provide a framework for understanding fiber optic sensing technologies and to provide insights into the direction of the market.

Fiber optic sensors are capable of measuring a wide variety of parameters from mechanical measurements like strain and position to chemical composition and liquid level. Fiber sensors are lightweight, robust and immune to electromagnetic interference. While at the same time, they are highly sensitive. Broadly speaking, most fiber optic sensors fall into two categories: intrinsic and extrinsic. This paper will primarily focus on intrinsic fiber optic sensors.

[Click here to read about applications and keep up on industry trends](#)

Understanding the Fiber Optic Sensing Landscape

Extrinsic vs. Intrinsic

At a very basic level, extrinsic sensors use the fiber to guide the light to a sensing region where the optical signal leaves the waveguide and is modulated in another medium. There are many different variations of extrinsic sensors and in some cases, the optical fiber is used only to transmit data from the sensor to the data acquisition unit. One benefit of this method is the ability to reach places that would otherwise be inaccessible. For example, by using a fiber to transmit radiation into a radiation pyrometer located outside the engine, extrinsic methods can measure temperature inside of an aircraft jet engine.

Use Cases/Methods

Extrinsic fiber optic sensor use cases include:

- Optical Coherence Tomography—most commonly used to create images of the retina
- Encoders—can measure linear and angular position.
- Laser Doppler velocimetry—the Doppler shift in a laser can be used to take flow measurements by determining the velocity of a substance.
- Pyrometers—a remote sensing thermometer whereby an optical system focuses the thermal radiation of an object onto a detector.
- Spectroscopy—used in laboratories to identify the chemical composition of sample

In the case of intrinsic sensors, the light remains within the waveguide so that it measures the changes in the optical signal as it moves down the fiber. Intrinsic fiber optic sensors can utilize the natural backscattering of light, fiber Bragg gratings (FBGs) or other elements to obtain measurements. Intrinsic optical sensors can measure temperature, strain, pressure, and other parameters by monitoring the resulting changes in the intensity, phase, polarization, wavelength or transit time of light within the fiber. Sensors that vary the strength of light within the fiber are

the simplest to measure, as only one source and detector are required. Some intrinsic fiber optic sensors can provide distributed sensing along the entire length of the fiber.

Within the division of intrinsic sensors, the most common types of technology are scattering and FBG based techniques, and each have their own advantages. Scattering techniques offer fully distributed data points along a fiber. FBG techniques can either have a handful of sensing points or be fully distributed as well. By manufacturing a fiber with continuously inscribed FBGs, engineers can analyze the changes in the way the light reflects and interpret this information to provide accurate measurements. Scattering techniques depend on naturally occurring random imperfections in the fiber optic cable to attain readings. Since FBGs are purposefully fabricated and are well defined sensors they have a much higher signal to noise ratio and are much more reliable than scattering techniques. This enables interrogators (the data acquisition hardware) that use continuously written gratings to obtain precise measurements down to millimeters of spatial resolution even in harsh and dynamic environments. For example, Sensuron's interrogators collect spatially continuous information along the entire length of multiple fibers over a total sensing length of up to 104 m per platform. In contrast, most scattering technologies have spatial resolutions on the order of meters.

Many fiber optic sensing technologies are built upon the principles of interferometry, meaning they interpret the interference signal from two combined light signals to obtain measurements. More details about each of these can be found on [page 5](#) of this document.

Some Types of Interferometers used in fiber optic sensing:

- Mach-Zehnder—interference from a laser pulse in two arms can be used to determine physical parameters.
- Michelson—interference from a laser pulse in two arms can be used to determine physical parameters using reflection modes.
- Sagnac—uses a fiber loop whereby two beams propagate in opposite directions and is commonly used as a gyroscope.
- Fabry-Perot—utilizes two parallel reflecting surfaces that are separated by a determined distance. Interference occurs between the reflected and transmitted beams and then calculated into measurements

Intrinsic fiber optic sensor types include:

- Scattering based sensors, such as:
 - Raman— utilizes Raman anti-stokes signals to obtain temperature measurements.
 - Rayleigh—utilizes the Rayleigh backscatter as a function of length in an optical fiber. Strain and temperature cause spectral shifts in Rayleigh backscattering which can be identified by an interrogator.

