Lec 21: Applications: Fiber Bragg Grating

Hello students, welcome to lecture 21 of the online course on Photonic Crystals Fundamentals and Applications. Today's lecture will be covering applications of fiber break grating.

Lecture Outline

- Fiber Bragg Gratings in Optical Communication
  - Introduction
  - Types of Fiber Bragg Grating
  - Fiber Bragg Grating in Optical Communications
    - Filtering and Multiplexing
    - Compensation for Chromatic Dispersion
    - Laser diodes
    - Fiber lasers
    - Amplifiers
- Fiber Bragg Gratings in Sensors
  - Temperature sensors
  - Strain sensors

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So, here is the lecture outline. We will be discussing about fiber break gratings in optical communication, different types of fiber bragg grating and their application mainly in filtering and multiplexing, compensation for chromatic dispersion, laser diodes, fiber lasers, amplifiers and so on. We will be also discussing the applications of fiber break grating in sensors, particularly as a temperature sensor and strain sensor.

Fiber Bragg Gratings in Optical Communication

Introduction

- **Structure:** Fiber Bragg Gratings (FBGs) are made up of a periodic modulation of the refractive index in the core of single-mode optical fibers.
- **Development:** Over the past few decades, Fiber Bragg grating sensors have seen widespread development.
- **Advantages:**

Small Size: Allows for use in compact spaces.

EMI Resistance: Immune to electromagnetic interference, making them suitable for environments where electronic sensors fail.

Ease of Installation: Simplifies deployment in challenging or remote locations.

Long-term Stability: Ensures reliable performance over extended periods.

Wavelength Multiplexing: Enables multiple FBGs to be used simultaneously without interference.

Figure: Schematic diagram of Fiber Bragg Gratings

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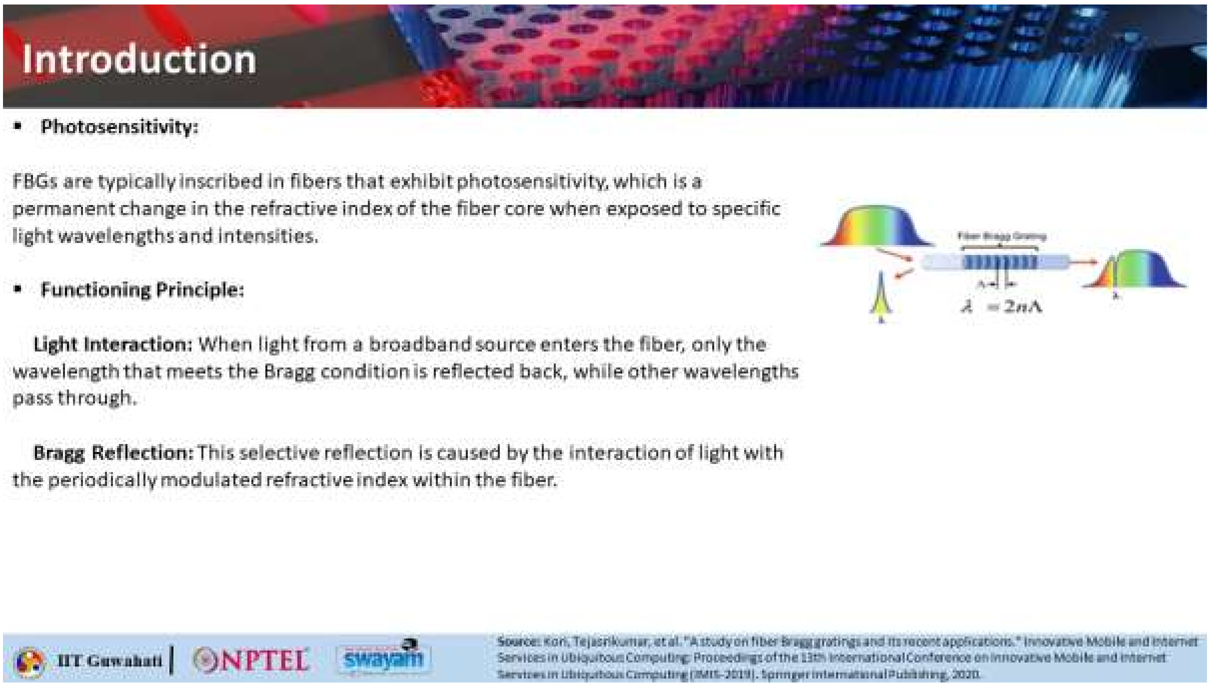
Source: Kori, Tejasrikumar, et al. "A study on fiber Bragg gratings and its recent applications." Innovative Mobile and Internet Services in Ubiquitous Computing: Proceedings of the 13th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS-2019). Springer International Publishing, 2020.

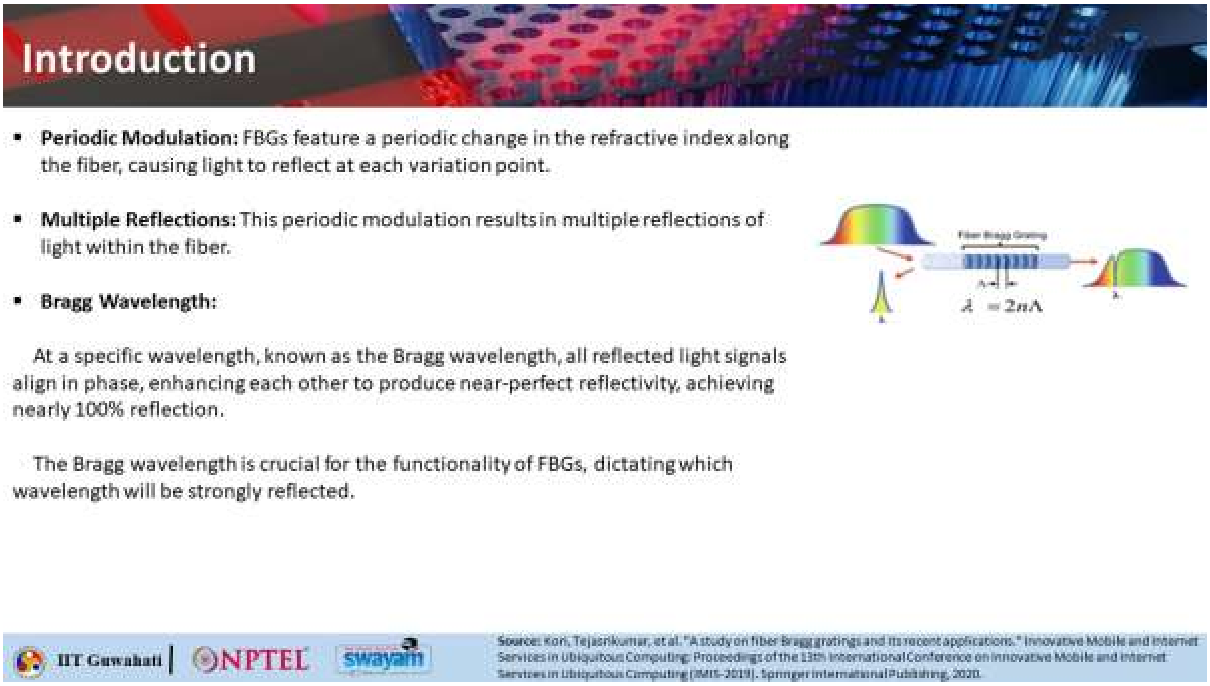
So fiber bragg grating as you know is a very important component in optical communication and why we are discussing about optical communication because that actually is the backbone of all the high speed data transmission that is happening in today's world.

So it is a very important device and if you remember that this is basically a 1D periodic grading yeah or it is a one you can think of you know 1D photonic crystal somewhere very close to that. So, fibre break gratings are basically made of periodic modulation of the refractive index inside the core of a single mode optical fibre. And over the past few decades, fibre break grating sensors have been seen widespread development. What is the reason? It allows for using compact spaces and also it shows

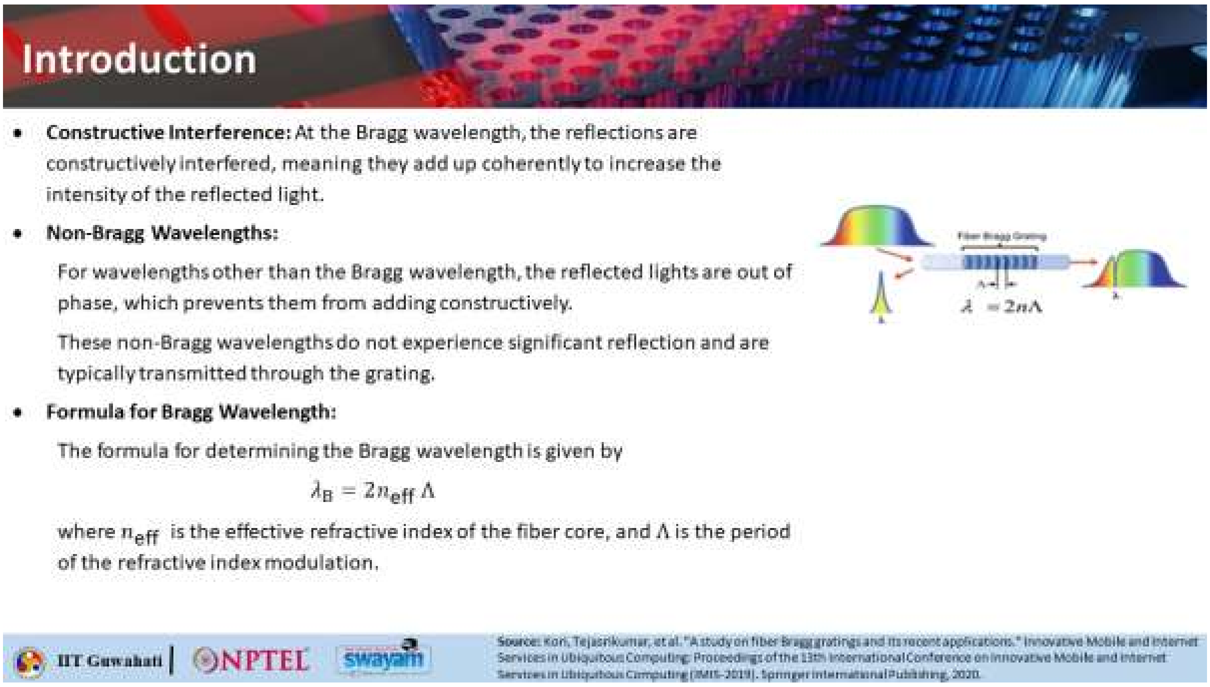
EMI electromagnetic interference resistance that means they are immune to different kind of you know EMI or electromagnetic interfaces making them suitable for environments where typically electronic sensors would fail.

