Satellite and Optical Communication

BEC515D

MODULE 5

Wavelength Division Multiplexing (WDM)

Wavelength Division Multiplexing (WDM)

- WDM is the technology of combining a number of independent, information-carrying wavelengths onto the same optical fiber.

- It takes advantage of the wide spectral region (e.g., over 400 nm in the O-band through L-band) where optical signals can be transmitted efficiently.

- This allows a dramatic increase in the information capacity of a single fiber.

- High-capacity optical light sources (lasers) emit light in a very narrow wavelength band (less than 1 nm).

- An optical fiber's efficient transmission spectrum is extremely wide in comparison.

- Therefore, many different, independent optical channels can be used simultaneously in different segments of the fiber's available wavelength range.

Concepts of WDM

Concepts of WDM

- Original optical fiber links (around 1980) were simple point-to-point connections with one light source and one photodetector per fiber.

- This design greatly underutilized the large bandwidth capacity of the fiber.

- Wavelength Division Multiplexing (WDM) was first used to upgrade the capacity of these installed links.

- This early WDM used wavelengths separated by tens or even 200 nm, which avoided the need for strict wavelength-tolerance on the components.

Concepts of WDM

- With high-quality light sources that have very narrow emission widths (less than 1 nm), many independent channels can be placed on the same fiber.

- These channels can be spaced less than a nanometer apart, allowing WDM to dramatically increase the fiber's capacity.
  - For example, each new wavelength can support an independent transmission rate, such as 10 Gb/s.

- Another key advantage is that these optical channels can support different transmission formats, allowing differently formatted signals to be sent simultaneously and independently.
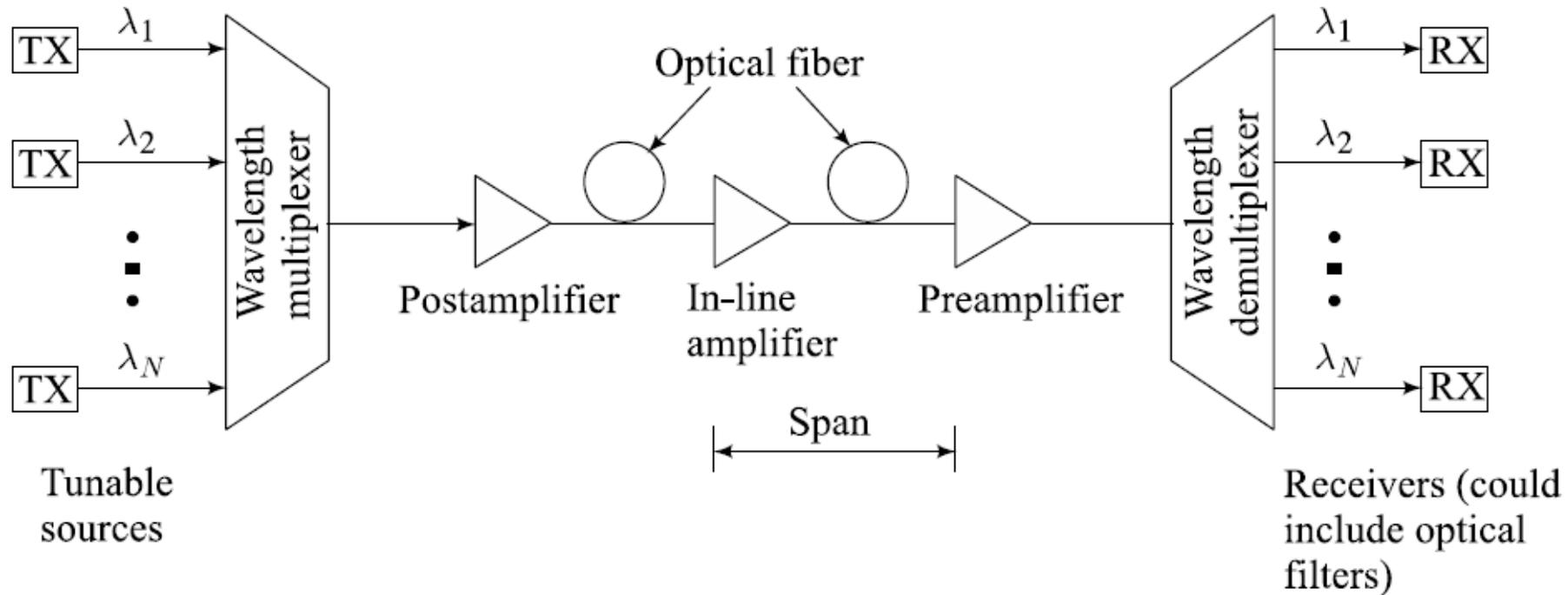
WDM Operational Principles

- A characteristic of WDM is that the discrete wavelengths form an **orthogonal set** of carriers.

- This means they can be separated, routed, and switched without interfering with each other.

- This isolation holds as long as the total optical power intensity is kept low enough to prevent **nonlinear effects** (like stimulated Brillouin scattering and four-wave mixing).

WDM Operational Principles

- WDM networks require a variety of **passive** and **active** devices to manage the optical power at different wavelengths.

- **Passive devices** require no external control and are used to split, combine, or tap off signals, but have limited flexibility.

- **Active devices** can be controlled electronically or optically, providing high network flexibility. Examples include optical amplifiers, wavelength switches, and wavelength converters.

WDM Operational Principles

Fig. 10.1 Implementation of a typical WDM network containing various types of optical amplifiers

WDM Operational Principles

- At the transmitting end, several independently modulated light sources each emit a unique wavelength (λ).

- A wavelength multiplexer is needed to combine these optical outputs into a continuous spectrum and couple them onto a single fiber.

- At the receiving end, a wavelength demultiplexer is required to separate the optical signals back into their individual detection channels for processing.

- Active devices, like optical amplifiers, are often used within the link to compensate for power losses.

WDM Operational Principles
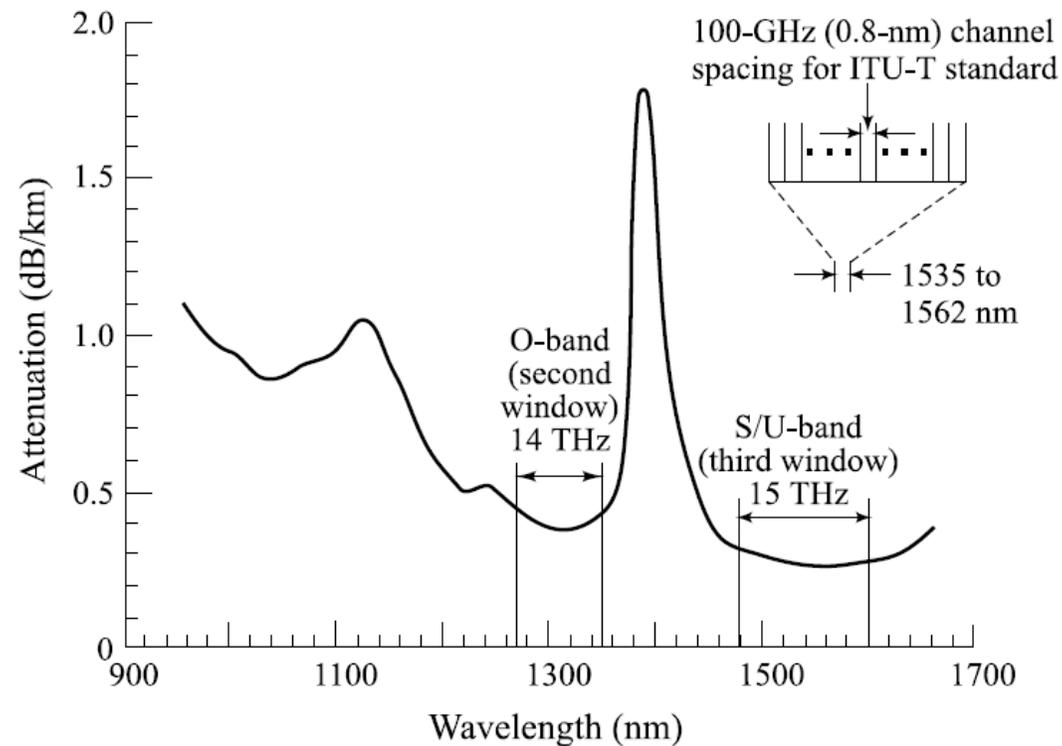
Fig. 10.2 The transmission-band widths in the O-band and C-band (the 1310-nm and 1550-nm windows) allow the use of many simultaneous channels for sources with narrow spectral widths, such as the ITU-T standard 100-GHz channel spacing for WDM

WDM Operational Principles

- There are many independent operating regions across the spectrum (O-band through L-band) where sources can be used.

- These regions can be viewed by spectral width (wavelength, λ or optical bandwidth (frequency, ν).

- The fundamental relationship is $c = \lambda\nu.$

- The frequency deviation $\Delta\nu$ corresponding to a wavelength deviation $\Delta\lambda$ is:

$$|\Delta v| = \frac{c}{\lambda^2}|\Delta\lambda|$$

WDM Operational Principles

- The operational frequency band allocated to a single light source is typically **25 to 100 GHz**.

