

Module 18 : Fiber Bragg Grating Based Devices

Lecture : Fiber Bragg Grating Based Devices

Objectives

In this lecture you will learn the following

- Principle
 - Frequency Response of a Uniform FBG
 - Non-Uniform Fiber Bragg Grating
 - Narrow Band Filter
 - Add-Drop Multiplexer
 - Dispersion Compensator
 - Gain Equalizer
 - Mode Converter
 - Sensor
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- In recent years fiber Bragg grating based have become popular due their extremely stable characteristics.
- The Fiber Bragg Grating (FBG) is a periodic structure fabricated inside the core of the
- optical fiber. The periodicity could be mechanical like variation of the core diameter or it could be electrical like variation of the refractive index of the core.
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- In the periodic structure like the FBG the coupling of energy between different co-propagating and counter-propagating modes of the fiber takes place. The mode coupling phenomenon is a strong function of wavelength.

- In FBG two identical counter propagating modes get coupled and the energy is transferred from the forward traveling to the backward traveling mode. Consequently we get reflection of the modal energy which is wavelength dependent. The FBG therefore reflects certain wavelengths keeping propagation of other wavelengths practically un-affected.

- The FBGs find applications in variety of devices.

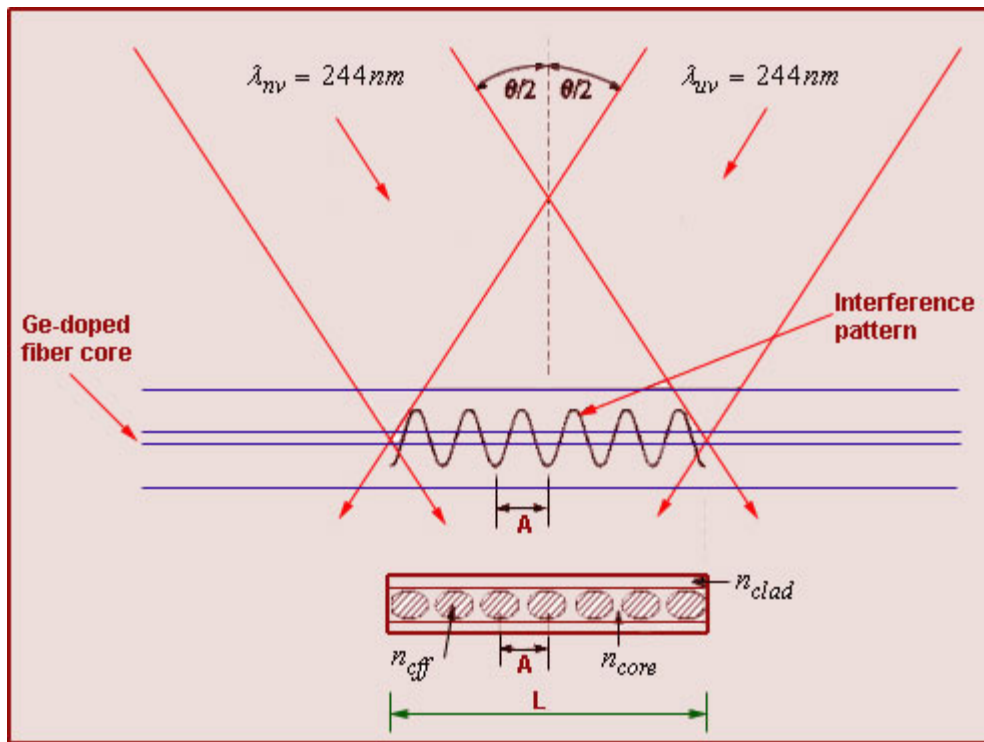
- Applications of Fiber Bragg Grating

- (1) Narrow band filtering
- (2) WDM Add/Drop Mux/DeMux
- (3) Dispersion compensation
- (4) Gain Equilization
- (5) Fiber laser
- (6) Raman Amplifier
- (7) Phase conjugator
- (8) Wavelength converter
- (9) Mode converter

Principle

- The Fig Shows the basic FBG fabrication process.
- If a hydrogen loaded fiber core is exposed to intense ultra violet beam, the refractive index of the fiber gets modified permanently.