- Brillouin—sensitive to both strain and temperature, has the longest measurement distance of the scattering technologies.
- Fiber bragg grating sensors—wavelength selective mirrors inscribed into fiber which reflect only a specific wavelength. Strain and temperature cause spectral shifts in the reflected wavelength which is identified by an interrogator.

While traditional electronic sensors such as strain gages and thermocouples only look at critical points, distributed FOS can provide a profile between critical points, which allows engineers to obtain precise measurements of full strain fields, load distributions, temperature distributions, and other parameters. Both scattering and FBGs use various demodulation techniques. Wavelength division multiplexing (WDM) is the most common demodulation technique for FBG based technology. However, optical frequency domain reflectometry (OFDR) offers significant advantages over WDM in many circumstances.

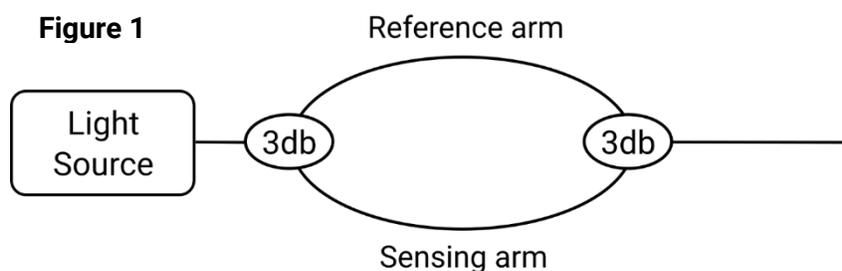
Unlike WDM systems, OFDR technology does not have the limitation of having only tens of sensors on a single fiber. Instead, OFDR is able to provide spatially continuous information along one or more fibers. Thus, OFDR is well suited for applications that require monitoring more than just critical points, or for measuring multiple parameters simultaneously. For example, NASA uses Sensuron’s OFDR technology to monitor stress, distributed loads, and to observe the shape of a UAV wing in flight and in real-time.

[Click here and download the case study: NASA UAV Deflection and Strain Monitoring](#)

The abilities and use cases of fiber optic sensing technology are endless. While each method has its own unique capabilities, choosing the right one will always depend on the application. Sophisticated FOS systems enable engineers to collect and analyze material and structural data to ensure precise measurement and optimal performance every time.

Types of Interferometers Used in Fiber Optic Sensors

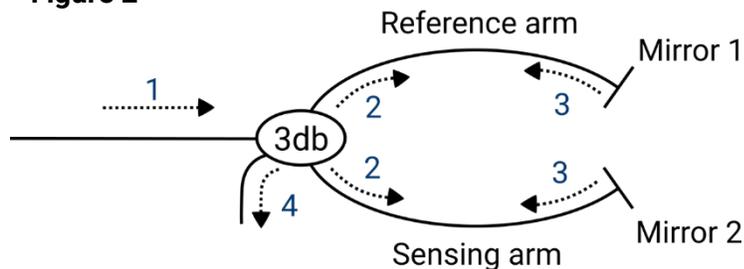
There are multiple types of interferometers that have been applied across industries and used in diverse applications. While examining each method is beyond the scope of this article, Mach-Zehnder, Michelson, Sagnac, and Fabry-Perot interferometers, the most common types, will be discussed.



Mach-Zehnder (MZ) sensors use interference from a laser pulse in two arms to determine physical parameters (Figure 1). A reference arm is isolated from the external environment so that only

light in the sensing arm is affected. A fiber coupler splits the light so that it propagates down each arm and another coupler recombines the signal. When the sensing arm is affected by temperature or strain, the physical length and the refractive index of the fiber is altered. This changes the optical signal in the sensing arm while leaving the signal in the reference arm unaltered. After the two signals recombine, the interference signal is detected by an interrogator. MZ interferometers are relatively common due to the flexibility of their configuration. This type of interferometer is commonly used in the telecommunications industry to test networks and can be used as a single point temperature sensor.

