

Microrobotics

Prof. Palani Iyamperumal Anand

Department of Mechanical Engineering

Indian Institute of Technology, Indore

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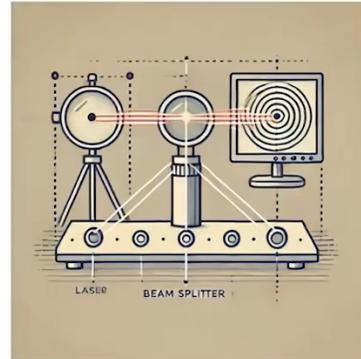
Micro Sensors and Micro Transducers - Module 05

Here, the focus is on the micromanipulators, especially on microsensors and microtransducers, with more emphasis on optical-related and opto-mechatronics-related microtransducers and microsensors. Different configurations of opto-mechatronics-based microsensors are examined in detail. Now, we will discuss these interferometers for micro-sensing; interferometers are widely used in micro-sensing applications due to their high sensitivity, precision, and ability to detect minute changes in physical parameters. They operate on the principle of interference, where two or more light waves combine to produce variations in intensity based on phase differences. The interference-based sensing is a powerful technique that leverages the principle of wave interference to detect changes in the physical, chemical, or biological environments. It is widely used in applications such as optical sensors, biosensors, and environmental monitoring.

One of the key aspects of wave interference is that interference occurs when two or more waves superimpose, leading to regions of constructive interference, which is characterized by an amplitude increase, or destructive interference, which is due to the amplitude decrease. This principle is fundamental in designing sensors that rely on changes in phase, amplitude, or frequency. The optical path length and phase shift; the interference-based sensor often relies on the optical path length. So, OPL depends on the refractive index n of the medium and d , the physical distance at which the wave travels.

Interferometers for Micro-Sensing

Interferometers are widely used in micro-sensing applications due to their high sensitivity, precision, and ability to detect minute changes in physical parameters. They operate on the principle of **interference**, where two or more light waves combine to produce variations in intensity based on phase differences.



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In the case of constructive interference, the overall configuration is this, and in the case of destructive interference, this is a kind of overall configuration that we could observe. Now when we try to classify the type of interferometric sensors, the interferometric sensors are classified based on the configuration, application, and the overall construction of the system. In this particular interferometric sensor, based on the configurations, it is classified as a Michelson interferometer, a Mach-Zehnder interferometer, and a Fabry-Perot interferometer. Now let us see the overall construction of a Michelson interferometer; this is the actual configuration of a Michelson interferometer. The Michelson interferometer is a widely used optical system in micro sensing applications due to its high sensitivity to small changes in distance and refractive index of material properties.

Principles of Interference-Based Sensing

Interference-based sensing is a powerful technique that leverages the principles of wave interference to detect changes in physical, chemical, or biological environments. It is widely used in applications such as optical sensors, biosensors, and environmental monitoring.

- **Wave Interference**

Interference occurs when two or more waves superimpose, leading to regions of constructive (amplitude increases) or destructive (amplitude decreases) interference. This principle is fundamental in designing sensors that rely on changes in phase, amplitude, or frequency.

- **Optical Path Length & Phase Shift**

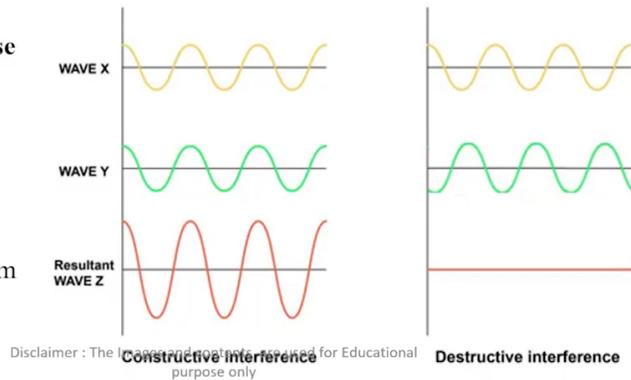
Interference-based sensors often rely on the optical path length

$$OPL = n \times d$$

where:

n = refractive index of the medium

d = physical distance the wave travels



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Destructive interference

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It works on the principle of wave interference, where a light beam is split into two parts, reflected by mirrors, and recombined to produce an interference pattern. In the overall construction of Michelson's interferometer arrangement, there are laser sources here that are illuminated and made to pass through the beam splitter. From the beam splitter, the beam is split into two. There are two mirrors, mirror M1 and mirror M2, and finally, the output is collected on a separate screen. In both cases here, we have considered two mirrors, mirror M1 and mirror M2. Mirror M1 may be fixed and mirror M2 may be movable, based on the objectives related to displacement. There will be a kind of movement in this M2 mirror; accordingly, we get a different interference pattern. In order to give you a better understanding of the schematic, this is how the overall configuration of the Michelson interferometer looks. It has mirror M1. Ideally, it starts with the light source.