They are also easy to install okay and you can deploy them in challenging and remote locations. and they ensure reliable performance over the extended periods. Wavelength multiplexing that like enables multiple fiber break grating sense to be used simultaneously without any interference from one another. okay and they also show photosensitivity that means the FPGs are typically inscribed in fibres that exhibit photosensitivity which is basically a permanent change in the refractive index of the fibre core. when exposed to specific wavelengths and intensities.





So, what is the great thing about this fiber? When you actually send a wide spectrum of wavelengths, only one particular wavelength will get reflected. So, that is how it operates. So, that is the functioning principle. So, when light from a broadband source will enter the fiber, only the wavelength that meets the bragg reflection criteria or bragg condition will get reflected back and other wavelengths will get passed through. So, in the transmission spectrum, you will see there is a notch and that is coming because of the strong reflection from one particular wavelength.

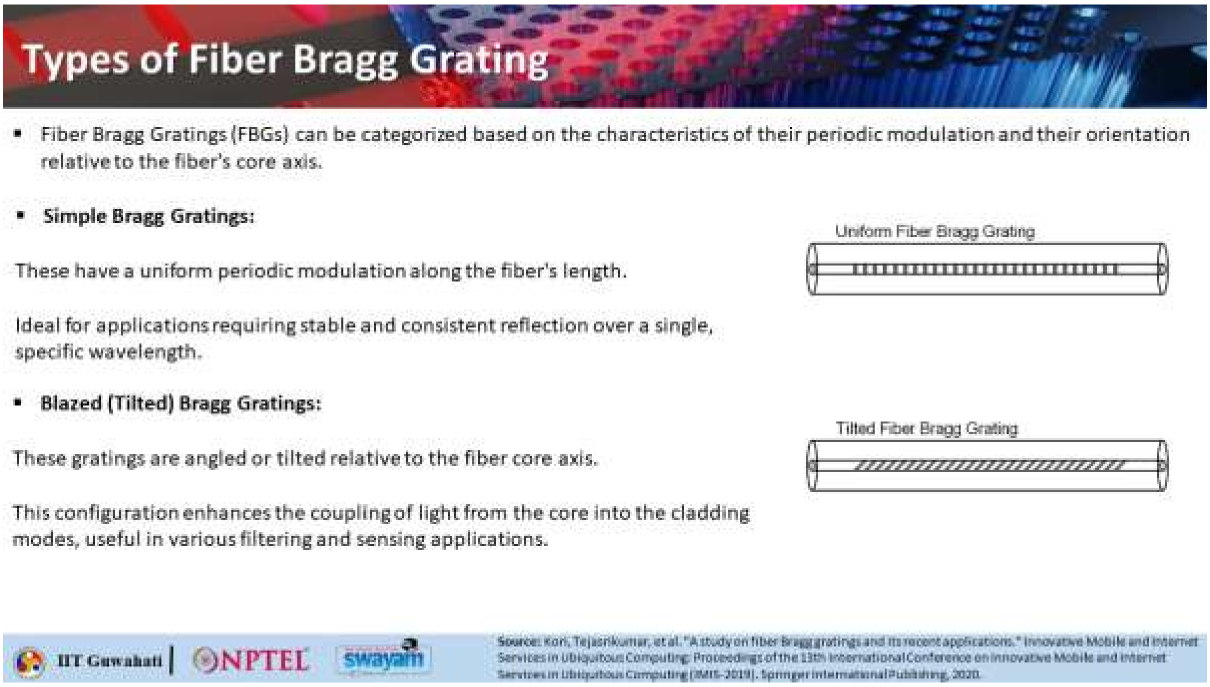


So, if your grating period is given as capital lambda, the small lambda is the Bragg wavelength which is getting reflected and that satisfies this particular equation 2n lambda. We will come to these details what is this n and what is lambda, capital lambda in more details in the subsequent slides. So Bragg reflection basically is a selective reflection which is caused by the interaction of light with periodically modulated refractive index within the fiber. Now periodic modulation is nothing but you know periodic change in the refractive index along the fiber and what happens at each interface there will be some reflection, is not it? And this periodic modulation thus results in multiple reflection of light within the fiber.

So, at a particular specific wavelength you will see that you know all the reflected light signals they basically align in phase. So, they constructively interfere and that gives you nearly 100 percent reflection and that wavelength is called as Bragg wavelength. So, Bragg wavelength is crucial for the functionality of this fiber Bragg grating dictating which wavelength will be strongly reflected as also shown here one particular wavelength is grating reflected back. Now, this is as I mentioned mainly happens at Bragg wavelength because of the constructive interference of different multiple reflected light from all these interfaces okay and they add up coherently to increase the intensity of the reflected light. Now what happens for other wavelengths that they do not satisfy this condition.

So, for wavelengths which are which do not satisfy the Bragg condition that is they are not the Bragg wavelength. For them the reflection still take place at each interface of this high-low, high-low, high-low kind of you know refractive index modulation. But all these reflected lights are basically not in phase. So, when they are out of phase they basically cancel out each other.

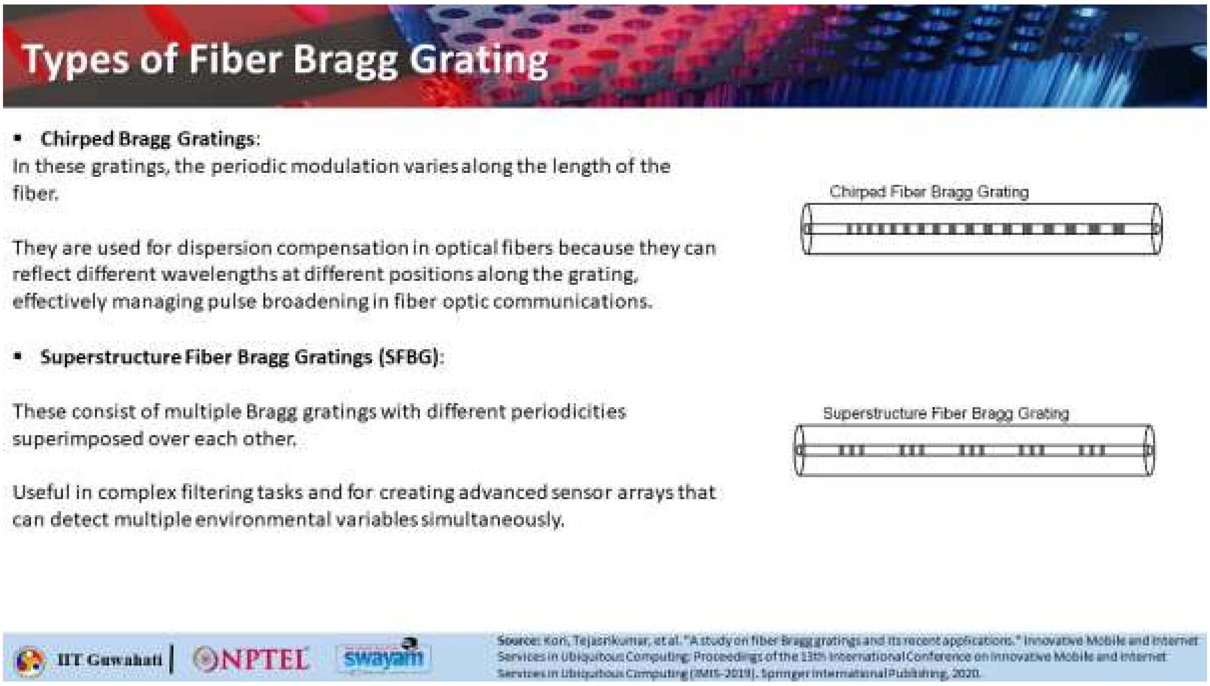
right. So, this non Bragg wavelengths do not experience significant reflection and that typically they are transmitted through the grating. So as I mentioned what is the formula that determines the Bragg wavelength? It is basically given by lambda B equals to N effective lambda. So one new term come here is N effective. So N effective gives you the effective refractive index of the fiber core and capital lambda is basically the period of the refractive index modulation.



So, fibre brake grating basically can be categorized based on the characteristics of their periodic modulation and their orientation relative to the fibres core axis. So, the first one that will come to your mind is simple brake grating. So, basically these are uniform fiber break grating. So, you have a uniform periodic modulation of the refractive index along the fibers core. So, that runs through the length of the fiber, whatever distance you require.

So, the grating is basically uniform. So this is ideal for applications requiring stable and consistent reflection over a single and specific wavelength. So this is the particular application area of the simple Bragg rating. You use this for you know stable and consistent reflection at specific wavelength. The next one is tilted or you can say blazed fiber back grating.

So, here the gratings are basically angled or tilted with respect to the fiber core axis as you can see in the diagram. So, this configuration enhances the coupling of light from the core into the cladding modes. So, these are basically useful in various filtering. or sensing kind of application so here the interaction with the you know cladding will be more



Then you have chipped Bragg grating. So in this particular grating, the periodic modulation varies along the length of the fiber.

So you see the periodicity is basically changing. So they are basically used for dispersion compensation in optical fibers because they can reflect different wavelengths at different position along the grating. So, they are able to manage you know the problem of pulse broadening that is typically seen in fiber optic communication. Another type of fiber break grating is superstructure fiber break grating. So, you can see this is a superstructure which is repeated periodically.

So, these are basically consists of multiple break gratings of different periodicities which are basically superimposed on each other. So, these are useful in complex filtering tasks and for creating advanced sensor arrays that can detect multiple environmental variables simultaneously. So, this is where the superstructure fiber break grating will be useful. So, one grating will cater to one particular variable, another grating can cater to another variable, but they are basically superimposed to give them this kind of multifunctional to make them multifunctional, right. So, break gratings are easy to integrate as well.

Fiber Bragg Grating in Optical Communications

- **Ease of Integration:**

  Fiber components like gratings and couplers are easily spliced to transmission fibers and other fiber components.

  They exhibit low insertion loss compared to planar-waveguide or micro-optic components, simplifying connections to external devices.

- **Polarization Characteristics:**

  Generally display extremely low polarization sensitivity, enhancing performance consistency.