- Now, making two coherent ultra violet beams interfere on the core of the fiber, the fiber is exposed to periodic ultra violet intensity variation. This then causes a permanent periodic variation of the refractive index of the core.



- The peak change in refractive index is of the order of 10^{-3} to 10^{-4} .
- The mode coupling phenomenon is weak and one needs a substantial length of the FBG to achieve good reflection of the signal. The size of the FBG is typically a few thousand wavelengths.
- According to the **mode coupling phenomenon**, the two modes show strong coupling if they satisfy the Bragg condition

$$\beta_1 - \beta_2 = 2m\pi / \Lambda$$

Where, β_1 and β_2 are the phase constants of the two modes, Λ is the period of the variation of the refractive index (it is assumed that the variation is sinusoidal), and m is an integer which defines the order of diffraction. For first order, $m = 1$.

- Now if we take two identical counter-propagating modes,

$$\beta_2 = -\beta_1$$

And the Bragg diffraction condition becomes

$$2\beta_1 = 2m\pi / \Lambda$$

- Now if the effective modal index is n_{eff} , where λ is the wavelength of the

$$n_{eff} \beta_1 = 2\pi n_{eff} / \lambda$$

signal. The Bragg condition then gives the wavelength called the Bragg wavelength λ_B which is strongly reflected by the grating as

$$\lambda_B = 2 n_{eff} \Lambda$$

- The important this to note here is that the period of the refractive index variation is of the order of the wavelength to be reflected. In optical communication since the wavelengths lie in the range of 1-2 μm , the grating period has to be of the order of 2-4 μm .
- The fabrication of FBG therefore is little difficult, however once the grating is made, it offers very stable performance.

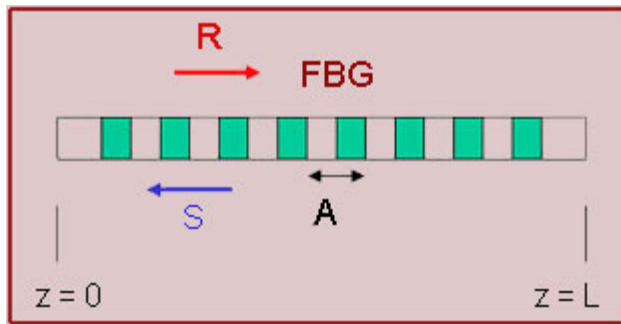
Frequency Response of a Uniform

FBG

- The Fiber Bragg gratings are analyzed using coupled mode theory. The formulation is very similar to that of a directional coupler discussed in the integrated optics section.

A schematic of a uniform FBG is shown in Fig. Here uniform FBG means, it has constant

- period and constant peak amplitude of the refractive index variation through out the length of the FBG.



Let the FBG has a spatial period Λ and length L . Let there be two identical modes

- propagating in opposite directions. Let R denote the amplitude of the forward mode and S denote the amplitude of the backward mode.

As given above, a wavelength is strongly reflected if it satisfies the Bragg condition.

- However, here we would like to see what is the frequency response of the FBG, that is how the reflectivity changes as a function of the wavelength around the Bragg wavelength.

- Let the refractive index of the FBG be given as

$$n(z) = \bar{n} \cos\left(\frac{2\pi z}{\Lambda}\right)$$

Where δn is the peak change in refractive index.

- The amplitudes of the forward and backward waves are governed by the following coupled differential equations.

$$\begin{aligned}\frac{dR}{dz} + j\sigma R &= -j\kappa S \\ \frac{dS}{dz} - j\sigma S &= -j\kappa R\end{aligned}$$