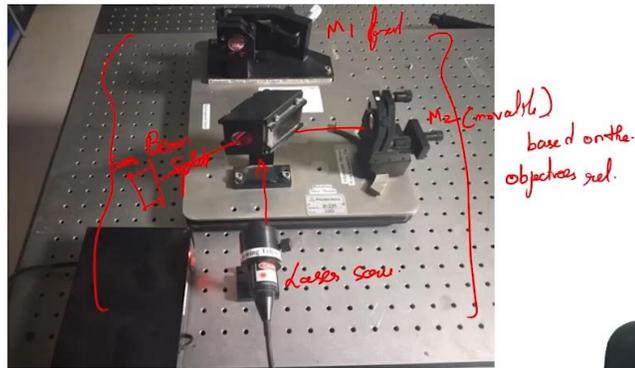
From the light source, there is a beam splitter; through the beam splitter, the beams are split into two. Which are mirror M1 and mirror M2, and then from the beam splitter, we have a reference beam taken from mirror M1 and a reference beam from mirror M2. These reflected beams from both mirrors M1 and M2 are superpositions finally ending up in a kind of interference. Ideally, a Michelson interferometer consists minimally of a mirror M1, a mirror M2, and a beam splitter M. As the source S emits light that hits the surface of the beam splitter M at point C, M is partially reflective.

A part of the light is transmitted through point B, while some is reflected in the direction of A. Both beams recombine at point C to produce an interference pattern instantly on the detector at that point. If there is a slight angle between the two returning beams, for

instance, then an imaging detector will record a sinusoidal fringe pattern. If there is a perfect spatial alignment between the returning beams, then there will not be any such pattern, but rather a constant intensity over the beam dependent on the differential path length. This is the overall configuration that is being used with reference to a simple Michelson interferometer.

Michelson Interferometer for Micro-Sensing

The **Michelson Interferometer** is a widely used optical system in micro-sensing applications due to its high sensitivity to small changes in distance, refractive index, or material properties. It works on the principle of wave interference, where a light beam is split into two paths, reflected by mirrors, and recombined to produce an interference pattern.



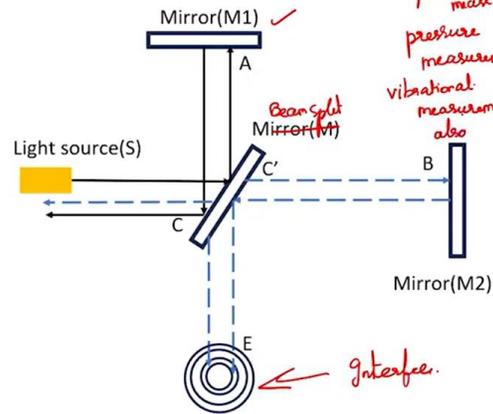
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These Michelson interferometers are efficiently used for displacement measurement, position measurement, and pressure measurement. In some cases, they are also effectively used for vibrational measurement. There is one more type of interferometer called the Fabry-Perot interferometer. This interferometer makes use of multiple reflections between two closely spaced partially silvered surfaces. Part of the light is transmitted each time the light reaches the second surface, resulting in multiple offset beams that can interfere with each other.

Working principle of Michelson Interferometer → displacement position measurement also vibrational measurement also

- A Michelson interferometer consists minimally of mirrors M_1 & M_2 and a beam splitter M
- A source S emits light that hits the beam splitter surface M at point C . M is partially reflective, so part of the light is transmitted through to point B while some is reflected in the direction of A .
- Both beams recombine at point C' to produce an interference pattern incident on the detector at point E .
- If there is a slight angle between the two returning beams, for instance, then an imaging detector will record a sinusoidal fringe pattern.
- If there is perfect spatial alignment between the returning beams, then there will not be any such pattern but rather a constant intensity over the beam dependent on the differential path length.