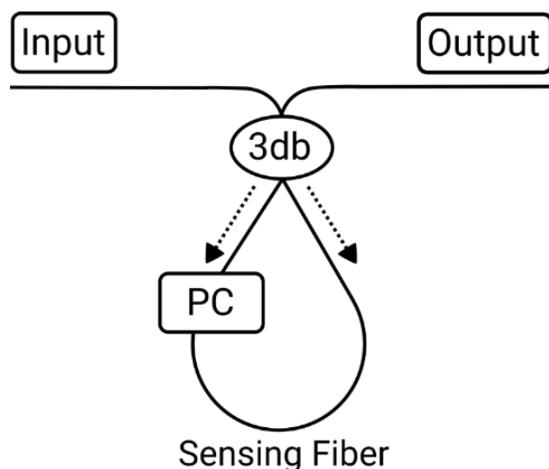
Figure 2



Michelson interferometers (Figure 2) are similar to the Mach-Zehnder technology in that they both use interference from a laser pulse in two arms to obtain measurements. However, Michelson interferometers use reflective modes to cause the interference. A coupler splits the

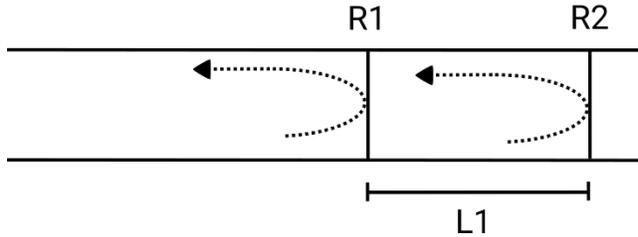
incident light so a signal propagates down a reference arm and a sensing arm. A reflective surface is placed at the end of each arm and the light is recombined. Fiber Bragg gratings (FBG) or other reflective elements can be inscribed along the sensing arm to provide sensing points. Michelson sensors are typically more compact than Mach-Zehnder sensors and can be multiplexed. This enables the development of fully distributed sensors rather than just point sensors. Distributed sensors are advantageous in that they provide data along the entire length of a fiber rather than individual points. This ensures that events that occur between critical points are captured so engineers can see the entire picture of what is happening to their application rather than a handful of snapshots.

Figure 3



Sagnac interferometers (Figure 3) use a fiber loop in which light is split into two beams so that they propagate in opposite directions down a fiber loop. The opposing signals are recombined by the coupler. Sagnac sensors use birefringent (the refractive index seen by the light is dependent on the signal's polarization state) fiber in the sensing region. A polarization controller is used at the beginning of the sensing region to adjust the polarization. As environmental parameters affect the sensing region, the path of the signal is altered resulting in a phase shift and a different interference pattern. Sagnac interferometers are sensitive to rotation and spurred the development of gyroscopes which are now widely adopted.

Figure 4



Fabry-Perot interferometers (Figure 4) utilize two parallel reflective surfaces that are separated by a determined distance. The cavity between the two surfaces can either be external or internal to the fiber. Interference occurs between the reflected and transmitted beams. When strain or temperature act on the fiber, the length of the cavity is changed. This causes a change in

the reflected light and alters the resulting interference signal. Fabry-Perot sensors are found across industries due to their relatively simple and cost effective fabrication. They are widely used in civil applications to monitor critical structural components and in the oil and gas industry to monitor downhole pressure.

Scattering Based Fiber Optic Sensors

What makes scattering technologies unique is that they utilize naturally occurring backscattering light to create the interference signal. The scattering occurs due to random imperfections in the lattice structure of the fiber optic cable created during manufacturing. There are three different types of signals that are used in scattering based fiber optic sensors: Raman, Rayleigh and Brillouin. Since fiber Bragg gratings or other engineered reflective surfaces are not used, scattering based systems can use telecom grade fiber with special fiber terminations and coatings.

Generally speaking, scattering based sensors have spatial resolution on the order of meters and refresh rates of 10-30 seconds at best. As the sensing length increases, the refresh rate significantly decreases. One limitation of scattering techniques is a low signal to noise ratio. By comparison, fiber Bragg grating based sensors have much higher signal to noise ratios, making them ideal for modular installations, dynamic environments, or installations requiring bends and complex routing of the fiber. Applications that are well suited for scattering technologies are ones that do not require real time measurements, require kilometers of sensing length, and do not need the spatial resolution to be less than a meter. The three different types of scattering technologies have some key differences that will be discussed below.

Raman

Raman signals are composed of stokes and anti-stokes components, however, only the anti-stokes component is used to obtain temperature measurements. Unlike Brillouin and Rayleigh components, Raman backscattering is a result of thermally induced vibrations. As a result, Raman based systems, commonly referred to as Distributed Temperature Sensing (DTS) systems, are sensitive to temperature, but not to strain. Raman scattering is the most common type of scattering based systems on the market. The most common

uses include oil and gas pipeline monitoring for security and leak detection, and linear heat detection systems.