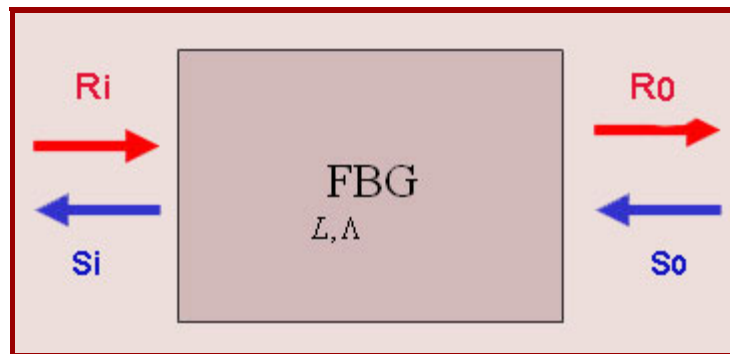
Where we have defined

$$\text{DC coupling coefficient : } \sigma = \frac{2\pi \delta n}{\lambda_B} + \delta$$

$$\text{AC coupling coefficient : } \kappa = \frac{\pi \delta n}{\lambda}$$

$$\text{Tuning parameter : } \delta = \frac{2\pi}{\lambda} - \frac{2\pi}{\lambda_B}$$

- Let us now consider the FBG as a 4-port device as shown in Fig.



- The solution of the coupled equation can be written as

$$\begin{bmatrix} R_o \\ S_o \end{bmatrix} = \begin{bmatrix} A & jB \\ jB & A^* \end{bmatrix} \begin{bmatrix} R_i \\ S_i \end{bmatrix}$$

Where

$$A = \cosh \alpha L + j(\sigma / \alpha) \sinh \alpha L$$

$$B = -(\kappa / \alpha) \sinh \alpha L$$

$$\alpha \equiv \sqrt{(\kappa^2 - \sigma^2)}$$

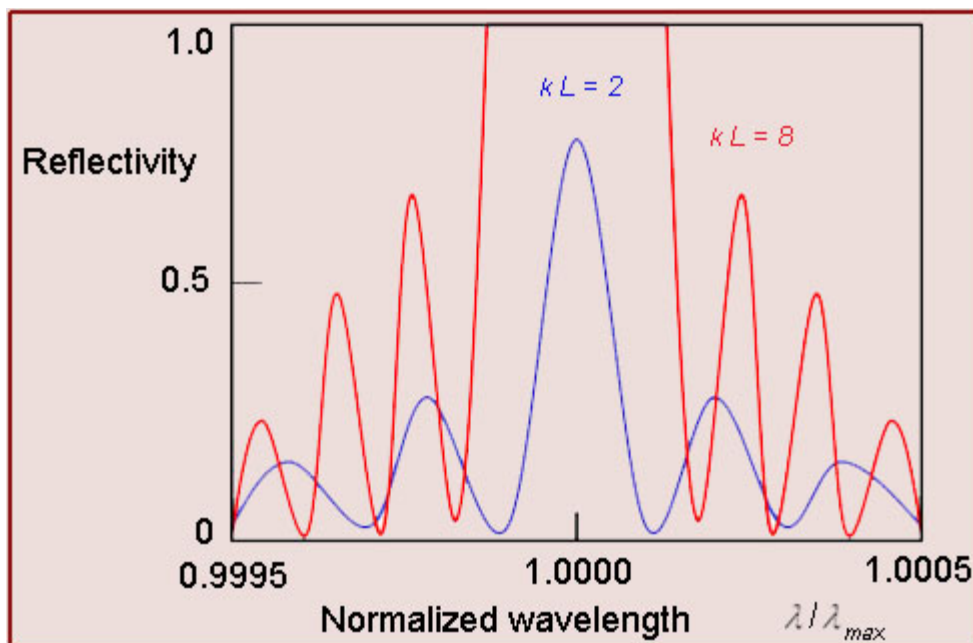
- The matrix representation would come handy when we investigate the non-uniform FBGs.
- The Amplitude reflection coefficient of the FBG then can be obtained by making $S_o = 0$ as

$$\rho = \frac{S_i}{R_i} = \frac{-jB}{A^*} = -\frac{\kappa \sinh \alpha L}{\sigma \sinh \alpha L + j\alpha \cosh \alpha L}$$