- This is equivalent to a spectral band of 0.25–0.8 nm at a 1550 nm wavelength.

- The selected band needs to be wide enough to account for possible drifts in the laser's peak wavelength.

- These parameter changes can be caused by effects like *component aging* or *temperature variations*.

WDM Operational Principles

- The key engineering challenge is to ensure each source is spaced sufficiently far from its neighbors to prevent interference.

- This requires **highly stabilized optical transmitters** to maintain the integrity of the independent message streams.

- For example, a designated source might be specified to have a wavelength of 1557.363 ± 0.005 nm (or 192.50 THz).

Standards for WDM

Standards for WDM

- WDM is essentially frequency division multiplexing at optical carrier frequencies.

- The ITU standards specify channel spacing in terms of frequency rather than wavelength.

- This is because when a laser is locked to an operating mode, it is the frequency that remains fixed.

- ITU-T Recommendation G.692 was the first specification, establishing a reference frequency of 193.100 THz (1552.524 nm).

- Suggested spacings include 100 GHz (~0.8 nm), 50 GHz (~0.4 nm), and 200 GHz (~1.6 nm).

Standards for WDM

- **Dense WDM (DWDM)** refers to operation with small wavelength separations, defined by **ITU-T Recommendation G.694.1**.

- It operates in the S-, C-, and L-bands for high-capacity MAN and WAN services.

- It uses narrow frequency spacings ranging from **100 GHz down to 12.5 GHz**.

- This requires stable, temperature-controlled, and frequency-locked laser diodes (e.g., ±0.02 nm tolerance for 25-GHz channels).

- *Note:* When frequency spacing is uniform, wavelength spacing is *not* uniform due to the inverse relationship between frequency and wavelength.

Standards for WDM

- DWDM uses a specific channel numbering convention based on the frequency.

- The frequency **19N.M THz** is designated as ITU channel number **NM**.

- For example, a frequency of **194.3 THz** corresponds to ITU channel **43**.

- For the 50-GHz grid, values are interleaved with the 100-GHz spacings (e.g., 186.00, 186.05, 186.10 THz).

Standards for WDM

Table 10.1 Portion of the ITU-T G.694.1 dense WDM grid for 100- and 50-GHz spacings in the L- and C-bands

L-band				C-band			
100-GHz		50-GHz offset		100-GHz		50-GHz offset	
THz	nm	THz	nm	THz	nm	THz	nm
186.00	1611.79	186.05	1611.35	191.00	1569.59	191.05	1569.18
186.10	1610.92	186.15	1610.49	191.10	1568.77	191.15	1568.36
186.20	1610.06	186.25	1609.62	191.20	1576.95	191.25	1567.54
186.30	1609.19	186.35	1608.76	191.30	1567.13	191.35	1566.72
186.40	1608.33	186.45	1607.90	191.40	1566.31	191.45	1565.90
186.50	1607.47	186.55	1607.04	191.50	1565.50	191.55	1565.09
186.60	1606.60	186.65	1606.17	191.60	1564.68	191.65	1564.27
186.70	1605.74	186.75	1605.31	191.70	1563.86	191.75	1563.45
186.80	1604.88	186.85	1604.46	191.80	1563.05	191.85	1562.64
186.90	1604.03	186.95	1603.60	191.90	1562.23	191.95	1561.83

Standards for WDM

- **Coarse WDM (CWDM)** emerged for low-cost links in access and local area networks using full-spectrum fibers.

- **ITU-T Recommendation G.694.2** defines the CWDM spectral grid.

- It consists of **18 wavelengths** between 1270 nm and 1610 nm (O-band through L-band).

- The channels are spaced widely at **20 nm** with a drift tolerance of ±2 nm.

- This wide spacing allows for the use of inexpensive light sources that do not require temperature control.

Standards for WDM
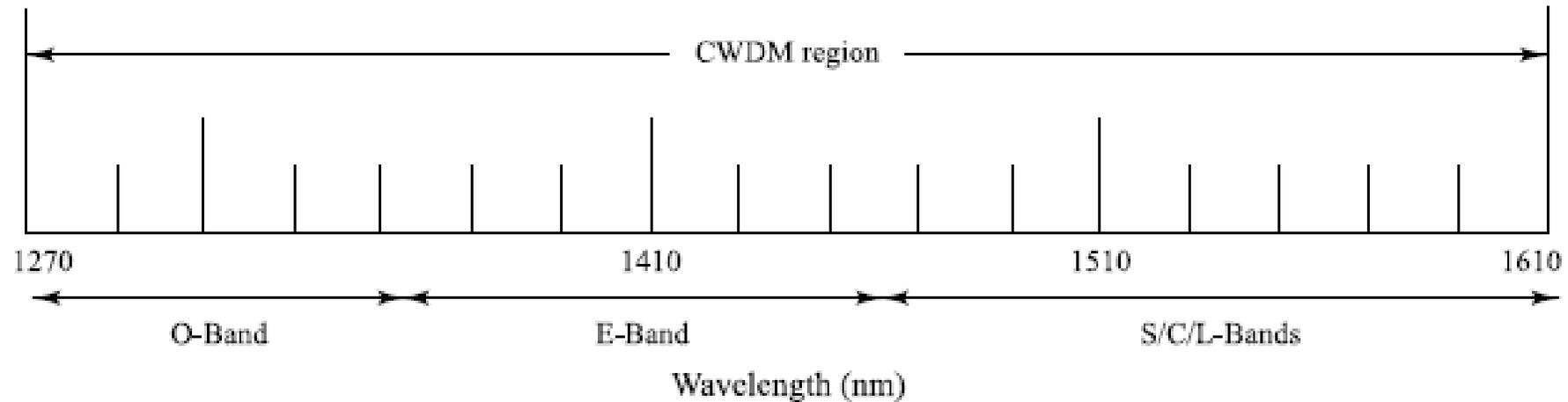
Fig. 10.3 Spectral grid for coarse wavelength-division multiplexing (CWDM)

Standards for WDM

- ITU-T Recommendation G.695 outlines optical interface specifications for CWDM.

- It covers distances of 40 km and 80 km.

- The standard supports both unidirectional and bidirectional systems (common in passive optical networks).

- Deployments typically use single-mode fibers specified in G.652 and G.655.

Isolators and Circulators

Isolators and Circulators

- In many applications, it is desirable to have a **nonreciprocal** passive optical device.

- A nonreciprocal device works differently when its inputs and outputs are reversed.

- Two common examples of such devices are:

  - Isolators

  - Circulators

Isolators and Circulators

- To understand these devices, one must first recall key facts about polarization:
  - Light can be represented as two **orthogonal plane polarization states** (a parallel vibration and a perpendicular vibration).
  - A **polarizer** is a device that transmits only one polarization component and blocks the other.
  - A **Faraday rotator** rotates the state of polarization (SOP) of light by a specific angular amount.
  - A **walk-off polarizer** (made from birefringent material) splits an incoming light signal into two orthogonally polarized beams, which then follow different paths.
  - A **half-wave plate** rotates the SOP clockwise by 45° for light going left-to-right, and counterclockwise by 45° for light going in the opposite direction.

Functions of
Optical Isolators

Functions of Optical Isolators

- Optical isolators are devices that allow light to pass through them in only one direction.

- This is important for preventing scattered or reflected light from traveling in the reverse direction.

- A common application is to keep this backward-traveling light from entering a laser diode, which could cause instabilities in the optical output.

- Simple isolator designs depend on the input light's state of polarization (SOP).

- This creates a problem for unpolarized light, as the device blocks half the signal, resulting in a **3-dB loss** (half the power).

- In practice, optical isolators must be **polarization-independent** because the light in an optical link is normally not polarized.

Functions of Optical Isolators

- A common design for a polarization-independent isolator is made of three miniature components.

- The core of the device is a 45° Faraday rotator.