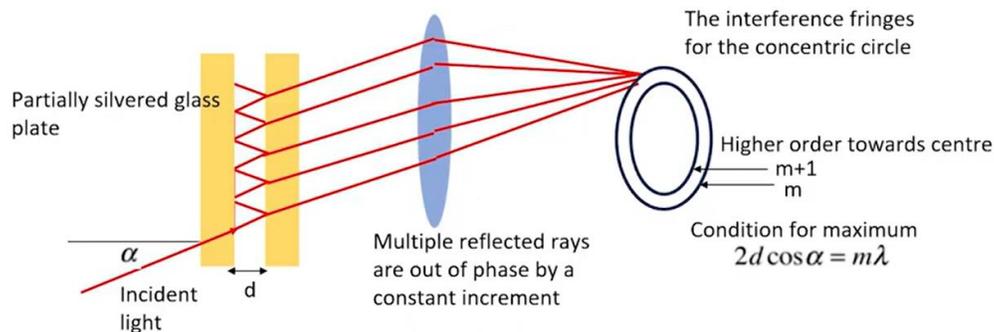


The large number of interfering rays produces an interferometer with extremely high resolution, somewhat like the multiple slits of a diffraction grating increase its resolution. The interferon fringes for concentric circles are the overall construction in which we have incident light. This incident light is made to pass through multiple reflections between the partially silvered glass, and through this, the multiple reflected rays are out of phase by a constant increment. Now the interference fringes for the concentric circles are present. The higher order towards the center is called $m + 1$, and the lower order is called m .

The condition for maximum is governed by $2d \cos \alpha = m\lambda$. λ corresponds to the wavelength, α corresponds to the incident angle, and d corresponds to the spacing. Apart from the Fabry-Perot interferometer, the Mach-Zehnder interferometer is also a type of interferometer that measures the relative phase shift between the two collimated light beams. It consists of two beam splitters and two flat mirrors. All the mirrors and the beam splitters are adjustable for alignment, and the back surfaces have multi-layer anti-reflective coating.

Fabry-Perot Interferometers

- This interferometer makes use of multiple reflections between two closely spaced partially silvered surfaces.
- Part of the light is transmitted each time the light reaches the second surface, resulting in multiple offset beams which can interfere with each other.
- The large number of interfering rays produces an interferometer with extremely high resolution, somewhat like the multiple slits of a diffraction grating increase its resolution.

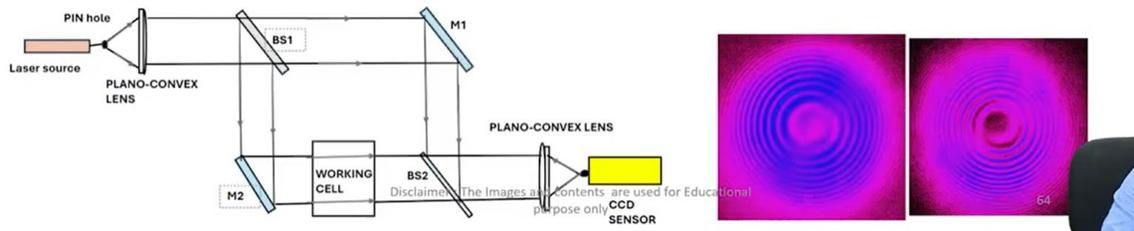


A red laser diode is used as an optical light source. This wavelength is visible and provides a significant advantage for aligning the mirrors and the beam splitters. An incoming laser beam of coherent light splits into two identical beams of equal intensity at the beam splitter BS1. Each of these two beams travels a diffracted path until they combine at the BS2 before arriving at the detector or a charge-coupled device. The difference in the distance and the medium traveled by each beam creates a phase difference between them.

This phase difference creates the interference pattern from the second beam splitter, BS2, up to the CCD camera. This phase shift is recorded by a digital system using a CCD camera. This is a kind of interference pattern that is basically observed since a helium-neon laser is used here. These helium-neon lasers are being converged using a planar convex lens. Then, using a kind of BS1 and BS2 appropriately, the beams are manipulated and collected to form an interferometric pattern as shown here.

Mach-Zehnder Interferometer

- The Mach-Zehnder interferometer is a type of interferometer that measures the relative phase shift between two collimated light beams.
- It consists of two beam splitters and two flat mirrors. All of the mirrors and beam splitters are adjustable for the alignment and the back surfaces are multi-layer anti-reflection coated,
- A red laser diode is used as an optical light source. This wavelength is visible and provides a significant advantage for the alignment of the mirrors and beam splitters. An incoming laser beam of coherent light splits into two identical beams of equal intensities at the beam splitter BS1. Each of these two beams travels a different path, until they are recombined in another beam splitter BS2 before arriving at a detector sensor or charge-coupled device (CCD) camera.
- The difference in the distance (different path lengths) and the medium (different refractive indexes) traveled by each beam creates a phase difference between them. This phase difference creates the interference pattern from the second beam splitter BS2 up to the CCD camera. This phase shift is recorded by the digital system (CCD camera)