Frequency Response of a Uniform

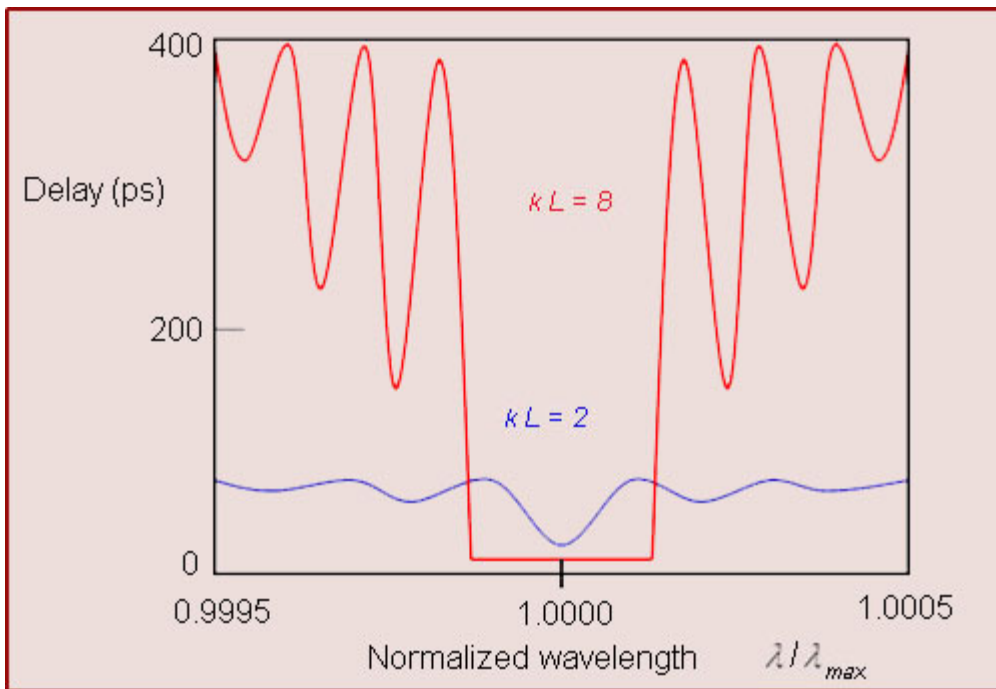
FBG (contd.)

- The plot of reflection coefficient and delay as a function of wavelength are shown in Figs.



- Following things can be noted from the amplitude and delay plots.

- (1) The fractional bandwidth of the FBG is extremely narrow (of the order of 0.01%). That means the FBG is an extremely tuned wavelength filter. At 1550nm wavelength we can achieve a bandwidth as narrow as 0.2-0.3nm.
- (2) For low value of κL the reflectivity is less than 1 but as κL increases, the reflectivity saturates to 1, and the bandwidth of the FBG increases. So by using FBG of proper parameters a perfect reflection of the signal can be obtained from an FBG.
- (3) In the pass band the delay is small and constant. Whereas on the edge of the pass band the delay rapidly increases as a function of wavelength, making the FBG dispersive.
- (4) The frequency response has rather high side lobes.



Non-Uniform Fiber Bragg Grating

- The problems associated with the frequency response of an uniform FBG, like the high side lobe can be overcome by apodizing the refractive index profile of the FBG. Also by using the complex refractive index profile the frequency response can be tailored to meet the desired requirements
- For a non-uniform grating, the spatial refractive profile can be written as

$$n(z) = \delta n(z) \left\{ 1 + \nu \cos \left(\frac{2\pi z}{\Lambda} + \phi(z) \right) \right\}$$

Here ν is called the visibility of the FBG and its value lies between 0 and 1, $\phi(z)$ is the spatial chirp of the FBG, and $\delta n(z)$ is a slowly varying function of z .