- The rotator is placed between two wedge-shaped birefringent plates (also called walk-off polarizers).
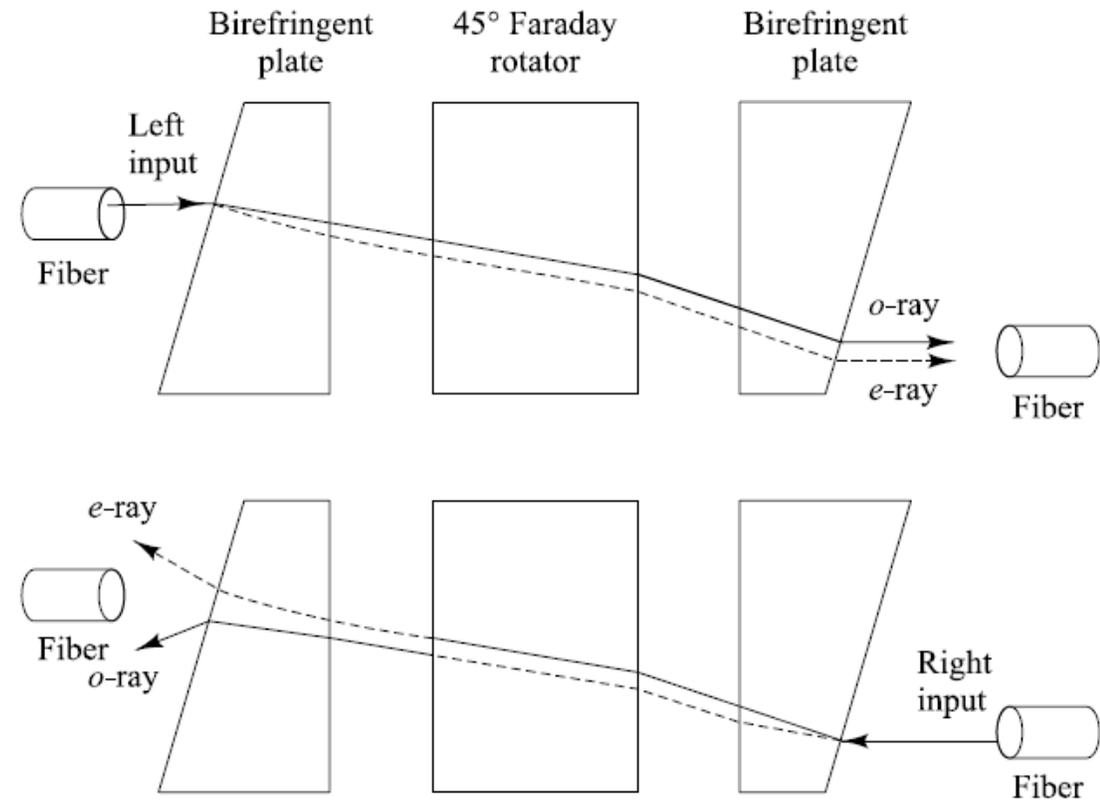

Fig. 10.17 Design and operation of a polarization-independent isolator made of three miniature optical components

Functions of Optical Isolators

- In the **forward direction**, the first plate splits light into ordinary and extraordinary rays. The Faraday rotator rotates both by 45°. The second plate is aligned to maintain their relationship, refracting them in an identical parallel direction so they are coupled to the fiber.

- In the **reverse direction**, the process is nonreciprocal. When the rays exit the Faraday rotator, their relationship is reversed. This causes the rays to **diverge** when they exit the final plate, so they are not coupled to the fiber.
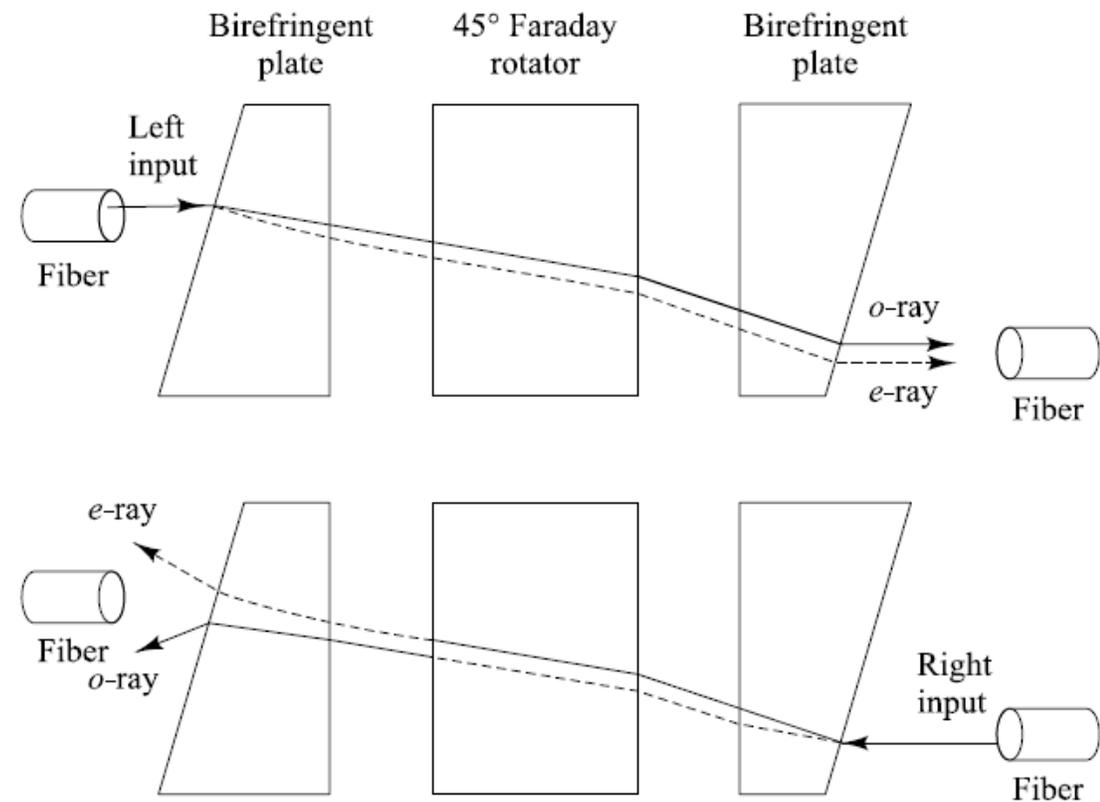
Fig. 10.17 Design and operation of a polarization-independent isolator made of three miniature optical components

Functions of Optical Isolators

Table 10.3 Typical parameter values of commercially available optical isolators

Parameter	Unit	Value
Central wavelength λ_c	nm	1310, 1550
Peak isolation	dB	40
Isolation at $\lambda_c \pm 20$ nm	dB	30
Insertion loss	dB	<0.5
Polarization-dependent loss	dB	<0.1
Polarization-mode dispersion	ps	<0.25
Size (diameter × length)	mm	6 × 35

Characteristics of Optical Circulators

Characteristics of Optical Circulators

- An optical circulator is a **nonreciprocal**, multiport passive device.

- It directs light sequentially from port to port in **only one direction**.

- Common applications include:

  - Optical amplifiers

  - Add/drop multiplexers

  - Dispersion compensation modules

# Circulator Operation and Construction

- The operation is similar to an optical isolator, but the construction is more complex.

- It typically consists of several components:

  - Walk-off polarizers

  - Half-wave plates

  - Faraday rotators

- Devices commonly have three or four input/output ports.

Three-Port Circulator Function

- A three-port circulator directs light in a specific sequence.
  - An input on Port 1 is sent out on Port 2.
  - An input on Port 2 is sent out on Port 3.
  - An input on Port 3 is sent out on Port 1.

Fig. 10.18 Operational concept of a three-port circulator
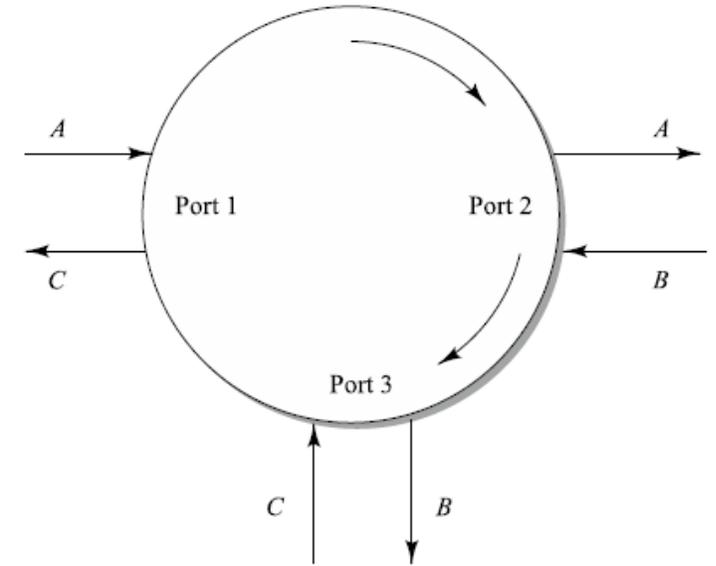
Four-Port Circulator Function

- A perfectly symmetrical four-port circulator is tedious to fabricate.

- In practice, ports are often specialized:

  - **Port 1**: Input-only

  - **Ports 2 & 3**: Input and output

  - **Port 4**: Output-only

Key Performance Characteristics

- A variety of circulators are available commercially.