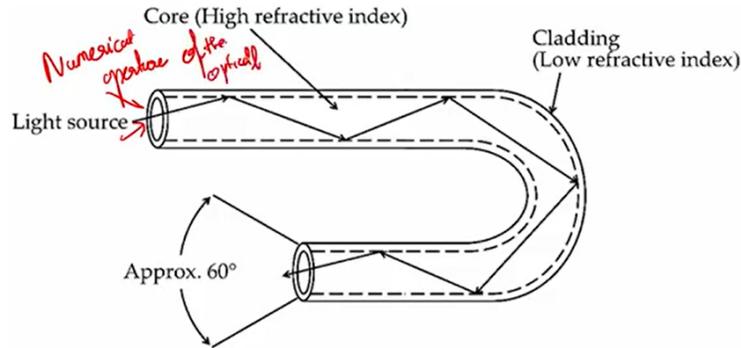


Now, as far as the application perspective point of view, these interferometers are ideally used for precision distance and displacement measurement, surface profiling and optical testing, vibration and strain measurement, medical imaging and diagnostics, and biosensor-related applications. At a macro level, it is used for satellite and spacecraft navigation; interferometric telescopes are widely used for a certain amount of applications; and optical coherence tomography and optical fibers are some of the key applications using these particular interferometers. Now, as far as the micro robotic perspective point of view, these are the four applications that cater to micro robotic applications. There are several pieces of research that focus on using an interferometer for micro robotic applications for these specific applications. Optical fiber sensors are considered to be one of the key successful sensors that are used for condition monitoring of systems, and they are also widely used for microsensing-related applications.

It utilizes light propagation in optical fibers to detect changes in environmental conditions. These sensors are highly sensitive and immune to electromagnetic interference, making them suitable for remote sensing-related applications. In this optical fiber-based sensor, we have a light source, there is a core that is available, and then there is a cladding. Through the core, the light is made to pass through. There is going to be a total internal reflection that occurs in this particular process, and the core has a high refractive index while the cladding has a low refractive index.

Optical Fiber-Based Sensors

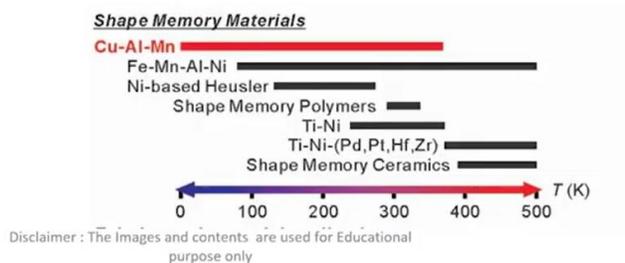
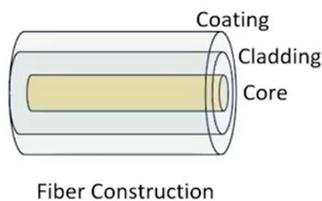
Optical fiber-based sensors utilize light propagation in optical fibers to detect changes in environmental conditions. These sensors are highly sensitive, immune to electromagnetic interference, and suitable for remote sensing applications



Since the core has a high refractive index, it results in multiple internal reflections of this particular light, and appropriately, this entry of the light is governed by a quantified parameter called the numerical aperture of the optical fiber. Based on the sensing characteristics, these optical fibers are characterized for temperature sensing, pressure sensing, strain sensing, and chemical sensing. Let us discuss the different configurations of sensing or microsensing using an optical fiber in detail. First, let us discuss temperature sensing; not only the measurement of temperature on the positive side, but there is also a need to measure the temperature on the negative side. The development of sensors for sensing the cryogenic environment is also one of the key aspects that we may need to look into.

Temperature Sensors

- Optical fiber-based temperature sensors offer a robust and versatile solution for temperature measurement across various environments. It is used both as an extreme high and low temperature sensor.
- Fiber-optic high-temperature sensors are gradually replacing traditional electronic sensors due to their small size, resistance to electromagnetic interference, remote detection, multiplexing, and distributed measurement advantages
- Optical fibers with a smart material coating, allowing them to withstand temperatures greater than 600°C
- Shape memory alloy coated optical fiber withstand extreme high and low temperatures



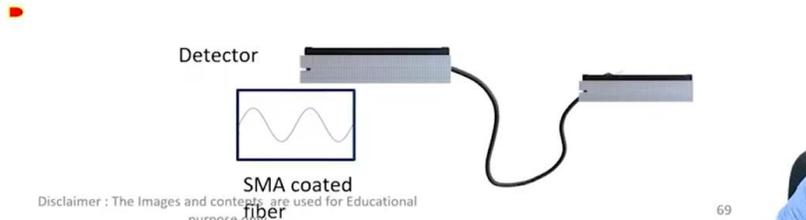
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In the majority of cases, optical fibers are directly used. However, in some specific cases where these optical fibers are coated with a certain amount of materials, these materials have the capability to sense temperature even in low temperature conditions. Optical fiber-based sensors offer a robust and versatile solution for temperature measurement across various environments. They are used as both extreme high and low temperature sensors. As far as this fiber optic high temperature sensors are concerned, they are gradually replacing the traditional electronic sensors due to their small size, resistance to electromagnetic interference, remote detection, multiplexing, and distributed measurement advantages.