- The DC coupling coefficient becomes

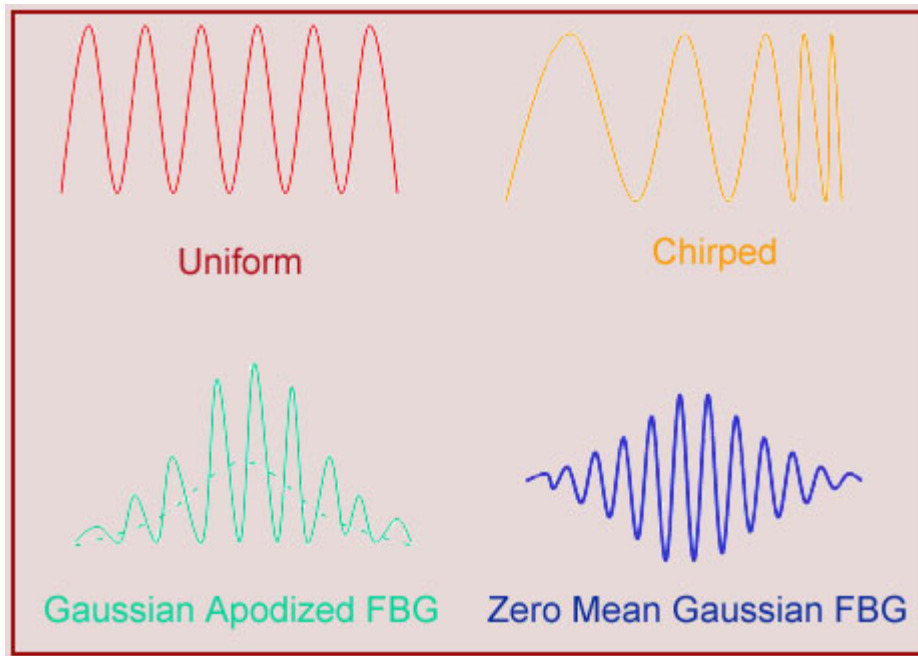
$$\sigma = \frac{2\pi \delta n(z)}{\lambda_B} + \delta - \frac{1}{2} \frac{d\phi}{dz}$$

And the AC coupling coefficient becomes

$$\kappa = \frac{\pi \delta n(z)}{\lambda}$$

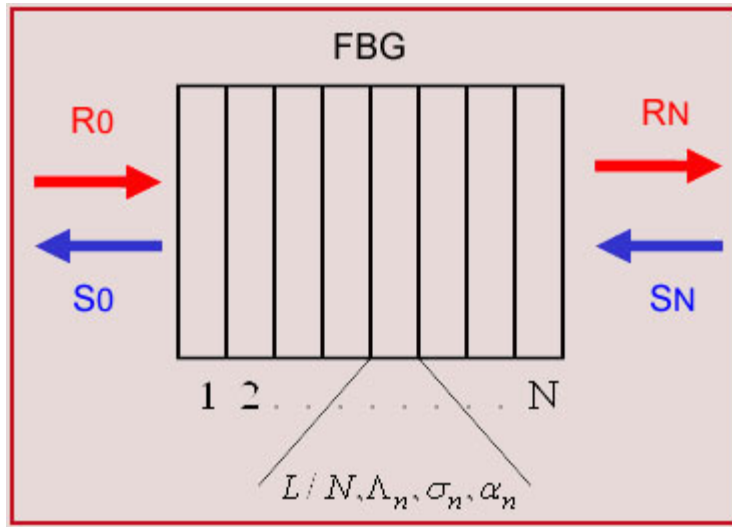
- Both DC and AC coupling coefficients are function of z in this case.

- By varying, the three parameters $\delta n(z)$, $\phi(z)$, ν , various types of gratings can be realized.
- Figure shows refractive index variation for various types of apodized gratings used in practice.



Non-Uniform Fiber Bragg Grating(contd.)

- A non-uniform FBG is analyzed by dividing the FBG into small sections. It is then assumed that over the small section the FBG parameters are constant. That is the a non-uniform grating is approximated by a piece-wise uniform grating.
- Let the FBG be divided in N-sections as shown in Fig.



- The forward and backward signals at the Nth section are written as

$$\begin{bmatrix} R_N \\ S_N \end{bmatrix} = T_N T_{N-1} \dots T_2 T_1 \begin{bmatrix} R_0 \\ S_0 \end{bmatrix}$$