- Ideal performance characteristics include:

  - Low **insertion loss**

  - High **isolation** over a wide wavelength range

  - Minimal **polarization-dependent loss (PDL)**

  - Low **polarization-mode dispersion (PMD)**

Key Performance Characteristics

Table 10.4 Typical parameter values of commercially available optical circulators

Parameter	Unit	Value
Wavelength band	nm	C-band: 1525–1565 L-band: 1570–1610
Insertion loss	dB	<0.6
Channel isolation	dB	>40
Optical return loss	dB	>50
Operating power	mW	<500
Polarization-dependent loss	dB	<0.1
Polarization-mode dispersion	ps	<0.1
Size (diameter × length)	mm	5.5 × 50

WDM Devices Based on Grating Principles
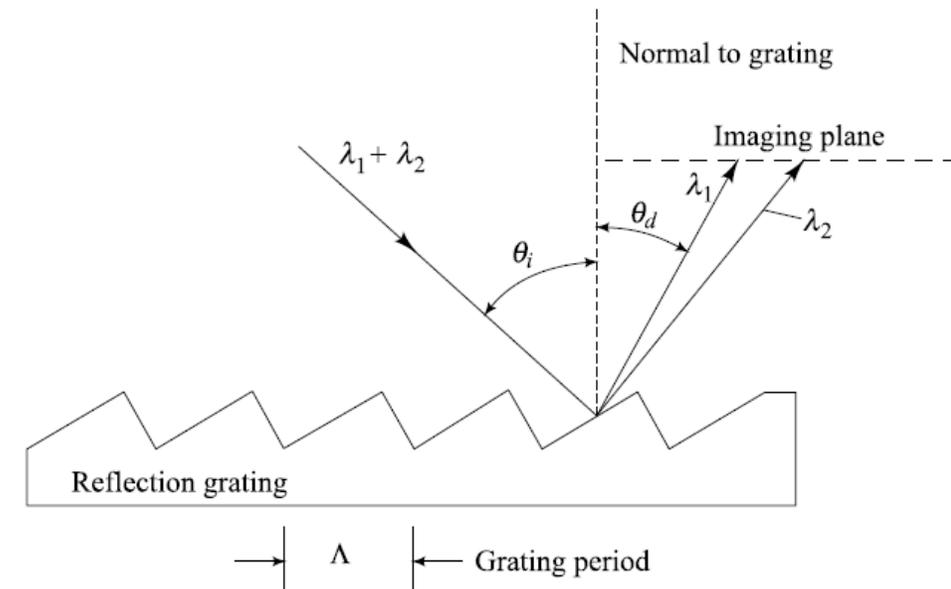
WDM Devices Based on Grating Principles

- A **grating** is an important element in WDM systems for combining and separating individual wavelengths.

- It is a periodic structure or perturbation in a material.

- This structure has the property of reflecting or transmitting light in a specific direction depending on the wavelength.

- Gratings can be categorized as **reflecting** or **transmitting** gratings.

Grating Basics

Grating Basics

- A grating is a periodic structure or perturbation in a material, used as a key element in WDM systems.
  - Λ (Period): The periodicity of the structural variation in the material.
  - θ_i (Incident Angle): The angle of the incoming light.
  - θ_d (Diffracted Angle): The angle of the diffracted light.
- For a transmission grating (equally spaced slits), the period Λ is called the pitch.

Normal to grating

Imaging plane

$\lambda_1 + \lambda_2$

λ_1

θ_d

λ_2

θ_i

Reflection grating

Λ

Grating period

Fig. 10.19 Basic parameters in a reflection grating

Grating Basics

- Constructive interference at a wavelength λ occurs when rays satisfy the grating equation:

$$\Lambda(\sin\theta_i - \sin\theta_d) = m\lambda$$

- m is called the order of the grating (in general, only the first-order, $m = 1$, is considered).

- A grating separates individual wavelengths because the diffracted angle (θ_d) that satisfies the equation is different for each different wavelength (λ)

Optical Fiber Bragg Grating (FBG)

Optical Fiber Bragg Grating (FBG)

- A **Fiber Bragg Grating (FBG)** is a high-performance device constructed within an optical fiber.

- It is used in dense WDM systems to access individual, closely spaced wavelengths.

- Because it is an "all-fiber" device, it has advantages like simple packaging, low cost, polarization insensitivity, and low insertion loss (around 0.3 dB).

- It functions as a **narrowband reflection filter**.
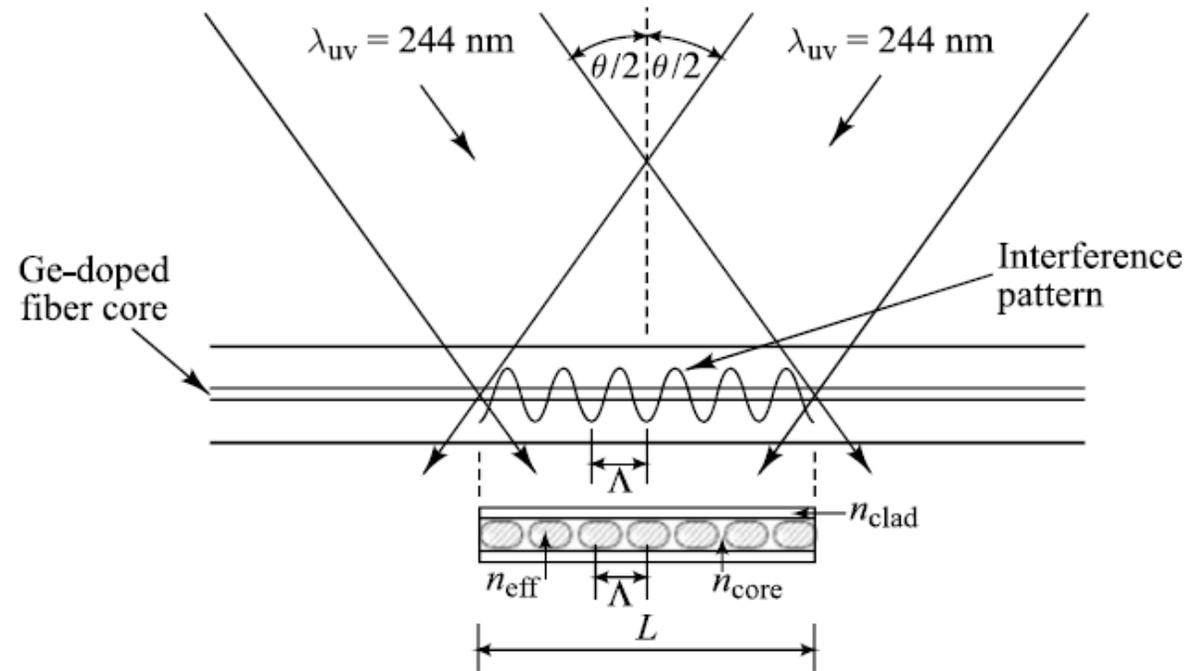
Optical Fiber Bragg Grating (FBG)

- One fabrication method is the **"external-writing" technique**.

- Two UV beams are directed transversely to irradiate the fiber.

- The beams create an **interference pattern** in the core.

- In the high-intensity regions, the core's refractive index increases, while in the zero-intensity regions, it is unaffected.

- This "writes" a permanent, reflective Bragg grating into the core.

Optical Fiber Bragg Grating (FBG)

- When a multi-wavelength signal encounters the FBG, it acts as a filter.

- Wavelengths that are phase-matched to the Bragg reflection condition are **reflected**.

- All other wavelengths are **transmitted**.

Optical Fiber Bragg Grating (FBG)

Fig. 10.20 Formation of a Bragg grating in a fiber core by means of two intersecting ultraviolet light beams

Optical Fiber Bragg Grating (FBG)

- The imprinted grating is a uniform sinusoidal modulation of the core's refractive index:

$$n(z) = n_{core} + \delta n \left[1 + \cos\left(\frac{2\pi z}{\Lambda} \right) \right]$$

where n_{core} is the unexposed core refractive index and δn is the photoinduced change in the index.

- Maximum reflectivity occurs at a specific reflection wavelength, λ_{Bragg}, defined by the Bragg condition:

$$\lambda_{Bragg} = 2\Lambda n_{eff}$$

Λ is the grating period and n_{eff} is the effective index of the core.

Optical Fiber Bragg Grating (FBG)

- The peak reflectivity (R_{max}) for a grating of length L and coupling coefficient κ is:

$$R_{\max} = \tanh^2(\kappa L)$$

- The full bandwidth λ over which the maximum reflectivity holds is

$$\Delta\lambda = \frac{\lambda_{Bragg}^2}{\pi n_{eff} L} \left[(\kappa L)^2 + \pi^2 \right]^{1/2}$$

- An approximation for the full-width half-maximum (FWHM) bandwidth is

$$\Delta\lambda_{FWHM} = \lambda_{Bragg} s \left[\left(\frac{\delta n}{2 n_{core}} \right)^2 + \left(\frac{\Lambda}{L} \right)^2 \right]^{1/2}$$

where $s \approx 1$ for strong gratings with near 100% reflectivity, and $s \approx 0.5$ for weak gratings.

Optical Fiber Bragg Grating (FBG)

- The coupling coefficient κ depends on the index change δn:

$$\kappa = \frac{\pi \delta n \eta}{\lambda_{Bragg}}$$

with η being the fraction of optical power contained in the fiber core.

- Under the assumption that the grating is uniform in the core, η can be approximated by

$$\eta \approx 1 - V^{-2}$$

where V is the V number of the fiber.

Optical Fiber Bragg Grating (FBG)

- Fiber Bragg gratings are available in a wide range of reflection bandwidths varying from 25 GHz and higher.

- Table 10.5 lists some operational characteristics of commercially available 25-, 50-, and 100-GHz fiber Bragg gratings for use in optical communication systems.