  Can be designed to be polarization-sensitive if needed, offering control over polarization for specific applications.

- **Robustness and Durability:**

  The encapsulation of light within fibers makes these components robust and relatively immune to mechanical disturbances.

  Their in-fiber design shields them from environmental factors that might affect other types of optical components.

Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

So, fiber components like gratings and couplers can be easily spliced to transmission fibers and other fiber components. And they typically exhibit very low insertion loss as compared to planar wipe guide and or micro optic components. So, they basically simplify the connection to external devices, okay. this brake grating nano imprinted on optical fibers have become essential for flattening the gain of amplifiers, stabilizing the wavelength of pumps or sources and also for fiber lasers. So, advantages are basically as I mentioned low insertion loss, low polarization sensitivity which we will see right now, the polarization characteristics and also extreme flexibility in designing.

So, these advantages basically make gratings very attractive candidates for applications of complex filtering or precise chromatic dispersion composition. Now talking about their polarization characteristics as I was mentioning that you know generally they display low polarization sensitivity that means it will ensure the performance consistency. However, you can still design them for particular polarization and make them polarization sensitive if your application demands so, okay. So that will actually offer you control over the polarization of light for a specific application. Talking about robustness and durability, the encapsulation of light within the fibers make these components robust and relatively immune to mechanical disturbances.

their in fiber design shields them for and from environmental factors that might have affected you know other types of optical components.

Fiber Bragg Grating in Optical Communications

- **Customization and Rapid Manufacturing:**

Fiber components are customizable and can be designed and manufactured quickly compared to other component technologies, enabling rapid prototyping and deployment.

- **Applications in Optical Communications:**

Photo-induced in-fiber Bragg gratings (IFBGs) offer great design flexibility and high spectral efficiency, making them versatile for various uses.

Commonly used as gain equalizers in erbium-doped fiber amplifiers (EDFAs) to smooth gain ripple, enhancing amplifier performance.

Serve as laser-diode pump stabilizers at wavelengths like 1480 nm and 980 nm, critical for maintaining stable operation in laser systems.

Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

So, these are some kind of you know important features of fiber break rating which are popularly used in optical communications. they also offer customization and rapid manufacturing so fiber components are customizable and can be designed and manufactured quickly compared to other technologies and applying rapid prototyping and deployment in field and the applications in optical communications include you know different usage so mainly the photo induced in fiber bragg gratings that is if FBGs in short they offer great flexibility and high spectral efficiency making them you know versatile for various usage something like you know gain equalizers in EDFAs which are erbium doped fiber amplifiers which are basically inline fiber amplifiers for boosting up the signal if there is propagation delay after you know the fiber is laid for couple of kilometers there will be drop in the signal. So, you require amplifier to boost up the signal. But then you know the amplifiers may have those gain ripples.

It means the gain may not be flat. So, you can use EDFA to smooth out those gain ripples and that will actually enhance the performance of the amplifier. You can make them serve as laser diode pump stabilizers at wavelengths like 1480 and 980 which are critical for maintaining stable operation in laser systems. So, this photo induced in fiber Bragg ratings are basically optical elements which are fabricated within the optical fiber using light. So, typically you use ultraviolet light.

Fiber Bragg Grating in Optical Communications

- Photo-induced in-fiber Bragg gratings (IFBGs) are optical elements fabricated within optical fibers using light, typically ultraviolet (UV), to induce changes in the refractive index of the fiber's core.
- This technology harnesses the principle of Bragg diffraction, allowing for the reflection of specific wavelengths of light while transmitting others, making IFBGs integral components in a variety of optical applications.
- **Sensitivity and Versatility:** IFBGs are highly sensitive to changes in temperature, strain, and pressure, which alters the Bragg wavelength—the specific wavelength that the grating reflects.

  This sensitivity makes them invaluable in sensor technology, where they are used to monitor structural health, detect environmental changes, or measure physical forces in engineering and medical applications.
- **Telecommunications:** In fiber optics communications, IFBGs serve as filters or wavelength-selective reflectors, improving signal quality and managing channel distribution in dense wavelength division multiplexing (DWDM) systems.

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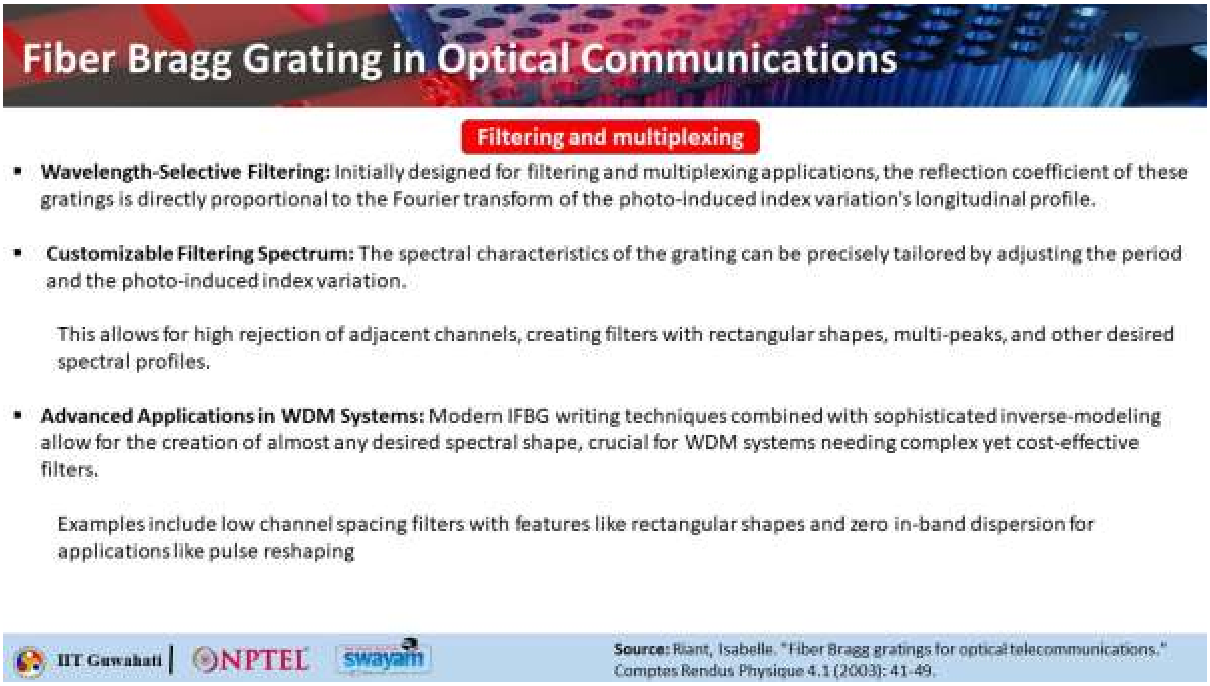
Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

and you use a mask to cover the core and then shine UV light through that mask to selectively cure some portion of the core and that will induce changes in the refractive index periodically and that is how you make the fiber Bragg grating. This technology harnesses the principle of Bragg refraction allowing for the reflection of specific wavelength of light while transmitting the remaining band, okay. So, that way you know this in fiber Bragg gratings or IFBGs they become integral component of various optical applications. now how do you use them as senses because this kind of Bragg grating, in fiber Bragg grating, they have shown sensitivity to changes in temperature, strain, pressure because they can all alter the bragg wavelength. That is, you know, that particular wavelength which is getting reflected from the grating can change if there is a change in temperature, strain or pressure which is applied onto your grating.

So this sensitivity makes them inviable for the sensor technology where you know this kind of bragg ratings can be used for monitoring structural health for say dam then bridges even you can use them for security for making fences in the border areas where you can detect any kind of intrusion. If somebody steps on your fiber which is buried in the soil, there will be change in the refractive index because of the stress being applied and that will change the wavelength which is typically reflected from that grating. in a unstressed condition and that can be easily detected. So, this kind of technology are being applied by border security forces to fence or protect the borders of territories. And you can also measure physical forces in engineering and other medical applications.

They are also useful in telecommunications where you know this kind of in fiber bragg ratings serve as filters or wavelength selective reflectors improving the signal quality and managing channel distribution in dense wavelength division multiplexing systems, okay.



One of the primary benefits that we can see in integrating, in fiber integrating is their ability to be integrated, you know, directly into the fiber without needing any bulky external component. And this integration has allowed them to provide a compact, efficient design, which are less susceptible to mechanical failure and environmental disturbances. So now let us look into you know filtering and multiplexing kind of application. So wavelength selective filtering can be achieved okay where the reflection coefficient of this grating is directly proportional to the Fourier transform of the photo induced index variation profile.

So, you can also make it customizable that they are filtering response can be customized. So, the spectral characteristics of the grating can be precisely tailored by adjusting the period and the photo induced refractive index variation. So, this allows for high rejection of adjusting channels and creating filters with rectangular shapes, multiple peaks and other desired spectral profiles. They are also useful in advanced applications in WDM systems. So modern IFBGs writing techniques combined with sophisticated inverse modeling allows for the creation of almost any desired spectral shape, which are crucial for WDM systems that needs complex yet cost effective filters.

Fiber Bragg Grating in Optical Communications

Filtering and multiplexing

- **Integration with Circulators:** To extract specific signals close to the Bragg wavelength, straight short-period gratings are typically used in conjunction with a circulator, as depicted in figure.

  The circulator allows light at specific wavelengths to be redirected from one port to another, facilitating effective signal extraction and routing.

- **Transformation into OADM:** By integrating a second circulator, these systems can be expanded into optical add-and-drop multiplexers (OADM), enhancing their functionality in network setups.

  This setup permits both the insertion and extraction of channels at designated wavelengths.

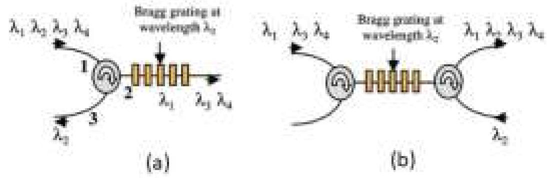


Figure: (a) Pass-band filter made of a Bragg grating associated with a circulator; (b) Optical add and drop multiplexer made of the association of a Bragg grating with 2 circulators.

Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

So some example could be low channel spacing filters with features like you know rectangular shapes and zero in band dispersion for applications like pulse reshaping. So here are some you know applications shown with integration for integration with circulators. So to extract specific signals close to the Bragg wavelength straight short period grating are typically used in conjunction with a circulator. So, here you can see that circulator the signal can go from 1 to 2, 2 to 3 and 3 to 1 like that ok, it cannot go back ok. So, here you can see in the first case it is basically a pass band filter ok.