$$T_n = \begin{bmatrix} A_n & jB_n \\ jB_n & A_n^* \end{bmatrix}$$

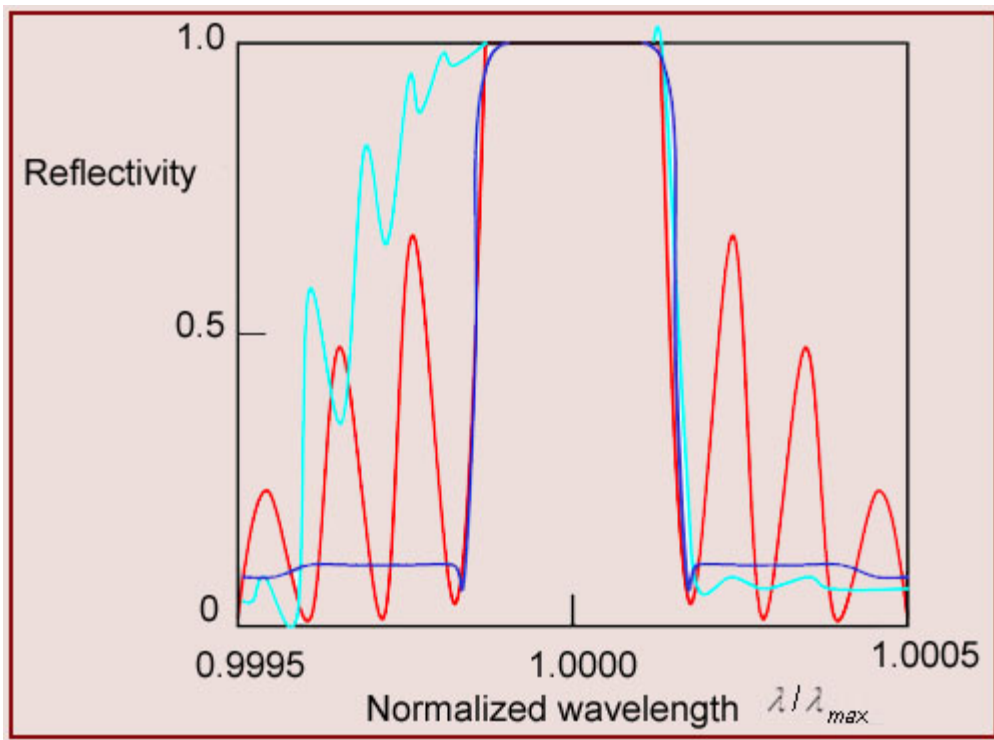
- And for nth section we have

$$A_n = \cosh(\alpha_n L/N) + j(\sigma_n / \alpha_n) \sinh(\alpha_n L/N)$$

$$B_n = -(\kappa_n / \alpha_n) \sinh(\alpha_n L/N)$$

$$\alpha_n \equiv \sqrt{(\kappa_n^2 - \sigma_n^2)}$$

- For a good convergence the FBG has to be divided into few hundred sections.
- Figure shows the frequency response of three FBGs, namely Uniform, Gaussian Apodized, and Zero-Mean Gaussian.



- As can be seen the zero-mean Gaussian FBG has good roll-off and very low side lobes. In practice therefore the apodized FBGs are more useful.
- The Gaussian apodized gratings show much higher delay compared to the uniform grating.
- The chirped gratings have very large dispersion.
- With today's technology gratings can be fabricated with a very high precision and their characteristics can be reproduced to a high accuracy.
- The FBG based devices have gained popularity in modern optical communication systems, especially the DWDM systems. Some of the applications are explained in the following.

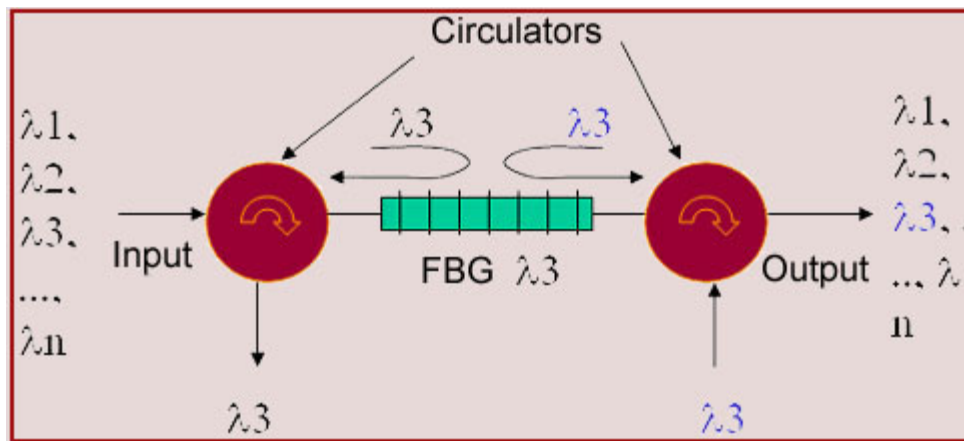
Narrow Band Filter

- Since the frequency response of the FBG has a very narrow pass band, it can be used as a narrow band filter. As mentioned earlier, at 1550nm wavelength a band width as narrow as 0.2-0.3nm can be achieved very easily.