Rayleigh

Rayleigh signals have more intensity than Raman signals and are more sensitive to strain than to temperature. This makes Rayleigh scattering systems most effective for measuring strain. Due to the manufacturing process, the density and composition varies throughout the fiber. This alters the refractive index of the lattice structure. Strain and temperature cause spectral shifts in Rayleigh backscattering, which can be identified by an interrogator. Rayleigh scattering based systems are not as common as Raman systems, but have been used in similar use cases. The biggest application for Rayleigh scatter based systems to date is distributed acoustic sensing (DAS). DAS systems show the most promise in downhole oil and gas solutions.

Brillouin

Brillouin scattering systems are sensitive to both strain and temperature and have the longest measurement distance of the scattering technologies. Unlike the other two techniques, there are few commercially available Brillouin based sensing systems. Applications that show the most promise for Brillouin scattering systems are similar to Raman and Rayleigh scattering applications. The main advantage Brillouin scattering will offer is the ability to cover longer distances and monitor both strain and temperature. These systems are being commercialized largely in the civil and oil and gas industries to monitor linear assets (such as pipelines and railways). Applications requiring long distances and very low sensor density are a good fit for Brillouin scattering based systems.

Fiber Bragg Grating Based Sensors

The majority of FOS systems in the market today employ the use of fiber Bragg gratings to reflect light back to the interrogator. Each manufacturer utilizes a unique configuration and demodulation technique—the method used to obtain and interpret the optical signal provided by the sensors. The technique has a significant impact on the performance that is possible with a FOS system. The refresh rate, sensing length, number of sensors, spatial resolution and the interplay of each is largely determined by the demodulation technique. Certainly, there are many other variables that impact the performance of a FBG-based FOS system, but understanding the capabilities and limitations of demodulation techniques is essential when evaluating such systems.

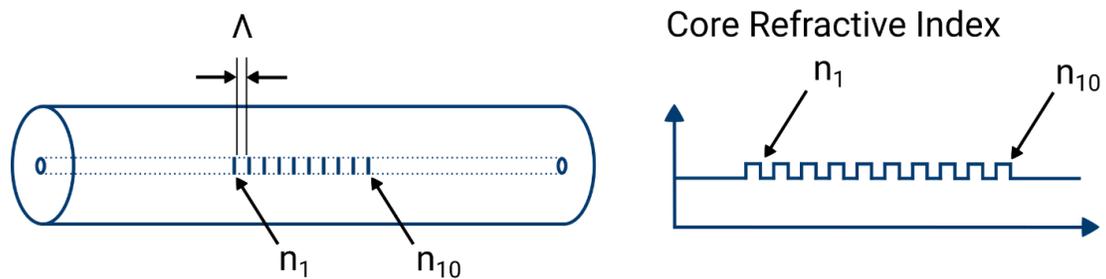
Fiber Bragg Gratings

Fiber Bragg gratings (FBG) operate as wavelength selective mirrors, meaning they reflect a single specific wavelength and transmit all others. The reflected wavelength is referred

to as the Bragg wavelength. One way to think about this is with white light. White light consists of the entire color spectrum, or in other words, many different wavelengths. If white light was sent down a fiber with a FBG, one would see a single color reflected, while everything else is transmitted.

When a grating is stretched, compressed, or undergoes thermal expansion and contraction, the Bragg, or reflected wavelength changes. The interrogator then uses a demodulation technique to observe the change in wavelength and translate this into strain and temperature measurements. The relationship between mechanical strain and the Bragg wavelength is described in the figure below.

Read more in the article "[Look Inside Fiber Optic Sensing](#)" on EDN.



$$\text{Bragg Wavelength } (\lambda_B) = 2n_e\Lambda$$

$$\left[\frac{\Delta\lambda_B}{\lambda_B} \right] = C_s\varepsilon + C_T\Delta T$$