SMA coated fiber actuation at extreme temperature

- Shape memory alloy coating on optical fiber actuate the fiber due to temperature change
- The change in temperature induces strain on SMA, which in turn bends the fiber
- Such bending in fiber results in optical signal attenuation at the detector end
- At high temperature, SMA straightening the fiber, whereas at low temperature, it bends the fiber

Laser Source



Optical fibers with smart material coating allow them to withstand temperatures greater than 600 degrees Celsius. The shape memory alloy-coated optical fibers withstand extreme high and low temperatures. From the overall configuration of these shape memory alloy materials, classify them based on the type of actuation behavior. So actuation behavior is nothing but like with reference to the actuation, there is going to be a kind of change in the displacement that it exhibits. Now, let us consider that I have a kind of strip; this strip will be highly sensitive to this particular temperature, which we call the actuation temperature.

Cryogenic Temperature Sensing

- Sensing cryogenic temperature is very difficult for conventional sensors
- Optical fiber-based sensors are a superior substitute due to their immunity to electromagnetic interference and power fluctuations
- Shape Memory Alloy (SMA) coatings on optical fiber certainly improve the sensor responses
- The displacement due to phase change of SMA's during exposure at extremely low temperatures
- The phase change induces thermal strain on the fiber leading to a change in the refractive index of the core and cladding which results in an intensity change of the optical output signal.
- The integration of SMA bimorph with SMA-coated fiber significantly enhances the displacement due to the enhanced induced strain which leads to attenuation of optical output
- Such attenuation of output signal relates to the low-temperature sensitivity of SMA coated optical fiber sensor.



Based on the material composition, there is a change in the actuation temperature. If you consider copper-based shape memory alloys, you will see that they have quite a good amount of efficiency both in low temperature conditions, especially up to minus 270 degrees Celsius, and they have an actuation temperature in the range of 250 to 350 degrees Celsius. Whereas, conventionally when you try to see the nickel titanium base structures, these nickel titanium base structures have a potential actuation temperature ranging from 80 to 130 degrees Celsius. Now, let us take an actual example where a shape memory alloy has been coated onto an optical fiber and is used for sensing extreme conditions. The shape memory alloys are coated on optical fiber, which actuates the fiber due to a temperature range, and the change in temperature induces a strain on the SMA.

So, the bending of the fiber, which in turn results in optical signal attenuation. At high temperatures, the shape memory alloy will straighten the fiber, whereas under low temperature conditions, we can see a kind of bending that occurs. So ideally, we have seen a lot of functionality regarding a shape memory alloy. So this is quite encapsulating the shape memory alloy as a sensing behavior. Shape memory alloy sensing behavior with reference to low and high temperature conditions has been investigated by depositing these shape memory alloys on an optical fiber and appropriately sensing their behavior.

The overall construction looks something like this, where we have a laser source and a detector that is available; this is a kind of SMA-coated fiber. By changing its characteristics appropriately, we can monitor the behavior. In this cryogenic sensing, we have an SMA bimorph. In this SMA bimorph, the SMA-coated optical fibers are

integrated appropriately. So as far as the SMA biomorph is concerned, we have discussed this in the earlier modules as well, including how these SMA biomorphs were developed and how these SMA biomorphs were deployed for different applications.

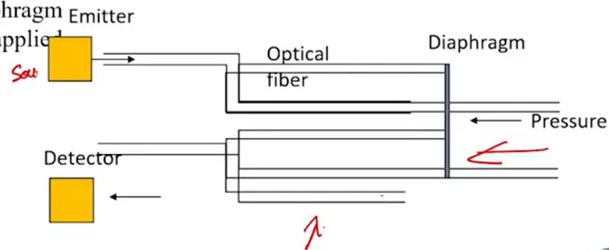
Now, like when we try to integrate this SMA-coated fiber along with SMA biomorph, this will improve the sensitivity of the system. Ideally, at room temperature, this will be the configuration; when it is exposed to a low temperature, it takes a curl shape. Now, once again, when I try to shift it back, it returns to this shape. Sensing this cryogenic temperature is one of the challenging tasks with reference to conventional sensors. However, optical fiber-based sensors are considered to be a superior substitute due to their immunity to electromagnetic interference and power fluctuations.

Shape-memory alloy coatings on optical fibers certainly improve the sensor response. The displacement due to phase change of SMAs during exposure to extremely low temperatures. The phase change induces thermal strain on the fiber, leading to a change in the refractive index of the core and cladding, which results in a change in the intensity of the optical output signal. The integration of the SMA bimorph with SMA-coated fiber significantly enhances the displacement due to the enhanced induced strain, which leads to the attenuation of the optical output. Such attenuation of the output signal relates to the low temperature sensitivity of SMA-coated optical fiber.