Table 10.5 Typical parameter values of commercially available fiber Bragg gratings

| Parameter	Typical values for three channel spacings		
	25 GHz	50 GHz	100 GHz
Reflection bandwidth	>0.08 nm @ −0.5 dB <0.2 nm @ −3 dB <0.25 nm @ −25 dB	>0.15 nm @ −0.5 dB <0.4 nm @ −3 dB <0.5 nm @ −25 dB	>0.3 nm @ −0.5 dB <0.75 nm @ −3 dB <1 nm @ −25 dB
Transmission bandwidth	>0.05 nm @ −25 dB	>0.1 nm @ −25 dB	>0.2 nm @ −25 dB
Adjacent channel isolation	>30 dB		
Insertion loss	<0.25 dB		
Central λ tolerance	$< \pm 0.05$ nm @ 25 °C		
Thermal λ drift	<1 pm/°C (for an athermal design)		
Package size	5 mm (diameter) × 80 mm (length)		

Optical Fiber Bragg Grating (FBG)

- In the fiber Bragg grating (FBG) illustrated in **Fig. 10.20**, the grating spacing is uniform along its length.

- It is also possible to make the spacing vary along the length of the fiber.
  - This type of FBG is known as a **chirped grating**.

- A *chirped grating* is used to reflect a range of different wavelengths, not just a single one.

WDM FBG Applications

WDM FBG Applications

- A simple demultiplexing function can be achieved using a Fiber Bragg Grating (FBG) and an optical circulator.
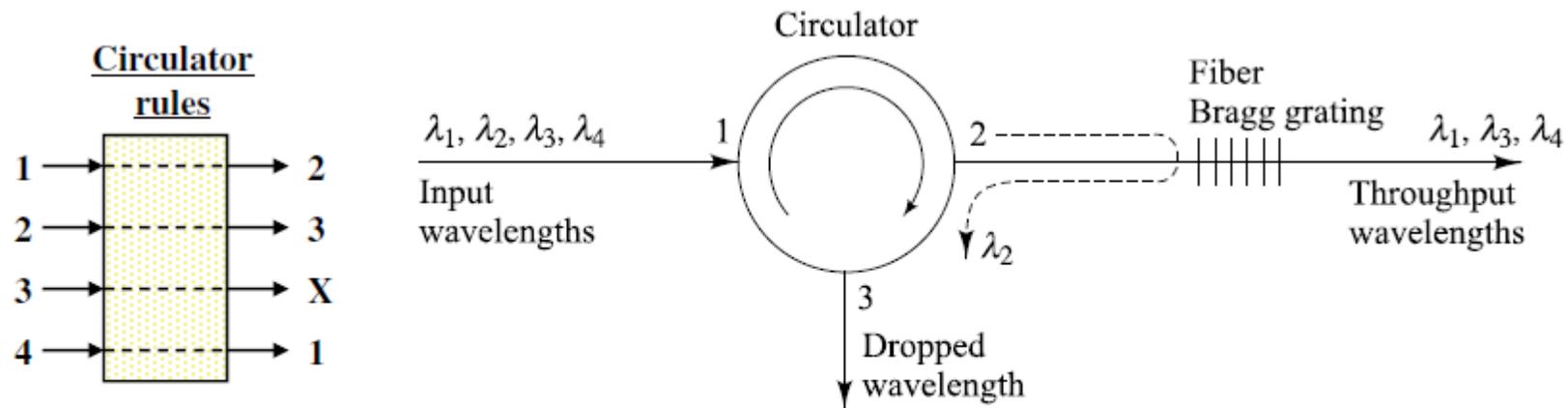
Fig. 10.21 Simple concept of a demultiplexing function using a fiber grating and an optical circulator

WDM FBG Applications

- To extract a single wavelength, the combined signal (e.g., four wavelengths) enters port 1 of the circulator and leaves from port 2.

- The signal then hits the FBG. The FBG is built to reflect only the desired wavelength (λ_2) and let all others ($\lambda_1, \lambda_3, \lambda_4$) pass through.

- The reflected λ_2 travels backward, enters port 2 of the circulator, and is directed to exit at port 3, successfully separated from the other signals.

WDM FBG Applications

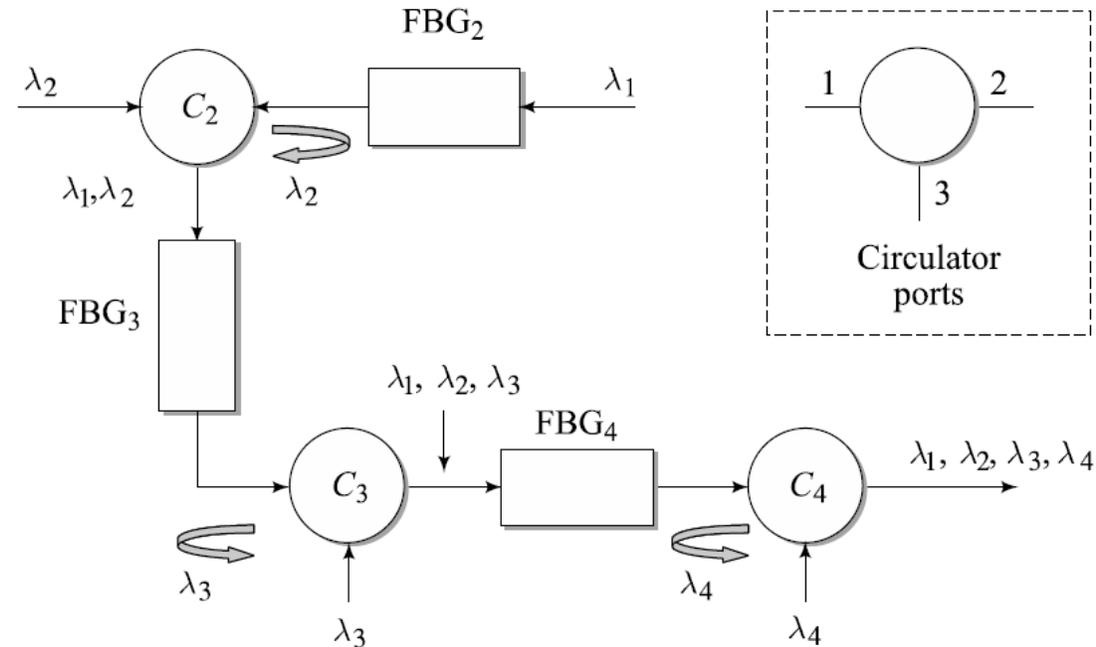- To combine (multiplex) or separate N wavelengths, one must cascade $N-1$ FBGs and $N-1$ circulators.

Fig. 10.22 Multiplexing of four wavelengths using three FBG devices and three circulators

WDM FBG Applications

- To combine (multiplex) or separate N wavelengths, one must cascade $N-1$ FBGs and $N-1$ circulators.

- A four-wavelength multiplexer (λ_1,λ_2,λ_3,λ_4) would use three FBGs and three circulators (C2, C3, C4).

- The filters are constructed for specific wavelengths:
  - FBG2 reflects λ_2 and passes all others.
  - FBG3 reflects λ_3 and passes all others.
  - FBG4 reflects λ_4 and passes all others.

Fig. 10.22 Multiplexing of four wavelengths using three FBG devices and three circulators

WDM FBG Applications

- First, consider the combination of circulator C2 and FBG2.

- The incoming wavelength λ_1 passes through FBG2, enters port 2 of C2, and exits from port 3.

- The incoming wavelength λ_2 enters port 1 of C2 and exits from port 2.

- λ_2 is then reflected by FBG2, re-enters port 2 of C2, and exits from port 3, now combined with λ_1.
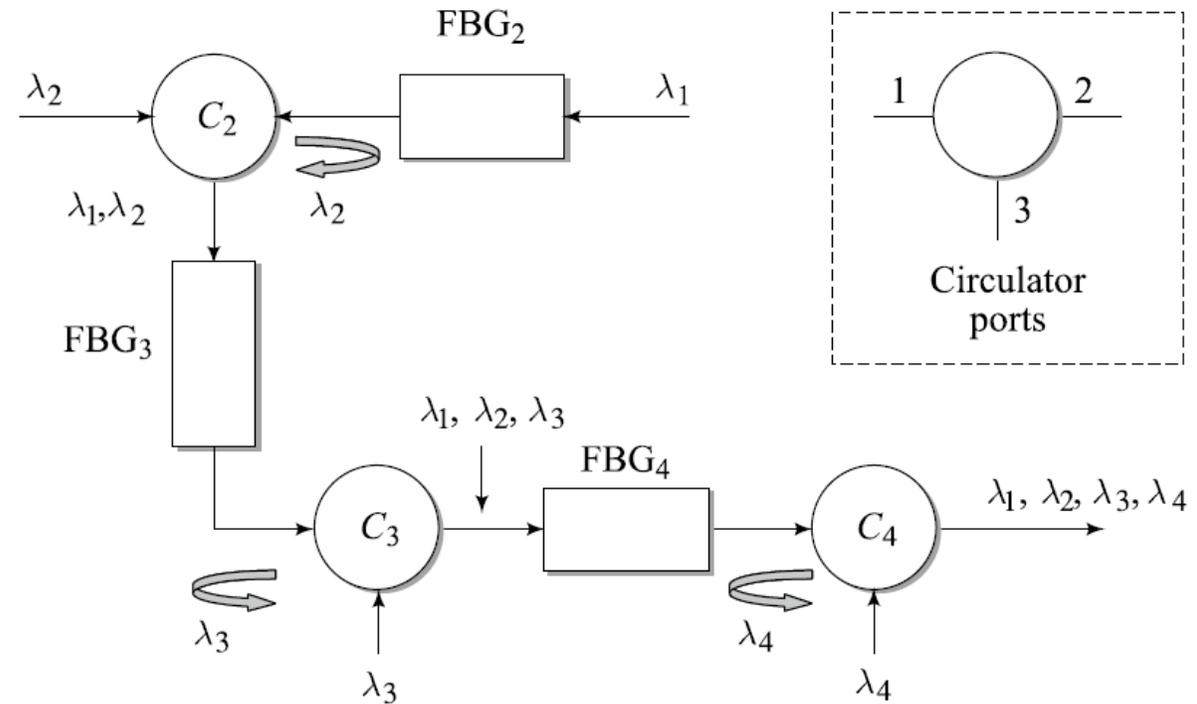
- These two wavelengths continue to the next stage.