It is a break rating that basically reflects lambda 2. So, what is happening? You are sending a light that has got lambda 1, lambda 2, lambda 3 and lambda 4, all these 4 wavelengths and then when it goes here, lambda 2 is reflected. So, the remaining passes through. So, lambda 1, lambda 3 and lambda 4 passes through, but lambda 2 is taken out or dropped from this particular port. You can also use another circulator here, something like this.

Say you have lambda 1, lambda 3, and lambda 4. And then you have one circulator. So the signal just goes in here. But this one reflects lambda 2.

So all the signal will simply pass through. And then if you put lambda 2 through this port, what will happen? It goes in. okay gets reflected back and will get connected and all the signals will get come out of the circulator. So, what is happening here you are adding lambda 2 into your stream. So, this can actually act as add and drop multiplexer right. So, that is how you actually transform this thing into a add and drop multiplexer.

So, they basically use circulator and fiber break grating for selective dropping or adding of you know channels in optical communication systems.

Fiber Bragg Grating in Optical Communications

Filtering and multiplexing

- **Alternative All-Fiber Devices:** Alternatives like the Mach–Zehnder interferometer and a 100% (or 0%) coupler, illustrated in figure, offer lower-cost solutions.

  While the Mach–Zehnder option is already commercialized, the coupler-based solution still faces challenges related to port isolation.

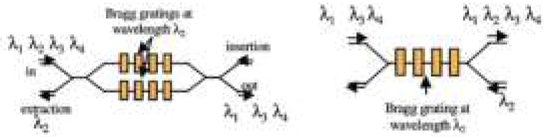


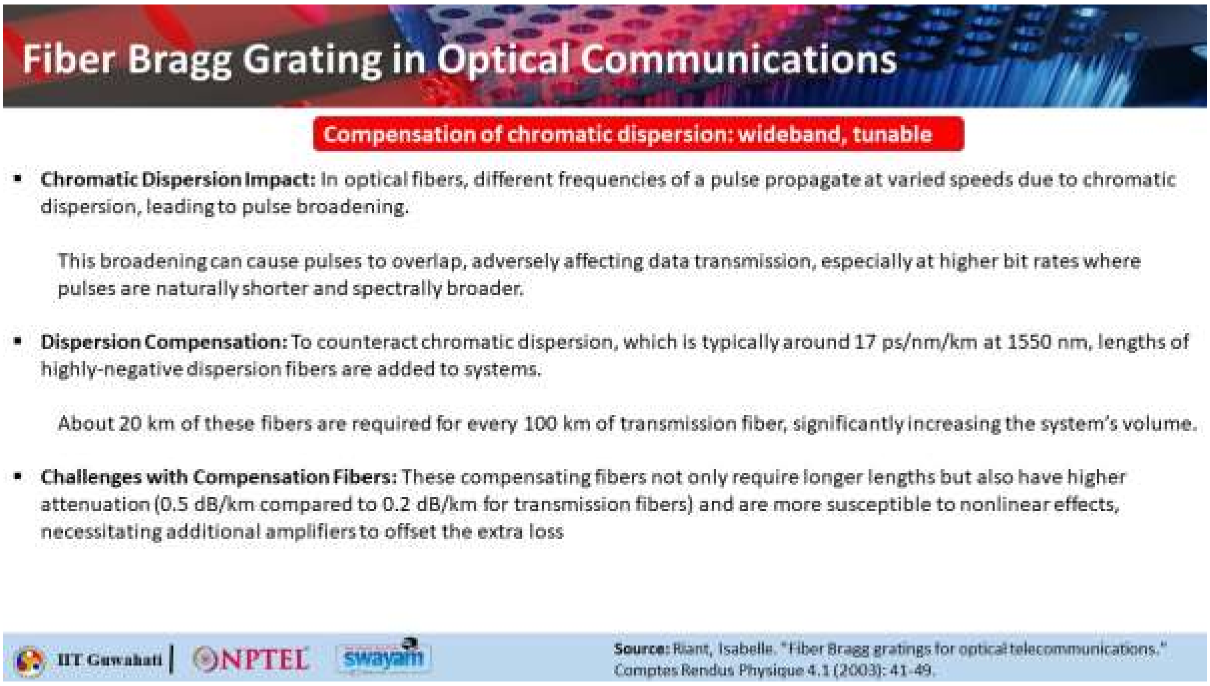
Figure: (a) Optical add and drop multiplexer based on a Mach–Zehnder interferometer (b) Optical add and drop multiplexer based on a 0% coupler

Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

Okay, you can also use, you know, all fiber devices, something like, you know, that's an alternative like Maxender interferometer and a, you know, 100% or 0% coupler that you can see here. So that these are basically, you know, offering low cost solution. So, the first figure actually shows two identical break grating both reflecting lambda 2 are photo written at the two arms of the interferometer. So, here what happens the function extraction of lambda 2 is represented.

So, this is again, this is the input. So, lambda 1, lambda 2, lambda 3, lambda 4 comes here and lambda 2 is extracted. So, what comes out is basically lambda 1, lambda 3 and lambda 4. ok. And you can see here as well. So, lambda 1, lambda 3 and lambda 4 are entering this particular port and here is the break rating.

So, from this port if you add lambda 2, it will get reflected and come back through this port where you will have all the wavelengths added up. So, again these are actually making an optical add drop multiplexer and this one is based on 0 percent coupler. You can also use them for compensation of chromatic dispersion in a wide band and tunable fashion.



So, in optical fibers What is this chromatic dispersion impact? In optical fibers, different frequencies of a pulse propagate at a different speed due to chromatic dispersion.

And because of that, the pulse gets broadened. And this broadening will cause pulses to overlap. and there will be loss of signal and that will affect the data transmission especially at high data rates where the pulses are naturally short and they are spectrally broader. So you need to find a method to you know compensate the dispersion and typically what people do you know to compensate this chromatic dispersion highly negative dispersion fibers typically say 17 picosecond per nanometer per kilometer is attached to the fiber optical link okay and this is the value of chromatic dispersion at 1550 right. So, you have to typically use 20 kilometers of this kind of fiber for every 100 kilometer of transmission fiber okay and you can see that significantly increases the system volume. Now, what is the challenge with this kind of dispersion compensating fiber? This compensating fibers not only require very long length, but also they suffer from high attenuation.

So, they typically have larger attenuation than a standard transmission fiber. So, they have 0.5 dB per kilometer attenuation as compared to 0.2 dB per kilometer attenuation for standard transmission fiber. so they are also more susceptible to non-linear effects and they will require additional amplifiers to compensate for this loss of signal so it's a complicated one so why not you use a chirped fiber break rating to do this kind of dispersion compensation so you can actually use linearly chipped grating that can be used.

Fiber Bragg Grating in Optical Communications

Compensation of chromatic dispersion: wideband, tunable

- **Chirped Grating Solution:** Linearly-chirped gratings have gained interest as an alternative to dispersion-compensating fibers.

  These gratings, used in reflection with a circulator, reflect longer wavelengths immediately while allowing shorter wavelengths to travel further.

  They effectively introduce a time delay and compensating for dispersion with lower loss, reduced volume, and decreased sensitivity to nonlinear effects

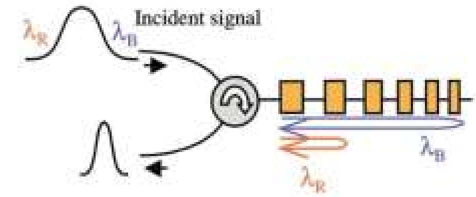


Figure: Principle of chromatic dispersion compensation using a linearly chirped Bragg grating with a circulator.

Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

So what happens here? this gratings used in reflection with a circulator, it can reflect longer wavelengths immediately and shorter wavelength can travel further and then get reflected. So, that way, it can actually, the wavelength which is lagging behind can be pushed forward and the wavelength which was leading can be pulled back and then you can actually gain the shape of the pulse back. So, they effectively introduce a time delay and compensate for the you know dispersion with a lower loss, reduced volume and decreased sensitivity to nonlinear effects. So, these are basically you know win-win for from all direction

Fiber Bragg Grating in Optical Communications

Compensation of chromatic dispersion: wideband, tunable

- The dispersion introduced by a grating-based compensator can be approximated by the expression

$$DC = \frac{2n_{\text{eff}}L}{c\Delta\lambda} \cong \frac{10L_{(\text{mm})}}{\Delta\lambda_{(\text{nm})}}\left(\frac{\text{ps}}{\text{nm}}\right)$$

  where L is the grating length and λ is the wavelength variation, both influencing the dispersion characteristic and effective index n_{eff} is of the core mode

- **Effective Use in Transmission Systems:** A grating shorter than 100 mm can effectively compensate for the dispersion of a 100 km long transmission fiber for a single wavelength channel, making it highly efficient for dense wavelength division multiplexing (WDM) systems where multiple gratings are concatenated for different channels.