This is a kind of LDS sensor that is deployed to investigate the overall actuation occurring on an SMA-coated optical fiber in a liquid nitrogen environment. We will discuss the optical fiber-based pressure sensor. So, as far as this optical fiber-based pressure sensor is concerned, this is the source and this is the detector. The optical fiber is integrated with the diaphragm, and pressure is induced on the diaphragm. The optical pressure sensor consists of three components: the sensing head with a metal diaphragm, a cable with two fibers, and an optoelectronic system with LED and photo detectors.

Pressure Sensors

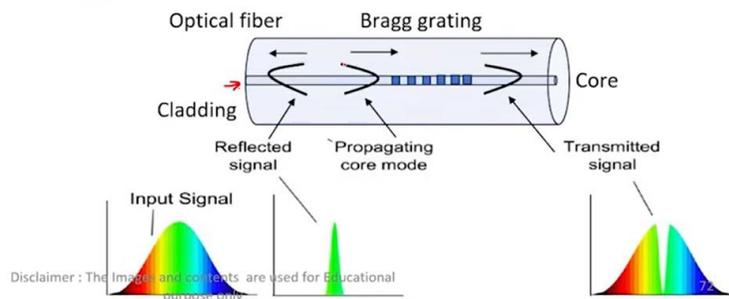
- Optic pressure sensor consists of three components viz. Sensing head with metal diaphragm, cable (with two fibers) and optoelectronic systems (with LED/ Photodetectors etc).
- Light from LED source is allowed to be transmitted through one fiber and the reflection from metal diaphragm is taken through the second fiber.
- This reflected signal is received by the detector and other signal conditioning circuit. Diaphragm displacement depends on the extent of applied pressure



The light from the LED source is transmitted through one fiber, and the reflection from the metal diaphragm is taken through the second fiber. This reflected signal is received by the detector and the other signal-conditioning circuit. The diaphragm displacement depends on the extent of the applied pressure that is available there. The interesting part is that such systems are highly compact, completely free from electromagnetic shielding, and the most important aspect is that these are reliable systems which can be used for continuous monitoring. This is a highly sensitive fiber-based system.

Fiber Bragg Grating Sensors ✓

- Fiber Bragg Grating (FBG) sensors are optical sensors that utilize the principles of fiber optics and Bragg reflection to measure strain, temperature, pressure, and other physical parameters.
- FBG is a periodic variation in the refractive index of a fiber optic core, created using ultraviolet (UV) light. When broadband light is sent through the fiber, a specific wavelength (Bragg wavelength, λ_B) is reflected while the rest is transmitted. This Bragg wavelength is given by:
- $\lambda_B = 2\eta_{eff}\Lambda$ where 2η is the effective refractive index of the fiber core and Λ is the grating period.
- Changes in strain, temperature, or pressure alter η_{eff} and Λ , causing a shift in the Bragg wavelength, which can be measured to determine the applied physical change



In this fiber-based system, in order to improve the sensitivity of an optical fiber, fiber Bragg grating sensors are employed. Fiber Bragg grating sensors are nothing but gratings inscribed inside the optical fiber, where there is a kind of core established, and then there is a propagation mode that exhibits and is concerned with the transmitter signal. So, light is incident on it; it is a kind of reflected signal, a propagating core signal, and a transmitted signal. These fiber Bragg grating signals are optical sensors that utilize the principle of fiber optics and Bragg reflection to measure strain, temperature, pressure, and other physical parameters. The FBG is a periodic variation in the refractive index of a fiber optic core created using ultraviolet light.

When broadband light is sent through the fiber, a specific wavelength, which is a Bragg wavelength, is reflected while the rest is transmitted. This Bragg wavelength is given by $\lambda_B = 2n_{\text{eff}} \Lambda$, where $2n_{\text{eff}}$ is the effective refractive index of the fiber core and Λ is the grating period. The change in the strain, temperature, or pressure alters the overall effect and the λ_B , causing a shift in the Bragg wavelength, which can be measured to determine the applied physical change. This applied physical change can be either pressure or, in certain cases, it might be strain; in certain cases, it might also be temperature. In the case of a strain sensor, let us consider that we have an input signal; this is the intensity, I_{in} .