- If a broad band or multi-wavelength signal is fed to the FBG, selectively a wavelength is reflected back without affecting the propagation of other wavelengths.

Add-Drop Multiplexer

- In a DWDM network wavelengths are used for labeling the packets. Also the network nodes are addressed by specific wavelengths. A particular node transmits and receives a particular wavelength assigned to it.
- The node needs a device which facilitates it to drop the signals at a particular wavelength and at the same time allows it to add the signals at that wavelength.
- The device is called the add-drop multiplexer (ADM).
- FBG can be used for realizing an ADM. An FBG based ADM consists of two optical circulators and a FBG as shown in Fig.



- The circulator has a property that signals can flow in one direction. The direction is indicated by an arrow. In the figure, the signals can propagate in clockwise direction only.
- The input signal gets connected to the FBG but the reflected signal from FBG is diverted to the lower port and not the input.
- Since the FBG has reflecting wavelength λ_3 , all wavelengths pass through the FBG except λ_3 . The wavelength λ_3 is dropped at the input circulator.

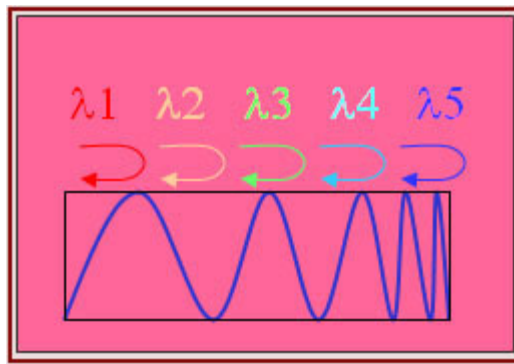
- The signal at the output of the FBG are devoid of λ_3 . However, if a new signal λ_3 is fed at the input of the output circulator, the signal gets connected to the FBG and gets reflected towards the output. It then gets combined with the incoming signals which are devoid of λ_3 .
- All signals are then connected to the output through the circulator. The output therefore has again all the wavelengths with old λ_3 replaced by new λ_3 .
- Instead of single FBG, if multiple FBGs of different wavelengths are placed between the circulators, multiple wavelengths would be dropped and added by the device.
- The ADM can also be used as wavelength router.

Dispersion Compensator

- In 1550nm window, the pulse broadening due to dispersion takes place because the shorter wavelengths travel faster and the longer wavelengths travel slower.
 - If a device can delay the shorter wavelengths compared to the longer wavelengths, dispersion compensation can be achieved.
 - In principle this can be done by the chirped FBG.
- Inside the chirped FBG different wavelengths get reflected from different location on the
- FBG. The wavelength is reflected when it is approximately equal to the Bragg wavelength. Since on a chirped FBG the spatial period Λ and consequently the Bragg wavelength is different at different locations, different wavelengths get reflected from different locations on the FBG.