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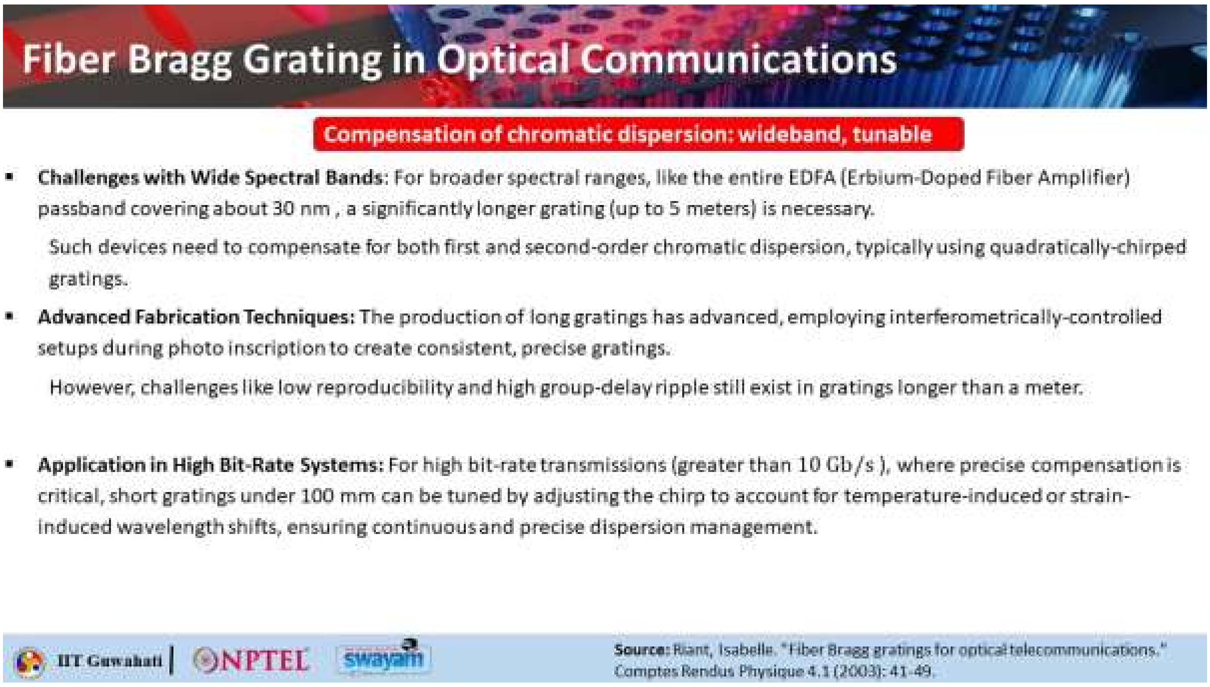
Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

. So, if you look into the equation that dispersion compensation that is introduced by a grating based compensator can be written as 2N effective L divided by C delta lambda.

So, typically it comes out to be you know 10 L in millimeter divided by delta lambda which is in nanometer and this whole thing dispersion compensation as you can see it is picosecond per nanometer. So, what is L here? L is the grating length, L is the wavelength variation both influencing the dispersion characteristic and you can see N effective is basically the effective refractive index of the core mode inside the fiber. So, effective use, so a grating shorter than you know 100 millimeter can effectively compensate for the dispersion that has happened over a 100 kilometer long transmission fiber for a single wavelength channel. So, you can understand previously for every 100 kilometer you have to use 20 kilometer long dispersion compensating fiber, but here you just require a grating which is 100 millimeter.



So, it is like very, very small. So, that is how you can actually use this kind of system for dense WDM system as well where multiple gratings can be needed or concatenated for different channels. Now, there are some challenges with wide spectral bands. So, for broader spectral ranges like the entire EDFA which is the Erbion Doped Fiber Amplifier that covers pass band about 30 nanometer okay. You have to significantly go for, you have to go for a significantly longer grating something like up to 5 meters, okay. And these such devices need to compensate for both first and second order chromatic dispersion and typically they use quadratically chirped gratings.

But still it is fine, it is just 5 meters that you will require, okay. So, the advanced fabrication techniques actually help create these precise gratings which employ interferometrically controlled setups using photo inscription. That is the method of creating the gratings in the fiber core. So, what are the challenges here? The challenges however is the low reproducibility and high group delay ripple that still exist in gratings which are longer than 1 meter. So, these are couple of challenges that are still there and that is why research is still ongoing.

And their application in high data rate system something like greater than 10 Gbps where precise compensation is very critical, short gratings under 100 millimeter can be tuned by adjusting the chip to account for the temperature induced or strain induced wavelength shifts and that will ensure continuous and precise dispersion management throughout the fiber.

Fiber Bragg Grating in Optical Communications

Laser diodes

- **Renewed Interest in IFBGs:** The technique of photo inscribing IFBGs in the pigtail of laser diodes for wavelength selection within the diode's gain bandwidth is gaining renewed interest as a cost-effective solution for WDM sources, as depicted in figure
- **Plug-and-Play Concept:** IFBGs enable a plug-and-play approach where the diode-chip and grating are packaged together.

  Wavelength selection is simplified by switching out the grating, allowing the same laser diode chip to be used across different configurations.

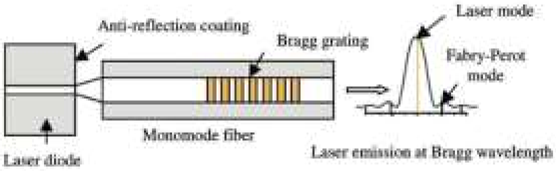


Figure: Laser diode with Bragg grating for wavelength control of the laser emission.

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Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

Let us now look into applications in laser diodes. So, laser diodes with fiber bragg grating for wavelength control of the laser emission can be seen here. And this has brought renewed interest in this in fiber break gratings. So, the technique of photo inscribing of fiber bragg gratings in the pigtail of laser diodes for wavelength selection within the diodes gain bandwidth is gaining much more attention because it is a cost effective solution for WDM sources, okay.

So, here you can see that this is the break grating that is part of this monomode fiber within this laser diode, okay. And this shows the laser mode and these are the Fabry-Perot cavity modes. Right. So they actually have this plug and play concept. So this in fiber break gratings enable plug and play approach where the diode chip and the grating are packaged together.

So wavelength selection is simplified by switching out of the grating, allowing the same diode laser to be used for different configurations. Right. So you can actually using the grating, you can actually change the wavelength that is coming out of your chip. So, these two are anti-reflection coating and this is the break rating

Fiber Bragg Grating in Optical Communications

- **Use of Comb Filters:** Comb filters are particularly interesting for creating multi-wavelength or tunable light sources, as illustrated in figure.

  These filters allow for the precise selection and tuning of multiple wavelengths simultaneously, enhancing the functionality of WDM systems.

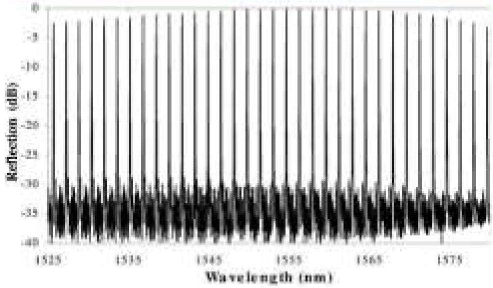

Figure: Spectral response of a "comb" filter with peaks spaced by 200 GHz.

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Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

So, Cobb filters are particularly interesting for creating multi wavelength or tunable light sources as you can see here.

These are spectral response of a comb filter. These are very high reflections. So, here the peaks are basically spaced by 200 gigahertz only. So, these filters allow for precise selection and tuning of multiple wavelengths simultaneously that enhances the functionality of WDM systems. You can also see the application of gratings, fiber break gratings in fiber lasers.

Fiber Bragg Grating in Optical Communications

Fiber lasers

- **Optimal Solution for Fiber Lasers:** Photo-inscription of fiber Bragg gratings is considered the best method for closing the cavity of rare-earth-doped fiber lasers, ensuring efficient and integrated mirror functionality with low loss.
- **Integration and Versatility:** These gratings can be directly written in the doped fiber or in a pigtail fiber that is easily spliced to it.

  This allows for the production of lasers emitting at various wavelengths by selecting appropriate dopant and grating wavelengths, such as 1.5 μm with erbium and 1.3 μm with thulium.

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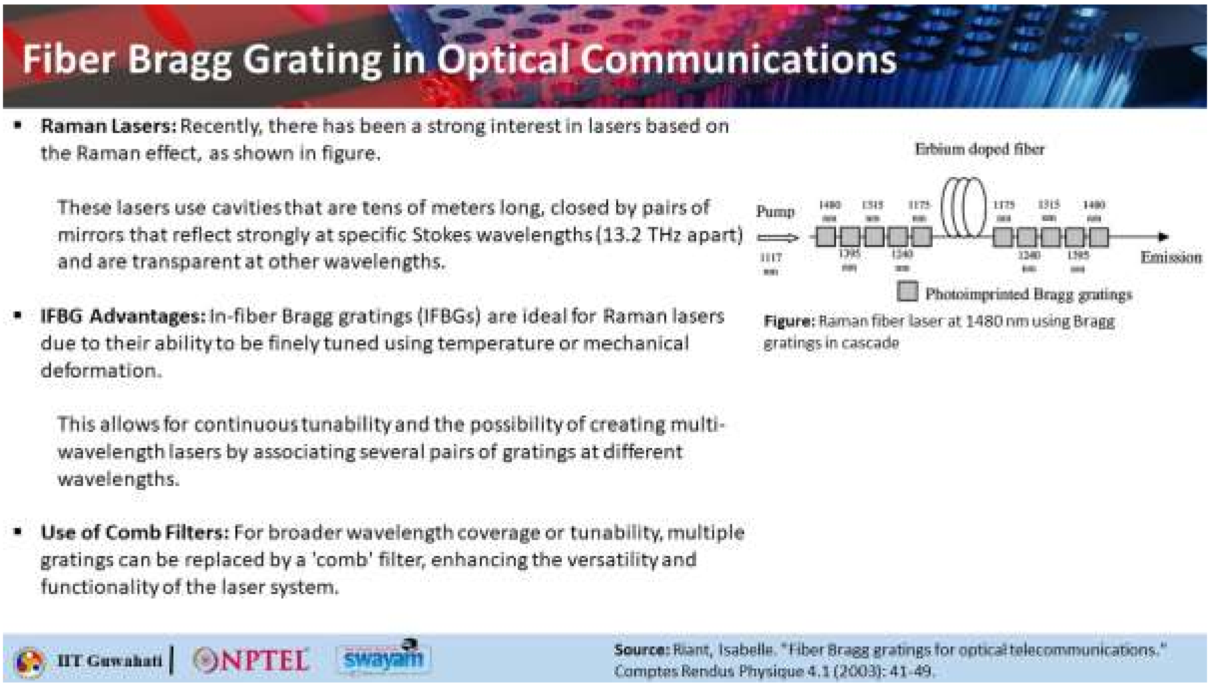
Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

So where they can provide optimal solution. So the photo inscription that we do in fiber bragg grating is considered to be the best method for closing the cavity of rare earth doped fiber lasers that ensures, efficient and integrated mirror functionality with minimal loss. This gratings can be directly written on the doped fiber or in a pigtail fiber that can be spliced to it okay, splice means that can be easily connected to it okay. This allows for the production of lasers emitting at various wavelengths by selecting appropriate dopant and grating wavelength such as you know 1.5 micrometer with erbium and 1.3 micrometer with thulium ok.