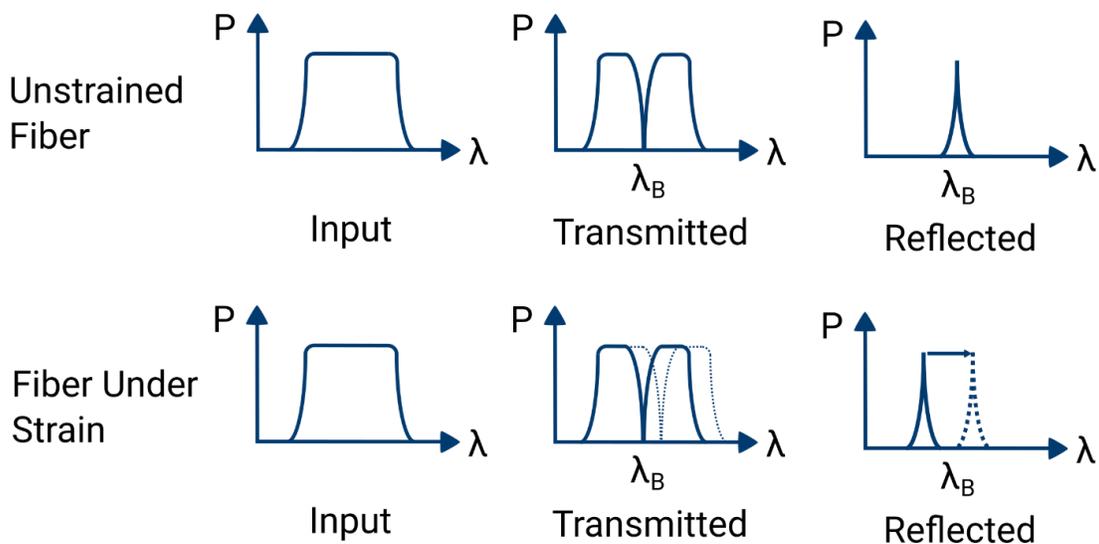


Figure 5. Diagram of the working principles behind fiber Bragg gratings and the relationship between the Bragg wavelength, strain and temperature.

Demodulation Techniques

Wavelength Division Multiplexing

For WDM systems, each grating must be written to reflect a different Bragg wavelength. Since lasers emit a finite number of wavelengths, this means that WDM systems are limited to the number of sensors they can interrogate on a single fiber. Typically only tens of FBGs can be multiplexed on a single channel. Additionally, in most cases only one channel can be interrogated at a time.

The amount of sensors per channel is limited because the reflected wavelengths cannot be written close to each other. If the Bragg wavelengths are too similar, a grating under strain could shift to reflect the same wavelength as another grating making the data useless.

While WDM systems can have high refresh rates, each additional sensor added to a channel will significantly reduce its capabilities. Another limiting factor for WDM systems is that the user must specify exactly where the gratings need to be written on the sensing fiber. This means that each fiber must be customized for each project, a cumbersome process. The process of identifying where the gratings need to be inscribed, as well as lead times for custom fibers can be lengthy.

Applications well suited for using WDM systems are ones that only require a handful of sensing points at very high speeds. For example, WDM systems can be used to measure strain on crash test dummies or monitor detonation velocity.