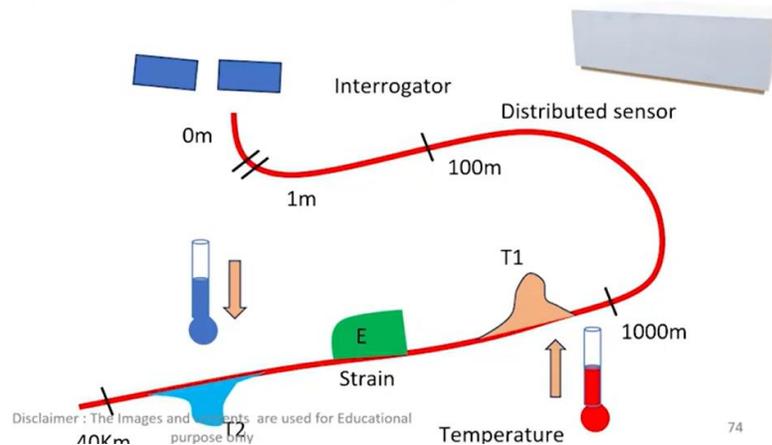
This is the input signal or the incident signal. So, if we try to quantify the grating period, this is Δn , A , n_{core} , and $n_{\text{effective}}$ grating period. If this is going to be the input light, we will appropriately be getting two different responses. One response is the reflected light, and the other response is the transmitted light. So it's a kind of intensity; this is from the reflected light, in the case of transmitted light. A fiber optic strain sensor is used here for structural strain measurements.

To create the actual strain sensor, the optical fiber is inscribed with the FBG grating, which is basically a pattern of material interference that reflects light differently from the rest of the fiber. Ideally, when we try to look into the overall sensing capability of an optical fiber, we should consider various factors. One way of sensing can happen through intensity modulation; another way of sensing can occur due to wavelength shift. With fiber Bragg grating, we can detect the wavelength shift. However, without a fiber Bragg grating, we will have a kind of intensity modulation.

So, the material interference, the slices are placed at certain intervals when the fiber is stretched or compressed, and it is therefore subjected to positive or negative strain. These intervals change when the fiber is stretched; it lengthens, and the spaces get bigger, and vice versa. The FBG sensor reflects a specific wavelength of light, λ_B , based on the grating period, Λ , and the refractive index in n_{eff} . When the strain is applied, the Λ changes, causing a shift in the reflected wavelength, which can be represented by this particular equation. This wavelength shift is proportional to the strain applied to the fiber.

Distributed Optical Fiber Sensors

- The basic operation of distributed fiber sensing requires illuminating a length of optical fiber by repetitive pulses of coherent light. The equipment used is referred to as an interrogator.
- Each pulse is subject to a transmission delay as it works its way along the fiber.
- At individual positions throughout the fiber a highly attenuated backscatter signal arises and will return to the source in a known time (propagation delay) determined by its time-of-flight

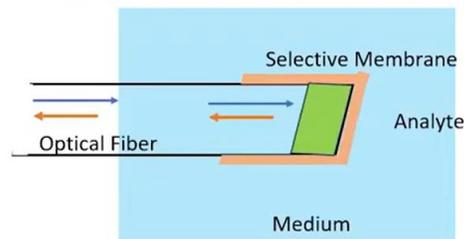


Ideally, based on the reflected signal and the transmitted signal, we can have an idea of the measurement of the strain, or we can continuously monitor the strain we are looking for. When we try to look into the distributed sensing of an optical fiber sensor, these optical fiber sensors have the capability to sense different positions in different optical regions. The basic operation of a distributed fiber sensing system requires illuminating a length of optical fiber with a repetitive pulse of coherent light. The equipment used is referred to as an interrogator. Each pulse is subjected to a transmission delay as it works its way along the fiber; the individual positions throughout the fiber have a highly attenuated backscattered signal that arises and will return to the source.

In known time, there is a kind of propagation delay which is determined by its time-of-flight measurements. Overall, like in a 40-kilometer range, we can use strain measurements, a temperature measurement, distributed measurements, and interrogated measurements. With reference to a micro robotics perspective, if we are working in a particular domain where we are trying to actuate micro robotic sensors, these sensors are continuously and efficiently used for condition monitoring of this domain, so the actuation behavior can be appropriately managed. Now let us see how an optical fiber chemical sensor uses optical fiber to detect and measure the presence of a specific chemical substance. A sensor operation is based on the changes in the optical properties of light, such as intensity, wavelength, phase, or polarization, when exposed to a specific chemical, such as absorption-based sensing, which means a chemical absorbs a specific wavelength of light, altering the transmitted signal.

Chemical Sensors

- Optical fiber chemical sensors use optical fibers to detect and measure the presence of specific chemical substances.
- Sensor operation based on the changes in the optical properties of light (such as intensity, wavelength, phase, or polarization) when exposed to a specific chemical. Such as,
 1. Absorption-based sensing – A chemical absorbs specific wavelengths of light, altering the transmitted signal.
 2. Fluorescence-based sensing – A fluorescent chemical marker emits light at a specific wavelength upon excitation.
 3. Surface Plasmon Resonance (SPR) – Changes in refractive index near a metal-coated fiber surface affect light propagation.
- In this method, the lifetime is obtained from the phase shift between emission signal from the chemical sensor and the excitation signal used. Currently, some analytical instruments that enable the measurement of a large number of analytes such as pH, carbon dioxide, or oxygen, are known.