You can also see that you know recently there has been a strong interest in the lasers based on the Raman effect as you can see in this figure. So this is the Raman fiber laser operating at 1480 nanometer that uses brake grating in cascade. So you see these are all different you know photo imprinted brake grating and this is an RBM doped fiber. So this laser actually uses the cavities that are tens of meters long and closed by pairs of mirrors. So, the mirrors are basically the Bragg mirrors here that reflect strongly at specific Stokes wavelength which are 13.2 terahertz apart and they are basically transparent to all other wavelength. So, what is the advantage of using in fiber break grating here? So, this gratings are ideal for fiber lasers due to their ability to be finely tuned using temperature or mechanical deformation. So, that can give you this kind of you know fine strokes wavelength alignment to give you the Raman laser. So, this allows for continuous tunability and possibility of creating multi-wavelength lasers by associating several pairs of gratings as you can see at different wavelengths. You can also use them as comb filters for broader wavelength coverage or tunability. Multiple gratings can be replaced by a comb filter that enhances the versatility and the functionality of the laser system.

Fiber Bragg Grating in Optical Communications

Amplifiers

- **Gain Flattening in EDFAs:** IFBGs are crucial for gain flattening in EDFAs, which is essential for Wavelength Division Multiplexing (WDM) systems.

  The insertion of an optical filter, whose spectrum matches the inverse of the EDFA gain ripple, is currently the unique solution for this application.

- **Customization and Implementation:** IFBGs can be seamlessly spliced to the erbium-doped fiber and customized to match any specific gain-ripple characteristics, enhancing system efficiency and adaptability.

- **Challenges and Solutions:** Standard short-period gratings used for gain equalization must often be paired with an isolator to suppress back-reflection into the amplifier.

  Alternative gratings, like slanted short-period gratings and long-period gratings, can help overcome these back-reflection issues.

Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

You can also use fiber break grating as amplifiers or sorry in amplifiers and where they are used they are basically used for gain flattening in EDFAs. As I mentioned that you know the gain spectrum will have ripples and you can use this in fiber break gratings to cancel out those ripples and that flat gain pattern will be very useful for WDM system. So, insertion of an optical filter whose spectrum basically matches the inverse of the EDFA gain ripple will be able to cancel out and this unique solution has got this application of gain flattening. And as you understood that, you know, in fiber break ratings can be seamlessly spliced to the Erbium doped fiber and customized to match any specific gain ripple characteristics that basically enhances the system efficiency and adaptability. So, there is a lot of scope of customization and thus it has got more implementation.

Fiber Bragg Grating in Optical Communications

- **Advanced Grating Designs:** Slanted short-period gratings have been developed to create smooth envelopes in the coupling into cladding modes.

  These are designed to produce minimal back-reflection and tailored spectral responses for optimal gain flattening across a wide bandwidth.

- **Long-Period Gratings:** Offer negligible back-reflection and the ability to tailor spectral shapes through adjustments in the grating index profile and modulation.

  Their sensitivity to environmental changes can be utilized to dynamically adjust the filter's spectral shape, making them valuable as dynamic gain equalizers in advanced optical systems.

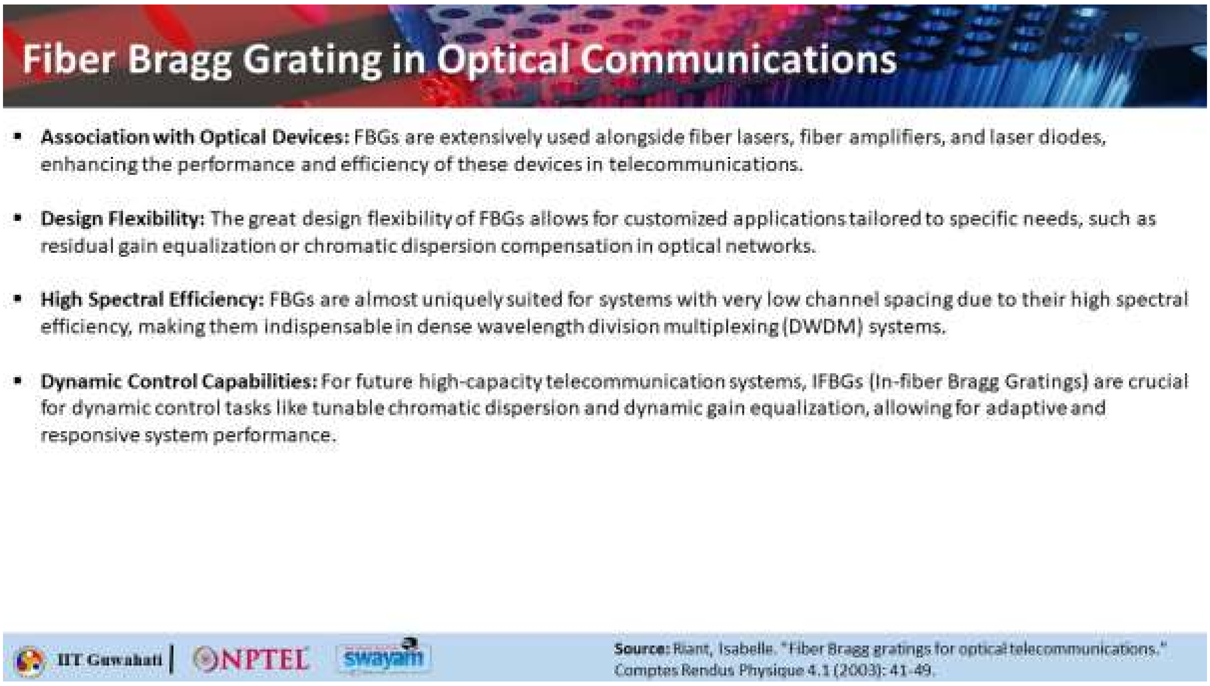
- **Innovative Adjustments:** Long-period gratings' sensitivity to the surrounding medium's refractive index can be exploited by using an external command, such as electromagnetic adjustments, to modify the filter spectral shape for precise control over the system's performance.

Source: Riant, Isabelle. "Fiber Bragg gratings for optical telecommunications." Comptes Rendus Physique 4.1 (2003): 41-49.

What are the challenges? The standard short period grating used for gain equalization must often be paired with an isolator. So, that will basically needed to suppress the back reflection into the amplifier. And alternative gratings such as slanted or blazed shortwave gratings and long period gratings can help overcome this kind of back reflection that may go into the amplifier. So you need an isolator in this case, but if you use this kind of slanted gratings, you can get rid of the isolator requirement. The slanted short period gratings have been developed to create smooth envelopes in the coupling into cladding modes.

So, these are the advanced gratings that people are designing because they are designed to produce minimal back reflection and tailored spectral response for optimal gain flattening. across a wide bandwidth, okay. So, here the getting the reflection is not the main purpose, here the gratings main job is to cancel out the ripples in the gain spectrum and that is why you know this kind of in fiber break gratings are very much in demand. If you think about the long period gratings, they also offer negligible back reflection and they have the ability to tailor spectral shapes within the adjustment in the grating index profile and modulation. Their sensitivity to the environmental changes can be thus utilized to dynamically adjust the filter's spectral shape, making them valuable as dynamic gain equalizers in advanced optical systems.

Long period grating sensitivity to the surrounding media mediums refractive index can also be exploited by using external command some such as electromagnetic adjustments to filter to modify the filter spectral response for precise control over the systems performance. And what is the association with optical devices? So, you can see that fiber bragg gratings are extensively used alongside fiber lasers, fiber amplifiers and laser diodes for enhancing their performance and efficiency okay in telecommunication systems. So, they are very much easy to associate with that traditional optical devices. And the great design flexibility of this fiber bragg gratings allows for customized application which can be tailored for specific needs something like residual gain equalization or chromatic dispersion compensation in optical networks of today. They also offer high spectral efficiency because these FBGs are almost uniquely suited for systems with the very low channel spacing due to their high spectral efficiency because the channels are very close to each other.



So you are using almost the entire spectrum very efficiently. So making, you know, you know, Because FBGs are very useful in this kind of low spacing scenarios, so they are indispensable in dense WDM systems. For future, high-capacity telecommunication systems in fiber bragg ratings are crucial for dynamic control tasks like, tunable chromatic dispersion and dynamic gain equalization that allows for adaptive and responsive system performance

Temperature sensors

Sensor construction

- **Optical Source to Transducer Connection:** The sensor architecture includes an optical source that sends light through a fiber optic cable to a transducer, which is the sensitive optical element responding to external changes.
- **Signal Conversion and Processing:** Variations in the measurand cause the transducer to modify the characteristics of the initial optical signal.

  This modified signal is detected by a sensor, processed by actuation circuitry, which compares it to the reference signal to derive information about the measurand.

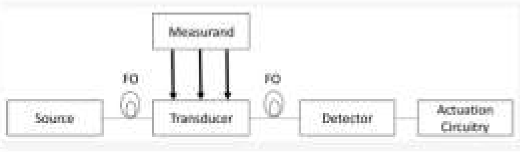
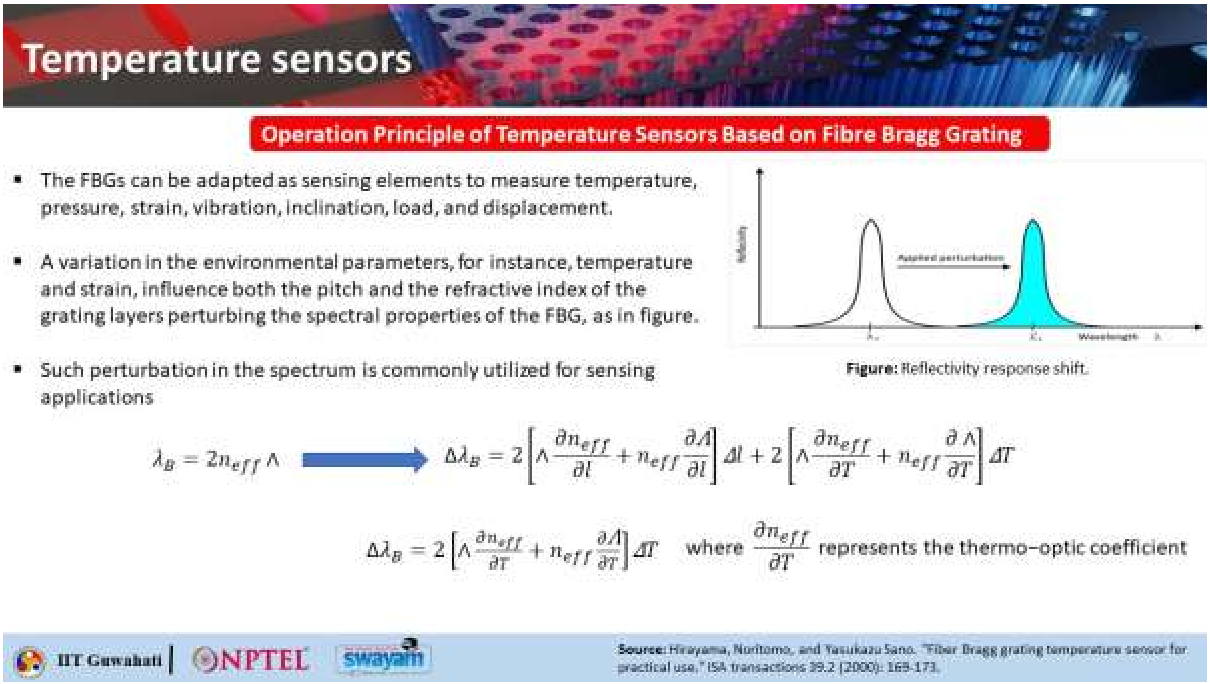


Figure: Fiber optic sensor simplified architecture.