Fig. 10.22 Multiplexing of four wavelengths using three FBG devices and three circulators

WDM FBG Applications

- At circulator C3, the incoming wavelength λ_3 enters port 3, exits from port 1, and travels toward FBG3.

- After being reflected by FBG3, it re-enters port 1 of C3 and exits from port 2, joining the combined λ_1 and λ_2 signals.

- A similar process takes place at circulator C4 and filter FBG4 to insert λ_4.

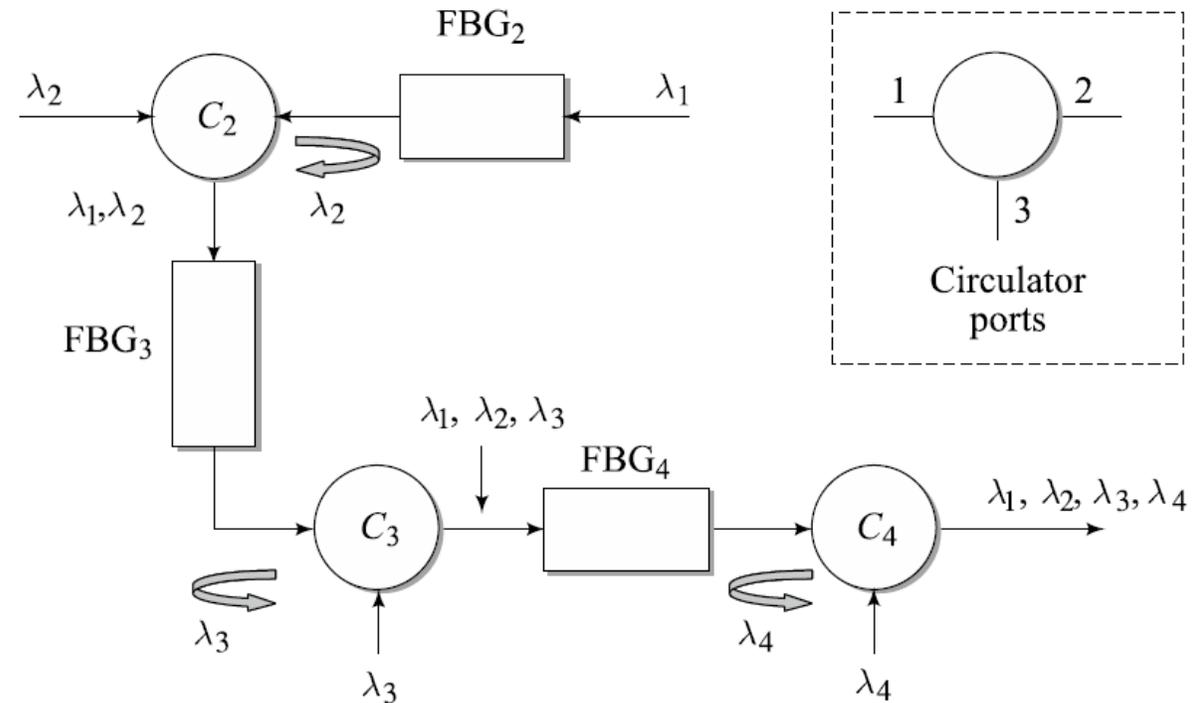- All four wavelengths now exit together from port 2 of circulator C4 and can be coupled into a fiber.

Fig. 10.22 Multiplexing of four wavelengths using three FBG devices and three circulators

WDM FBG Applications

- This FBG-based coupler design has limitations.

  - One filter is needed for each wavelength.

  - The operation is sequential, which means the losses are **not uniform** from channel to channel.

  - Each wavelength passes through a different number of circulators and gratings, and each component adds loss.

  - This loss differential between the first and last inserted wavelengths is a restriction for systems with a large number of channels.
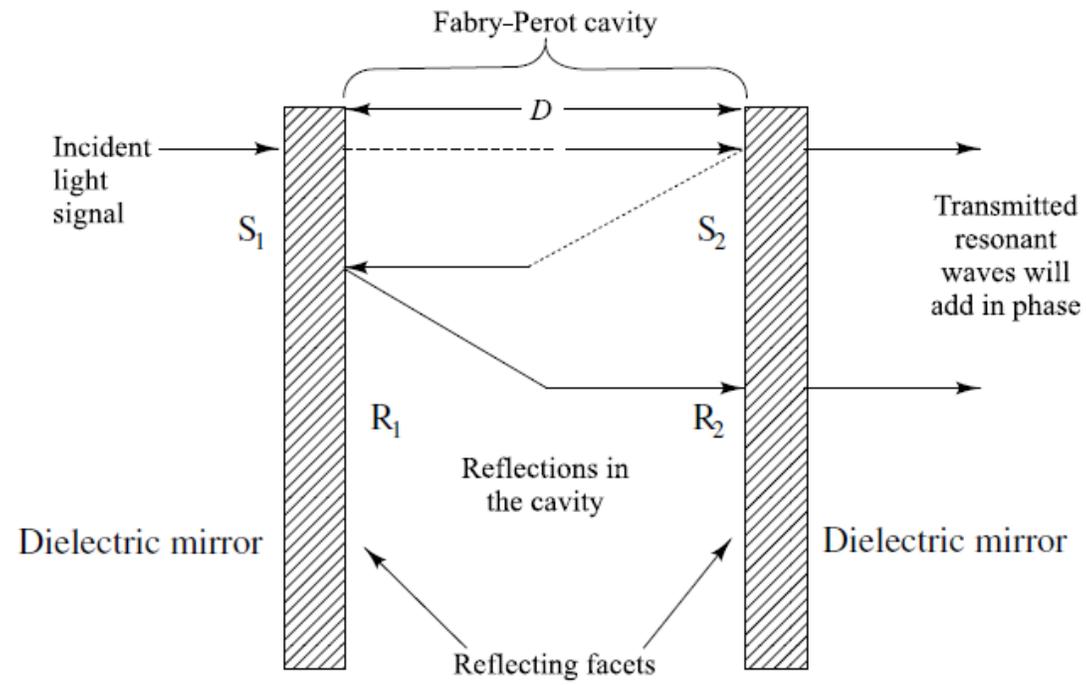
Dielectric Thin-Film Filter (TFF)

Dielectric Thin-Film Filter (TFF)

- A **Dielectric Thin-Film Filter (TFF)** is used as an optical bandpass filter.

- This means it is designed to allow a particular, very narrow wavelength band to pass straight through it.

  - It reflects all other wavelengths.

- The basis of these devices is a classical Fabry–Perot filter structure, which is a cavity formed by two parallel highly reflective mirror surfaces.

- .This structure is called a *Fabry–Perot interferometer* or an *etalon*.

  - It also is known as a *thin-film resonant cavity filter*.

Dielectric Thin–Film Filter (TFF)

Fabry–Perot cavity

D

Incident light signal

S_1

S_2

Transmitted resonant waves will add in phase

R_1

R_2

Reflections in the cavity

Dielectric mirror

Dielectric mirror

Reflecting facets

Fig. 10.23 Two parallel light-reflecting mirrored surfaces define a Fabry–Perot resonator cavity or an etalon

Applications of Etalon Theory

- The transmission T of an ideal etalon in which there is no light absorption by the dielectric mirrors is an *Airy function* given by

$$T = \left[1 + \frac{4R}{(1-R)^2} \sin^2\left(\frac{\varphi}{2}\right)\right]^{-1}$$

where R is the *reflectivity* of the mirrors (the fraction of light reflected by the mirror) and φ is the roundtrip phase change of the light beam.

- If one ignores any phase change at the mirror surface, then the phase change for a wavelength λ is

$$\varphi = \frac{2\pi}{\lambda} 2nD\cos\theta$$

where n is the refractive index of the dielectric layer that forms the mirror, D is the distance between the mirrors, and θ is the angle to the normal of the incoming light beam.