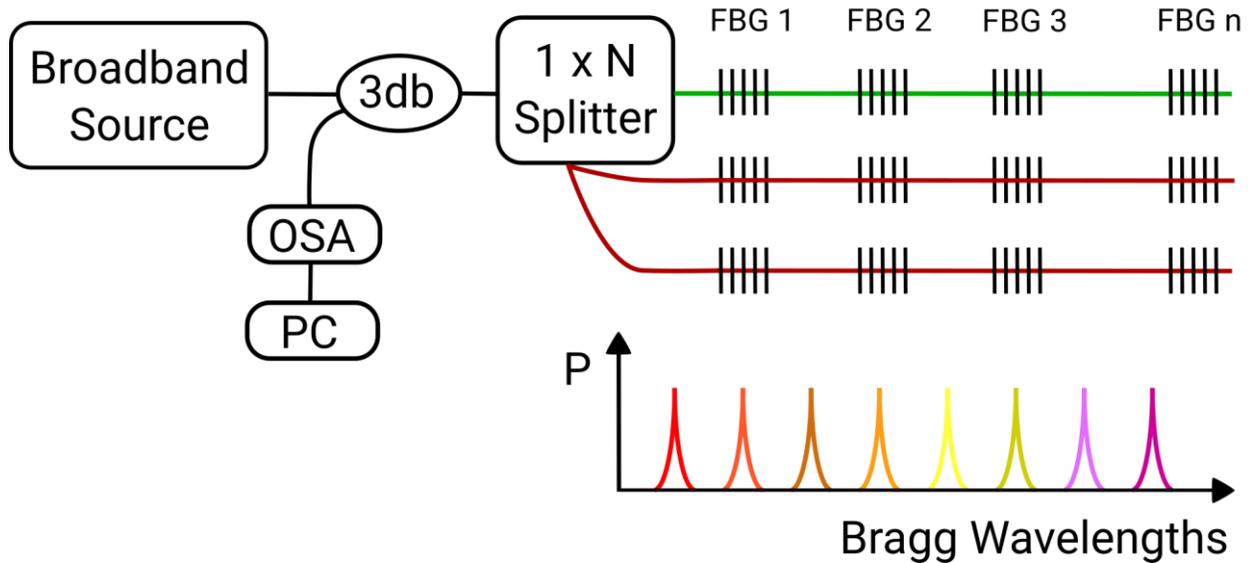


Figure 6. Diagram of a basic configuration for a WDM fiber optic sensing system.

Optical Frequency Domain Reflectometry

Optical frequency domain reflectometry (OFDR) can be applied to FBG-based sensors or to scattering technologies. Unlike WDM, when using OFDR, each grating is written at the same wavelength. Writing each grating at the same wavelength enables these systems to avoid the limitation on the number of sensors. Additionally, OFDR based fiber optic sensing systems can provide spatially continuous measurements instead of a handful of points.

OFDR technology has significantly higher spatial resolution and exponentially more sensing locations than WDM. One advantage that is unique to Sensuron's implementation of OFDR is that it is able to maintain high refresh rates even as the number of sensors increases. The combination of high spatial resolution, quick refresh rate, additional number of sensors, and full distribution set OFDR apart as the most sophisticated technology on the market today.

Unlike other fiber optic sensing technologies on the market, Sensuron's OFDR systems consolidate multiple technologies into a single, robust platform. In addition to sensing strain and temperature, Sensuron's OFDR technology can determine deflection, 3D shape, liquid level, pressure, operational load, and magnetic fields.

Another advantage of using an OFDR system is that the same fiber can be used for every project. For a new project, engineers can simply cut a new length of fiber, rather than waiting weeks or months for the custom fiber to arrive. The versatility of Sensuron's OFDR platform empowers customers to solve multiple problems with a single system.

OFDR based systems can be used in diverse applications. For example, Sensuron's systems have been used to monitor the strain and shape of a wing in real-time while in flight, the shape and position of medical tools, the liquid level of cryogenic fuel tanks, and much more. These applications would not be achievable with the single points of information provided by WDM systems.

While WDM is useful in certain applications, OFDR offers a solution for the future of monitoring technologies. Sensuron's implementation of OFDR combines the strengths of the point FBG technologies (precision, dynamic testing, and high acquisition rates) and scattering technologies (spatially continuous sensing) to provide a more robust solution for structural and thermal model validation, structural health monitoring, structural analysis and nondestructive damage evaluation. Sensuron has developed a number of multi-sensing platforms ([see page 12](#)) based on OFDR to help engineers solve the problems they face today and to innovate beyond the problems of tomorrow.