Source: Hirayama, Noritomo, and Yasukazu Sano. "Fiber Bragg grating temperature sensor for practical use." ISA transactions 39.2 (2000): 169-173.

Now we will look into the application of fiber break ratings as sensors.

The first one is the temperature sensor. So, here is the sensor construction. So, optical source to transducer connection. So you can see the sensor architecture includes an optical source that basically sends light through a fiber optic cable to the transducer, which is sensitive to the optical element that responds to the external changes. So there will be some detector that detects that change in the optical signal and then you have an actuation circuitry that generates the reading. So, the variation in the measurand cause the transducer to modify the characteristics of the initial optical signal and this modified signal is basically picked up by the detector processed by the actuation circuitry that which compares with the reference signal to find out how much is the actual measure end that has created this shift in the optical signal



So how it works you can see that you know the fiber break gratings can be adapted as sensing element to measure temperature, pressure, strain, vibration, inclination, load and displacement.

And what happens the break grating reflection under the perturbation of any of this will shift the reflection wavelength. okay and you have to measure the reflectivity response shift and that needs to be calibrated with the shift in the you know physical parameter that has changed the property of the grating. So, as I mentioned a variation in the environmental parameter for instance temperature and strain will influence both the pitch that is the periodicity and the refractive index of the grating layers and it will perturb the spectral property as you can see here. So, such perturbation in the spectrum is commonly utilized for sensing applications where lambda b if you remember it is written as 2 ineffective lambda. So, now you will have a change in this lambda b so that you can actually obtain as a function of change in this effective refractive index due to change in length that will be covering the strain and also the change with temperature.

So, the first term here tells you about the effect of strain and the second term here tells you about the effect of change in temperature delta T. So, if you only consider the temperature dependence of the brake wavelength, so this is it. So, only the second term tells you about the temperature dependence. So, here you can see doh n effective by doh t that is basically the thermo optic coefficient. So FBG technology is promising for future sensor applications by detecting shift in Bragg wavelength to measure temperatures and strain effects inside the fiber core.

Temperature sensors

Introduction

- **Measurement Concept:** FBG technology is promising for future sensor applications by detecting shifts in Bragg wavelength to measure temperature and strain effects on the fiber core.
- **First Applications:** Initial applications of FBG technology are primarily in temperature and strain sensing, with ongoing research enhancing their practicality and effectiveness.
- **Distributed Measurements:** FBG sensors facilitate distributed measurements through wavelength division multiplexing, making them ideal for large-scale monitoring across various environments.
- **Suitability in Challenging Environments:** Due to their immunity to electromagnetic interference and explosion-proof characteristics, FBG sensors are particularly suited for use in petrochemical plants and power electronics, as well as in traditional process applications where they can replace conventional sensors like thermocouples.
- **Application in temperature Sensing:** The sensitivity of FBGs to temperature changes makes them ideal for use in precise temperature sensing across various applications, leveraging their unique properties for environmental monitoring.

Source: Hirayama, Noritomo, and Yasukazu Sano. "Fiber Bragg grating temperature sensor for practical use." ISA transactions 39.2 (2000): 169-173.

So initial application of this technology is in mainly measuring temperature and strain sensing and they are very much you know giving practical solutions and very effective. So, they are also used in field applications and these FBG sensors they also facilitate distributed measurements through wavelength division multiplexing. So, that allows them for you know large scale monitoring across various environment. So, it makes you it makes it easy for you to cover a large area and then do a lot of monitoring using this kind of sensors. Now, why they are suitable in challenging environment? Due to their immunity to electromagnetic interference and explosion proof characteristics because of the fiber optic cables jacket layer.

Temperature sensors

Design concept

- **Distributed Sensor System Configuration:** As shown in Figure, the system utilizes wavelength division multiplexing (WDM) which enhances the capability to measure distributed signals effectively.
- **Sensor Type Requirement:** The system requires a "pass-through" sensor type to fully utilize the distributed measurement capabilities inherent to FBG sensors.
- **Housing Design for FBG Temperature Sensor:** The housing of the FBG temperature sensor is designed to match that of conventional electrical temperature sensors, facilitating ease of installation and maintenance with existing methods.

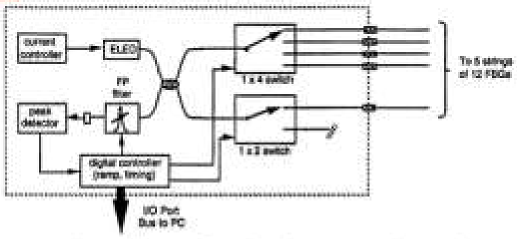


Figure: Schematic diagram of 60-channel FBG sensor electro-optics system

Source: Hirayama, Noritomo, and Yasukazu Sano. "Fiber Bragg grating temperature sensor for practical use." ISA transactions 39.2 (2000): 169-173.

Temperature sensors

Sensor construction

- **Sensor Configuration:** As illustrated in figure, the pass-through type FBG temperature sensor is embedded within the standard thermocouple housing.
- **Fiber Embedment:** The fiber is embedded by creating a U-turn with a small radius, which is then spliced to the FBG to ensure compact and efficient design.
- **High-Temperature Operation:** Polyimide is used as the coating for both the FBG and fiber to enhance the operating temperature range up to 250°C.

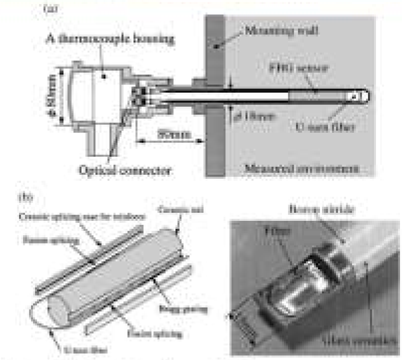
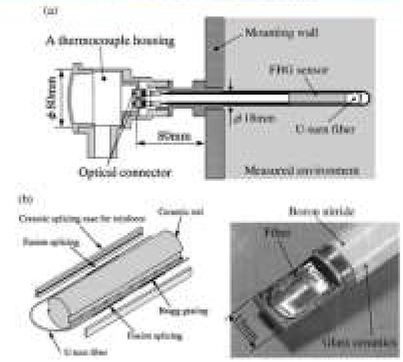


Figure: (a) Pass-through type FBG temperature sensor embedded in thermocouple housing; (b) detailed construction of the top of the sheath.

Temperature sensors

- **Durable Assembly:** The splicing section between the FBG and U-turn fiber is bonded to a ceramic case using polyimide adhesive and secured to a ceramic rod, ensuring stability and high temperature resilience.
- **Materials for Thermal Management:** Glass ceramic, matching the thermal expansion coefficient of fused silica, is used for the ceramic case, and boron nitride, known for its high thermal conductivity and machinability, is selected for the ceramic rod.



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Source: Hirayama, Noritomo, and Yasukazu Sano. "Fiber Bragg grating temperature sensor for practical use." ISA transactions 39.2 (2000): 169-173.

So, this kind of sensors are basically suited for petrochemical plants, power electronics, where the traditional or conventional sensors like thermocouples can be easily replaced. The sensitivity of this fiber break rating to temperature changes also make them ideal for precise temperature monitoring, something like environmental monitoring applications and so on. They are also very effective as strain sensor.

Strain sensors

- **Definition and Components of Strain:** Strain is described through a tensor that includes normal and shear components. The normal component accounts for stretching or compression along a material's line elements, while the shear component involves the sliding of layers within the material.
- **Types of Normal Strain:**
  Tensile Strain: Occurs when the length of a body increases.
  Compressive Strain: Occurs when the length of a body decreases.
- **Engineering Strain Formula:** Engineering strain, also known as nominal strain, is expressed as the ratio of total deformation to the initial state, calculated by the formula $\epsilon = \frac{\Delta L}{L}$, where ΔL is the change in length.
- **Fiber-Optic Strain Measurement:** In fiber-optics, strain is measured by the ratio of the total wavelength shift $\Delta\lambda$ to the initial wavelength λ, linked through the photo-elastic coefficient which, for a typical single-mode fiber like SMF28, follows the relation $\Delta\lambda/\lambda = 0.79\Delta L/L$.