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Fluorescent-based sensing involves a fluorescent chemical marker that emits light at a specific wavelength upon excitation. Surface plasmon resonance is a change in the refractive index near a metal-coated fiber surface that affects light propagation. In this method, the lifetime is obtained from the phase shift between the emission signal from the chemical sensor and the excitation signal used. Currently, some of the analytical instruments that enable the measurement of a large number of analytes, such as pH, carbon dioxide, or oxygen, are known. This is a kind of analyte that is kept in a selective membrane, and when absorption occurs, there will be a change in the overall characteristics based on the selective membrane.

Now, if we try to look into the overall application of it, these kinds of optical fiber sensors are efficiently used for structural health monitoring, aerospace and defense applications, biomedical applications, environmental monitoring, and the oil and gas industry. Some of the key advantages of these optical fiber sensors are that they have high sensitivity and high accuracy, and they detect minimal changes in strain, temperature, pressure, or chemicals. From the perspective of immunity to electromagnetic interference, it works in high voltage and high radiation environments. It is a lightweight and compact option suitable for aerospace, medical, and industrial applications. It can be used for long-distance sensing as well as short-distance sensing; it can transmit signals over a kilometer without any signal degradation.

As far as multiplexing capacity is concerned, these multiple sensors can be integrated with a single fiber. It has good resistance to corrosion; it is highly useful for underwater oil and gas and space applications. Remote and distributed sensing, which is useful for

monitoring large infrastructures like bridges, tunnels, and pipelines, etc. From the perspective of micro robotics, such optical fiber sensors are efficiently used for condition monitoring of the overall working window of these optical fibers, and in certain cases, to measure strain and temperature, such optical fibers are employed. So just to give you an overview, we had discussed the different concepts of microsensors.

We have introduced the microsensors and microtransducers. We have provided an exposure. This lecture basically gives you exposure to the overall configuration of microsensor development and how microsensors are deployed with reference to different parameters. So if we try to categorize the microsensors, there are two key elements that exhibit in a microsensor. One is a microsensing element, and the other is a microtransduction element. Based on the application, the micro sensing element and the micro transduction element are selected, and then the working principle of the micro sensors is established.

This is a template for the working principle of the micro sensor regarding the different sub-elements that are available in these micro sensors. Then the classification of the micro sensors is basically with reference to radiation, thermal micro sensors, magnetic micro sensors, mechanical micro sensors, and chemical micro sensors. The different transduction elements and the different sensing elements are discussed, including how they are used for robotic applications, the pressure transducers, piezoelectric transducers, capacitive transducers, and inductive transducers, as well as the fundamentals of an ultrasonic transducer. Then we had a discussion about the integration and signal processing. We had a discussion about this optomechatronic system design, the overall evolution of this optomechatronic system design, the different elements of optomechatronic system design, how these optomechatronic system designs are classified, and how they are effectively used for micro-mechanical applications.

These are the lists of functions of different optomechatronic systems and their applications, how optomechatronic systems are deployed in robotics. From the perspective of optomechatronic systems, they are efficiently used for displacement measurements as well as for force and strain measurements. Some of the components of optomechatronic systems are discussed in detail, and then this is a simple example where a kind of micro optomechatronic system is integrated with piezoelectric actuators, and the overall transformations are studied. Then the different applications of optomechatronic systems, regarding the configuration of an LDS sensor, involve various techniques related to optical displacement measurements, including the triangulation-based sensor, the interferometric displacement sensor, a confocal sensor, a time-of-flight sensor, and optical encoders. Then there is a discussion on the triangulation sensor and the interferometric displacement sensor.

The confocal sensor and time-of-flight measurements show how a shadow projection sensor is used for visualizing moving objects in a system that has potential applications in micro-robotic related applications, especially for magnetic actuation of nanoparticle-integrated micro-nano particle actuations, etc. We also had a discussion about these optical encoders and their overall applications. The influence of light intensity modulation in sensing, regarding the different concepts of light intensity modulation and classifications of light intensity modulation. We had a discussion about optical fiber sensors, sensor configurations, and how interferometers are used for microsensing. Different types of interferometers include a Michelson interferometer, a Max Zander interferometer, and a Fabry-Perot interferometer.

This is the overall construction of a Michelson interferometer and how it is being effectively deployed for different applications, including optical fiber-based temperature sensors, shape memory smart material-coated temperature sensors for cryogenic temperature sensing, high-temperature sensing applications, optical fiber-based pressure sensors, and the overall application of fiber Bragg grating in strain sensing-related applications. If we consider a large environment, these kinds of distributed optical fiber sensors are effectively used for sensing different levels. Then, about the chemical sensors, different applications, and advantages of this optical fiber, these are the references we have used for preparing these slides.