A dispersion compensating FBG at 1550nm band would be as shown in Fig

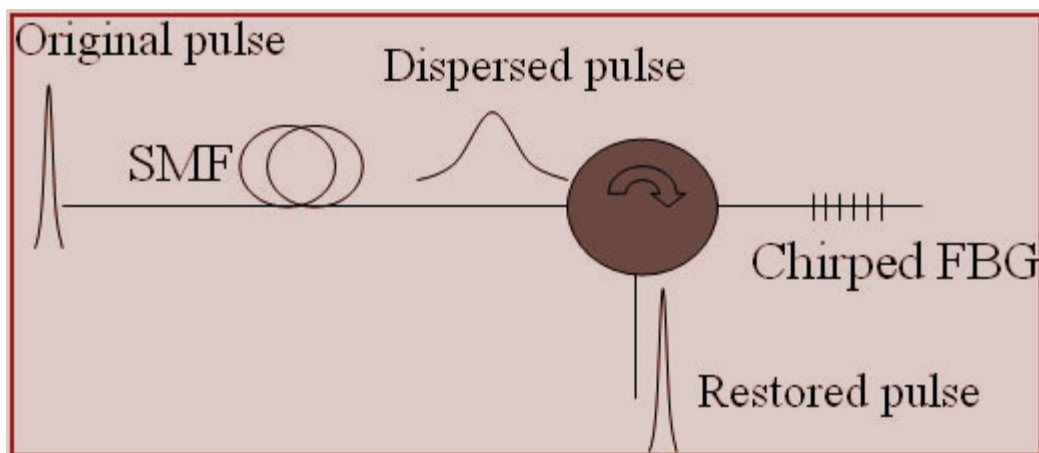
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- Here the FBG spatial period increases from input to output and we have

$$\lambda_1 > \lambda_2 > \lambda_3 > \lambda_4 > \lambda_5$$

- A few mm of the chirped FBG can compensate the dispersion caused by tens of Km of normal SM fiber.
- A schematic of dispersion compensating scheme is shown in Fig.



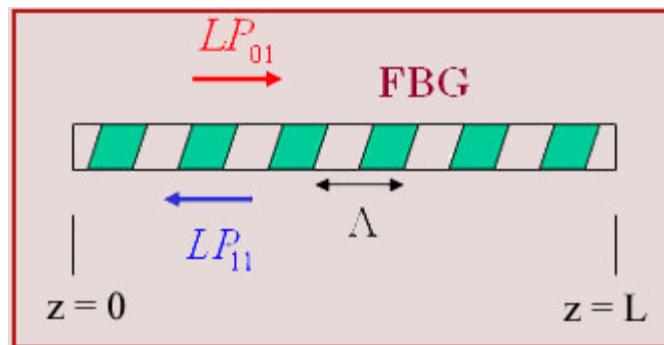
Gain Equalizer

- In a WDM system different wavelengths attenuate by different amount. Also in devices like the EDFA, the gain is not uniform across the band. This causes different SNR and consequently different BER in different channels.
- The gain of different channel has to be equalized for identical performance of all the channels.

- By controlling the FBG parameters, the reflectivity of different wavelengths can be controlled. In this case the FBG is not used in saturation mode. The wavelengths which have higher gain can be reflected with low reflection coefficient.
- By varying the visibility and the chirp of the grating complex reflection profiles can be realized for gain equalization.

Mode Converter

- Normally the SM fiber carries LP_{01} mode. However for dispersion compensation using dispersion compensating fibers, the signal has to be converted from LP_{01} mode to LP_{11} mode and vice versa.
- A tilted FBG as shown in Fig can be used for this purpose.



- The grating is tilted by few degrees with respect to the axis of the fiber. This causes coupling between circularly symmetric and circularly anti-symmetric modes and power from LP_{01} is converted to LP_{11} mode and vice versa.

Sensor

Temperature Sensor

- The FBG also has non-communication application. One of its important use is as a pressure or temperature sensor.
- Due to variation of temperature the fiber length changes and consequently the grating period changes. The Bragg wavelength then deviates from the original FBG wavelength.

- By measuring the deviation of the wavelength of the reflected signal one can estimate the temperature.
- Temperature to an accuracy of a fraction of a degree can be achieved using fiber sensors.

Pressure Sensor

- In pressure sensor, a normal fiber is passed through corrugated plates. The plates introduce a mechanical periodicity and therefore the fiber acts like a grating. There is no permanent grating in this case.
- Now as the pressure between the plates increases, the modulation of grating increases and the reflectivity increases.
- With proper calibration, the pressure can be measured by measuring the strength of the reflected signal.

Recap

In this lecture you have learnt the following

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- Frequency Response of a Uniform FBG
- Non-Uniform Fiber Bragg Grating
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- Mode Converter

- Sensor

Congratulations, you have finished Module 18. To view the next lecture select it from the left hand side menu of the page