Applications of Etalon Theory

- The transmission function is periodic, showing a series of peaks.

- The wavelength range that can pass through the filter is called the **passband**.

- The distance (in frequency or wavelength) between adjacent transmission peaks is called the **Free Spectral Range (FSR)**.

Fig. 10.24 The behavior of the resonant wavelengths in a Fabry–Perot cavity for three values of the mirror reflectivity based on the Airy function
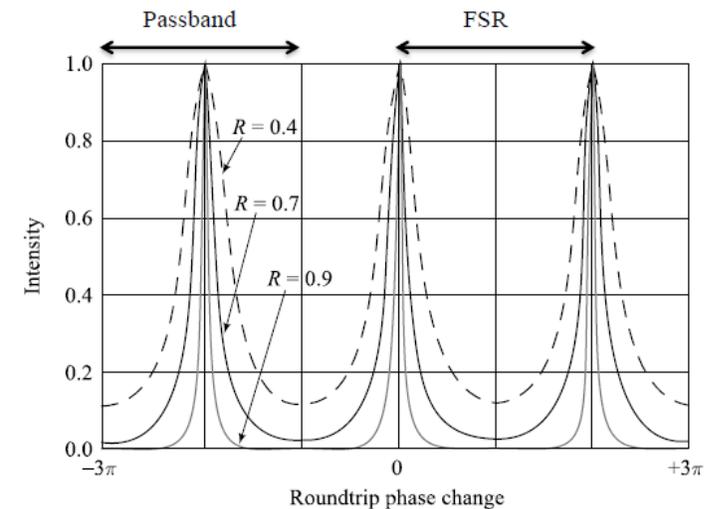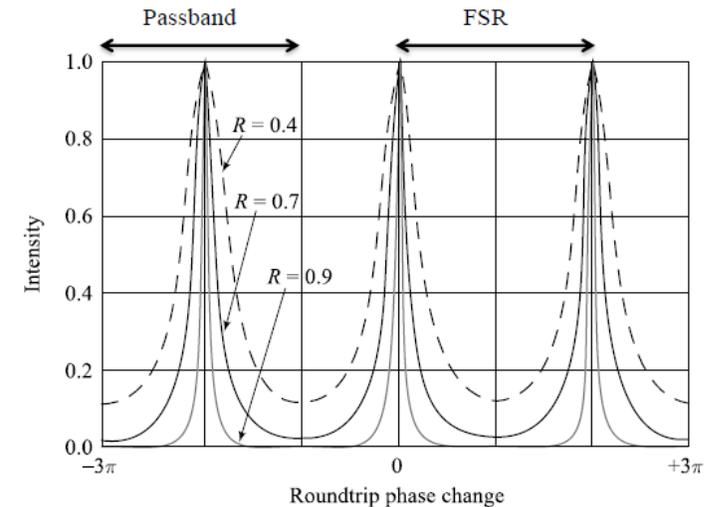
Applications of Etalon Theory

- FWHM (Full-Width Half-Maximum), denoted $\delta\lambda$ is a measure of the width of the transmission passband.

- Finesse (F) is a measure of the filter's sharpness and is the ratio of the FSR to the FWHM:

$$F = \frac{\Delta\lambda_{FSR}}{\delta\lambda}$$

- Finesse is primarily determined by the mirror reflectivity (R).

Fig. 10.24 The behavior of the resonant wavelengths in a Fabry–Perot cavity for three values of the mirror reflectivity based on the Airy function
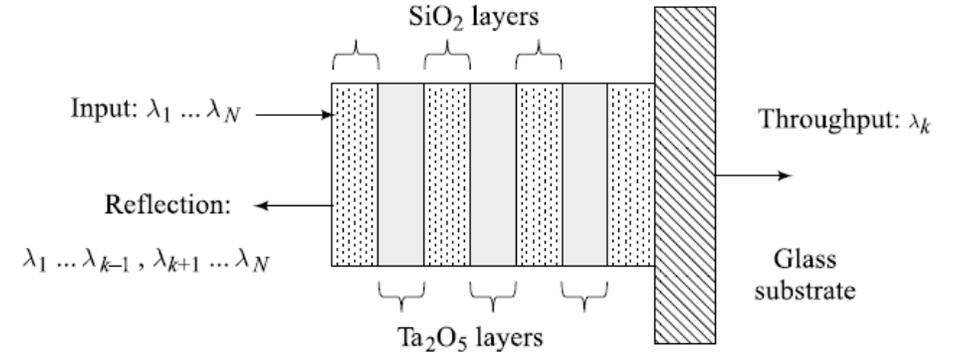
Applications of Etalon Theory

- Mirrors with greater reflectivities (e.g., $R > 0.5$) yield a higher finesse.

- A high finesse means the filter has sharper transmission peaks and a narrower passband.

- This allows the filter to be more selective, isolating a single wavelength more effectively.

- Absorption within the device (especially in the mirrors) reduces the sharpness of the peaks.

Applications of Etalon Theory

- A practical TFF consists of multilayer thin-film coatings deposited on a glass substrate.

- These are alternating layers of low-index (e.g., SiO_2) and high-index (e.g., Ta_2O_5) materials.

- This structure creates a **series of resonance cavities**, not just one.

Fig. 10.25 A multilayer optical thin film filter consists of a stack of several dielectric thin films separated by resonance cavities

Applications of Etalon Theory

- Using multiple cavities sharpens the passband significantly.

- This design also creates a flat top for the filter's passband, which is a desirable characteristic for practical WDM filters.

- The filter is made to pass only a specific wavelength (λ_k) while reflecting all others.

Fig. 10.26 Passband sharpening of a TFF when the number of resonance cavities increases
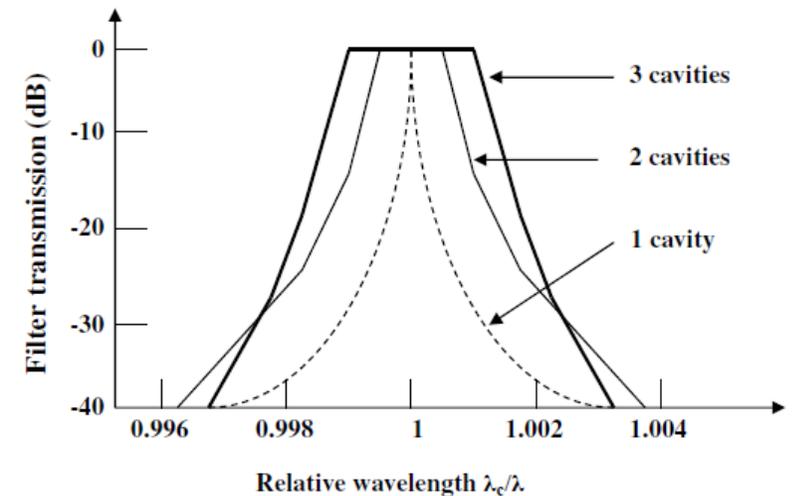
Applications of Etalon Theory

- TFFs are available in a wide range of passbands (from 50 GHz to 800 GHz or more).

Table 10.6 Typical parameter values of commercial available 50-GHz thin-film filters

| Parameter	Unit	Value
Channel passband	GHz	>±10 at 0.5 dB
Insertion loss at f_c ±10 GHz	dB	<3.5
Polarization-dependent loss	dB	<0.20
Isolation (adjacent channels)	dB	>25
Isolation (nonadjacent channels)	dB	>40
Optical return loss	dB	>45
Polarization-mode dispersion	ps	<0.2
Chromatic dispersion	ps/nm	<50

TFF Applications to WDM Links

- To create a multiplexing device for combining or separating N wavelength channels, one needs to cascade $N - 1$ thin-film filters.

- The filters are arranged physically at a slight angle.

- This angular arrangement is necessary to direct the reflected light from one TFF to the next in the cascade.

- Each specific filter is designed to pass one unique wavelength and reflect all others.

TFF Applications to WDM Links

- In a four-wavelength example (λ_1 through λ_4), three filters are used (TFF2, TFF3, TFF4).

- TFF2 reflects λ_1 and allows λ_2 to pass through; these two then travel to the next filter.

- TFF3 allows λ_3 to pass and join the reflected stream of λ_1 and λ_2.

- TFF4 allows λ_4 to pass and join the others.

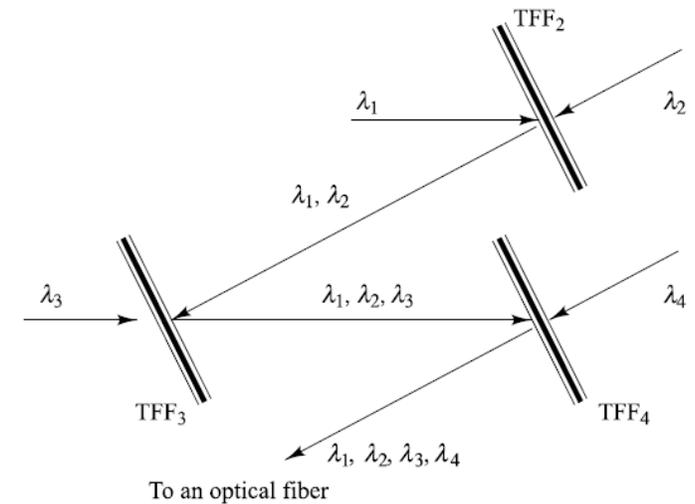- Finally, a lens mechanism couples the combined wavelengths into a fiber.