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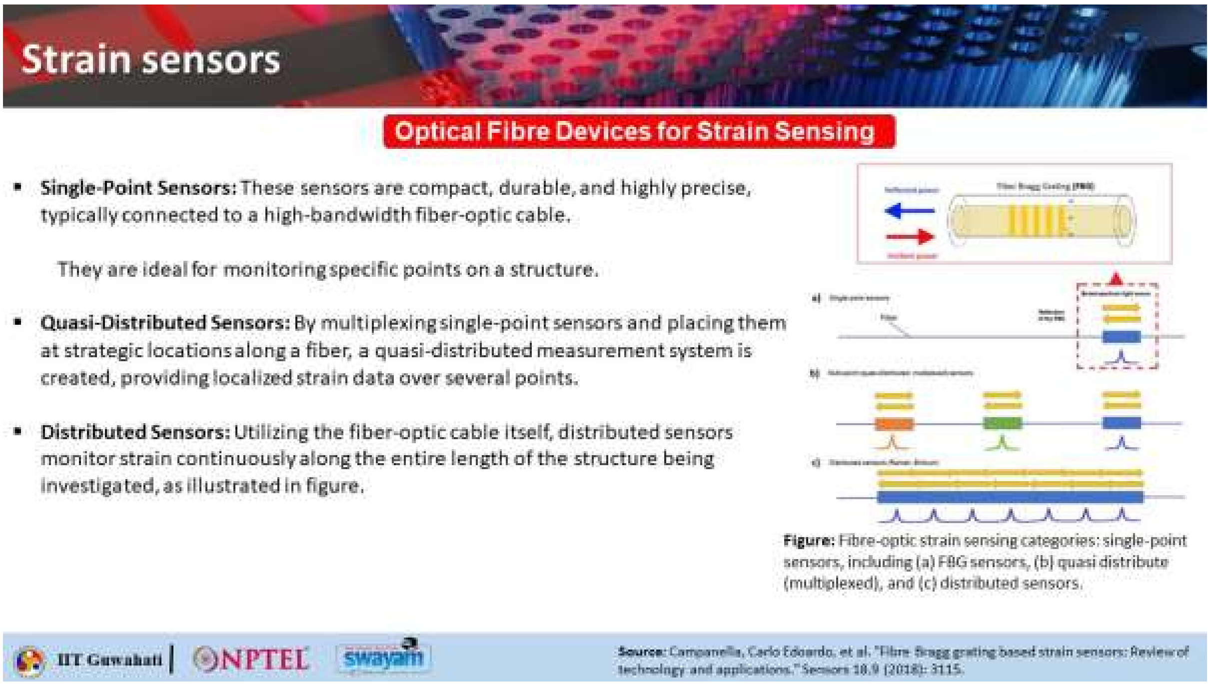
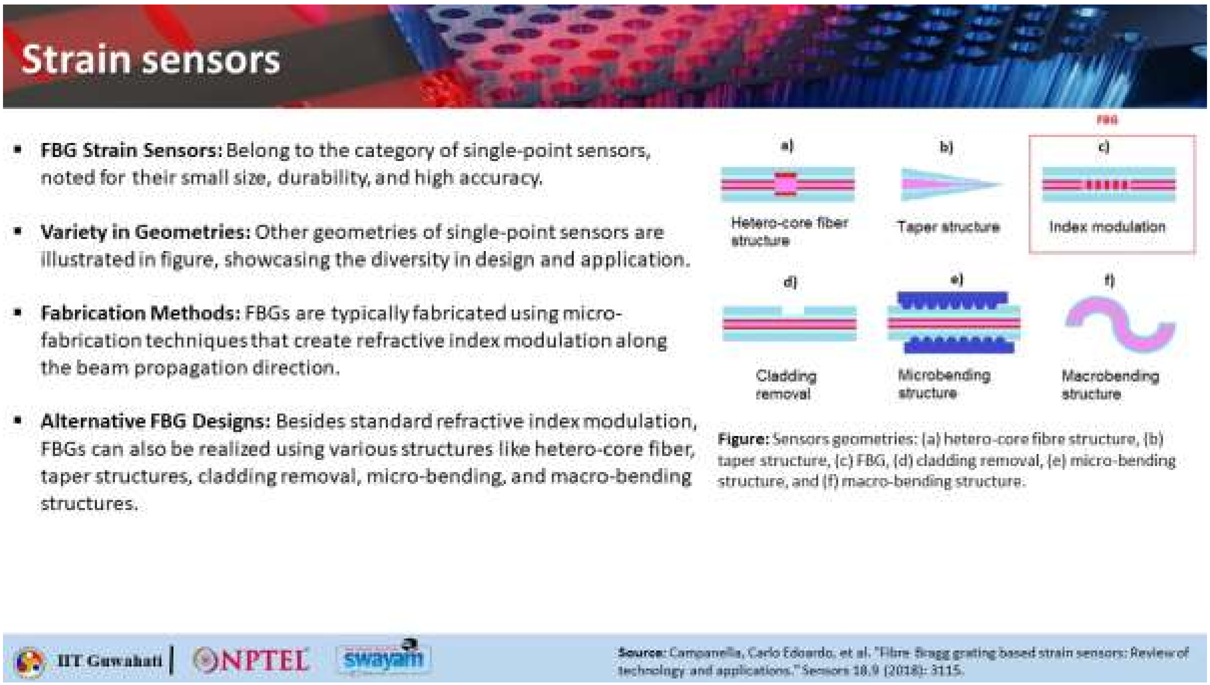
Source: Campanella, Carlo Edoardo, et al. "Fibre Bragg grating based strain sensors: Review of technology and applications." Sensors 18.9 (2018): 3115.

So, strain is described to a tensor that involves normal and shear components. The normal component typically accounts for stretching or compression along a materials line elements where the shear component basically involves you know sliding of the layers within the material.

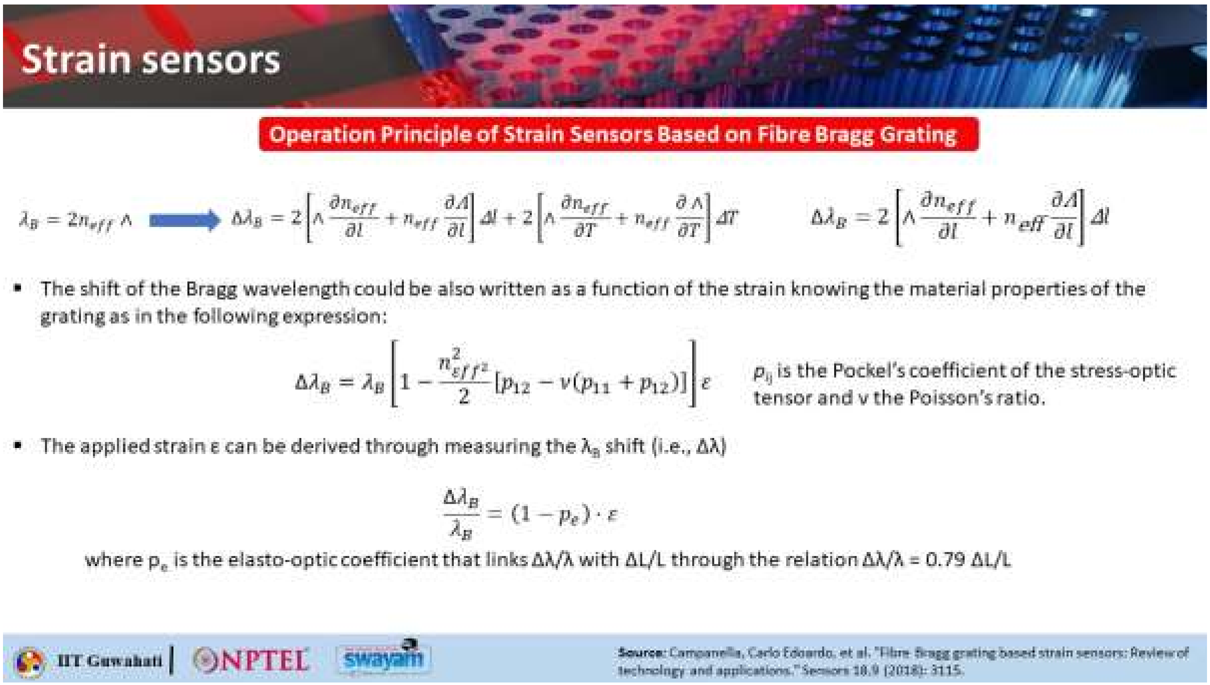
Now based on that the types of normal strain would be tensile strain. So that basically occurs when the length of a body increases and compressive strain occurs when there is compression or the length of the body decreases. Now the engineering strain which is also known as nominal strain can be expressed as the ratio of the total deformation to the initial state that is epsilon can be written as delta L over L. So delta L is basically the change in length. Now fibre optic strain measurement how you do it in fiber optics strain is also measured as the ratio of total wavelength shift divided by the initial wavelength and you link it to the photoelastic coefficient for a single mode fiber and there the relationship will be like this delta lambda by lambda equals 0.79 delta L by L. So, you can actually directly correlate the strain with change in the wavelength. So, that is how you do the measurement. So, here you can see single point sensors. So, these are basically you know sensors are compact, durable and highly precise and they are typically connected to a high bandwidth optical fiber cable. They are ideal for monitoring of a specific point on a structure.



You can also have quasi-distributed like this. So by multiplexing single-point sensors and placing them at different strategic location along the fiber, you can actually build a quasi-distributed measurement system. So, it is basically giving you localized strain data over several points. And then you can also make fiber optic cable itself as a distributed sensor that makes continuous measurement across the entire length of the structure as you can see in this particular figure. So, this is single point sensor, this is quasi-distributed sensors and this is distributed sensors. So, the fibre breaking strain sensors they belong to the category as we mentioned of single point sensors and noted for their small size, durability, and high accuracy.



There are different geometries which are typically used for single point sensors. As you can see, the first one is hetero core fiber structure, taper structure, FBGs, then you can also have through cladding removal, micro banding or macro banding. So, FBGs are typically fabricated using microfabrication techniques that are able to create refractive index modulation along the beam propagation direction. So, other types of this is so this is standard refractive index modulation. So, other than that FBGs can also be realized using various structures as I mentioned here, this hetero core fiber, then taper kind of structure, cladding removal and micro and macro bendings.



So again here you can see that this is the Bragg wavelength, this is the Bragg condition. So if you consider the change in the Bragg wavelength you will see the first term actually tells you about the strain sensor, okay. So this actually gives you the change in the Bragg wavelength due to strain, okay. So you can actually calculate delta lambda that is you know the shift in Bragg wavelength as a function of the material property. So, you can put in pij which is basically the Pockels coefficient that is coming from the stress optic sensors and nu here is the Poisson ratio of that particular material.

So, the applied strain epsilon can be derived through measuring delta lambda b, okay. So, final expression can be written as delta lambda b over lambda b is 1 minus pe times epsilon okay. So, here P is basically the elasto optic coefficient and that links your delta lambda by lambda with delta L by L and the relationship for that single mode fiber is typically like this. It is delta lambda by lambda equals 0.79 delta L by L right. So, that is how you can actually measured strain. So, one important thing to note here is that you have this term dou n effective by dou L that is basically the variation of the effective refractive index which is induced because of the strain, okay. And what is this one? Doh capital gamma by Doyle that is basically the change in the pitch of your grating because of the strain. So, all these things actually give you this change in the bright reflection

So that is all for this lecture on applications of fiber break rating. So if you have got any doubt regarding this lecture, you can drop an email to this particular email address mentioning MOOC, photonic crystal and the lecture number on the subject. Thank you.