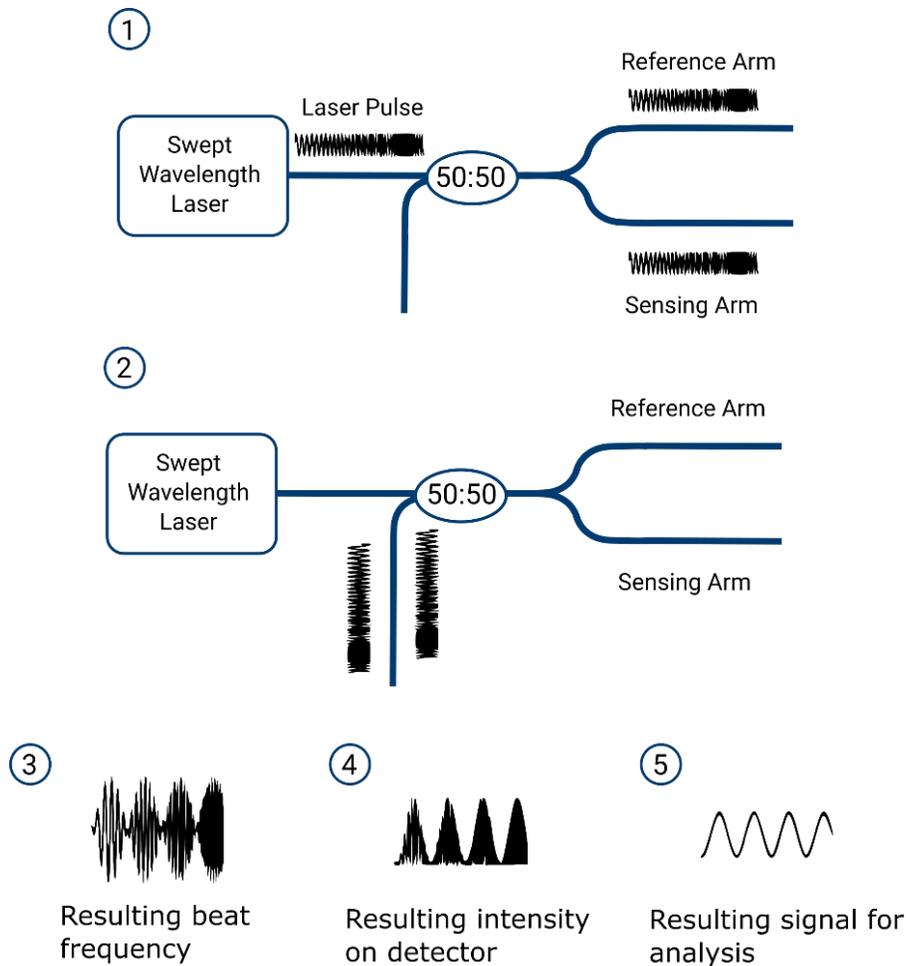


Figure 7. Diagram of the operating principle behind OFDR laid out from the laser pulse to the signal for analysis.

Multi-Sensing Platforms

At Sensuron, we see a sensing market at the cusp of a transition from point sensors to distributed sensors and smart data acquisition devices that can measure more than one parameter at a time. Point sensors have been the primary form of sensing technology essentially since sensors were invented. These technologies have been good enough for decades and will remain part of the landscape for years to come. The issue with technologies such as strain gauges, thermocouples, and other transducers is not a question of accuracy or reliability, rather, they do not provide enough information about the article they are measuring to test and monitor the innovations of today. In other words, point sensors can miss events that occur between critical points, leaving blank spaces in the picture painted by the data. Existing data acquisition hardware is capable of supporting multiple sensor types, however, the weight of the cables and tedious installation of sensors make legacy solutions cumbersome to deploy.

Multi-sensing platforms, simply put, are sensor technologies that can monitor multiple parameters (strain, temperature, deflection, etc.) simultaneously and are robust enough that they can be deployed in multiple applications across an organization and utilized throughout the

product lifecycle. It's not just about being able to monitor different parameters using the same data acquisition hardware. More than that, a multi-sensing platform can consolidate sensing technology so the same hardware, with minor changes in application techniques and sensor packaging, can adapt to cover multiple testing and monitoring needs of an organization. In order to accomplish this, the sensing system must obtain spatially continuous information in real time, be capable of taking dynamic measurements, be able to easily integrate with a network and perform well in the lab or harsh environments. These features allow multi-sensing platforms to be deployed in lifecycle monitoring applications from design validation to providing operational data for critical components and equipment.

Final Thoughts

Eventually, technology advances to the point where solutions that have been 'good enough' for decades are no longer 'good enough' for the innovations of today. The philosophy of 'good enough' is widely applied when developing a new product or solution. Businesses have to make decisions about what new technology features will receive the most attention to keep projects within scope and completed on time. This philosophy has a downside when applied to testing and monitoring. For decades, point sensing solutions like strain gauges and thermocouples have been 'good enough,' however, the mindset of 'good enough' often blocks innovation. Many of Sensuron's clients today have innovated beyond their ability to test with legacy technologies. Sometimes it takes a significant, expensive failure to admit that this is a human issue and not a technology issue. New, robust sensing technologies that can monitor beyond the scope of point sensors are necessary to enable the next generation of innovations.

Additional Resources

Click Here
to download case studies

Click Here
to register for an upcoming
webinar

Click Here
to learn more about our
products

Email Us
to discuss your specific
application needs