Fig. 10.27 Multiplexing of four wavelengths using thin-film filters
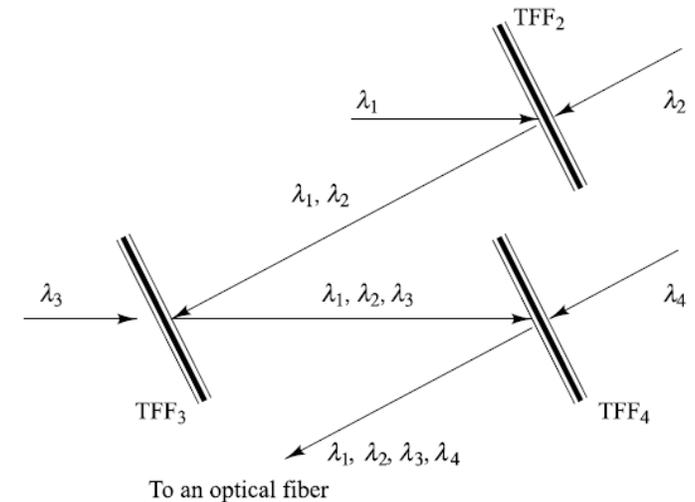
TFF Applications to WDM Links

- To perform **demultiplexing** (separating the wavelengths), the direction of the light is simply reversed.

Fig. 10.27 Multiplexing of four wavelengths using thin-film filters

TFF Applications to WDM Links

- A major limitation of this architecture is signal loss.

- Because light loses some power at each filter step (and the filters are not perfect), the loss accumulates.

- Due to this accumulated loss, TFF architectures are usually limited to 16 channels or less.

TFF Applications to WDM Links

Table 10.7 Typical performance parameters for 8-channel DWDM and CWDM multiplexers based on thin-film-filter technology

Parameter	50-GHz DWDM	100-GHz DWDM	20-nm CWDM
Center wavelength accuracy	±0.1 nm	±0.1 nm	±0.3 nm
Channel passband @ 0.5-dB bandwidth	±0.20 nm	±0.11 nm	±6.5 nm
Insertion loss (dB)	≤1.0	≤1.0	≤2.0
Ripple in passband (dB)	≤0.5	≤0.5	≤0.5
Adjacent channel isolation (dB)	≥23	≥20	≥15
Directivity (dB)	≥50	≥55	≥50
Optical return loss (dB)	≥40	≥50	≥45
Polarization dependent loss (dB)	≤0.1	≤ 0.1	≤0.1
Thermal wavelength drift (nm/°C)	<0.001	<0.001	<0.003
Optical power capability (mW)	500	500	500

WDM Applications of Diffraction Gratings

WDM Applications of Diffraction Gratings

- A diffraction grating is a conventional optical device used to **spatially separate** different wavelengths within a beam of light.

- The device consists of diffracting elements (such as narrow parallel slits or grooves) separated by a distance comparable to the wavelength of the light.

- These elements can be either **reflective** (reflection grating) or **transmitting** (transmission grating).

- A key advantage of diffraction gratings is that separating and combining wavelengths is a **parallel process**, whereas fiber-based Bragg gratings use a serial process.
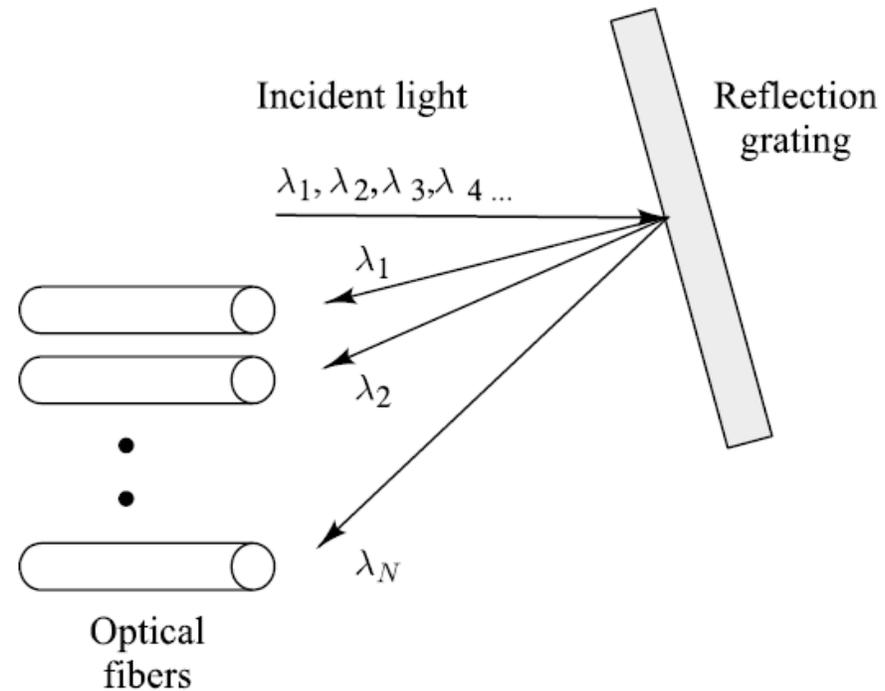
WDM Applications of Diffraction Gratings

- **Reflection gratings** feature fine etched parallel lines on a reflective surface.

- Light bounces off the grating at an angle dependent on its wavelength, causing the light to "fan out" into a spectrum.

- In DWDM applications, individual reception fibers are placed at the specific positions where each wavelength is focused.

- The device is **reciprocal**: if different wavelengths enter via individual input fibers, they will be focused back into a single output fiber (multiplexing).

- Photodiode arrays can replace receiving fibers for power monitoring functions.

WDM Applications of Diffraction Gratings

Fig. 10.32 The angle at which reflected light leaves a reflection grating depends on its wavelength

Incident light

Reflection grating

$\lambda_1, \lambda_2, \lambda_3, \lambda_4 \dots$

λ_1

λ_2

λ_N

Optical fibers

WDM Applications of Diffraction Gratings

- A common type of transmission grating is the **phase grating**, which uses a periodic variation of the refractive index.

- These gratings are characterized by the Q-parameter:

$$Q = \frac{2\pi \lambda d}{n_g \Lambda^2 \cos \alpha}$$

where λ is wavelength, d is the thickness of the grating, n_g is the refractive index of the material, Λ is the grating period, and α is the incident angle
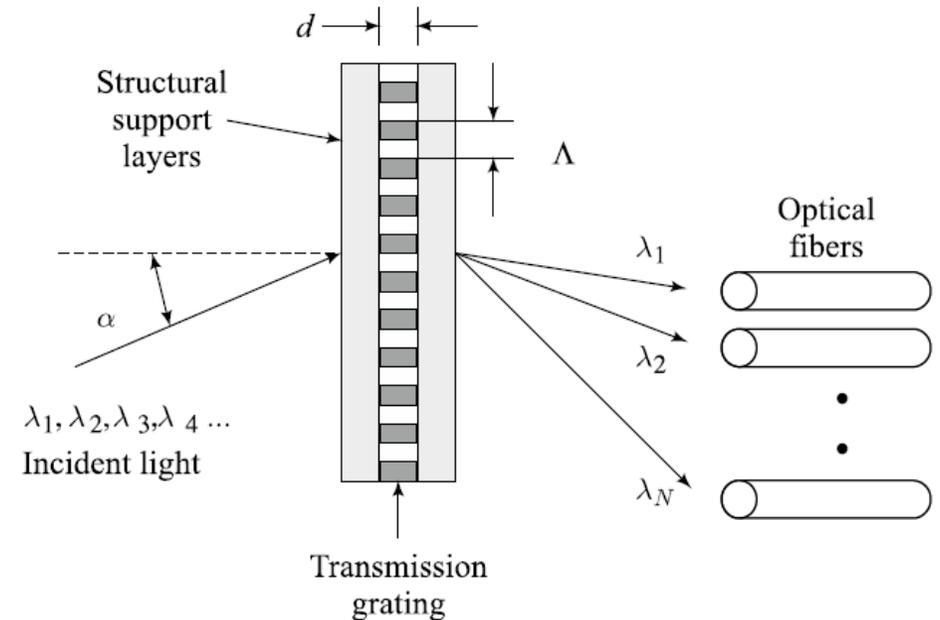
Structural support layers

$\lambda_1, \lambda_2, \lambda_3, \lambda_4 \ldots$
Incident light

Optical fibers

Transmission grating

Fig. 10.33 Each wavelength emerges at a slightly different angle after passing through a transmission grating

WDM Applications of Diffraction Gratings

- The phase grating is called *thin* for $Q < 1$ and *thick* for $Q > 10$.

- After a spectrum of wavelength channels passes through the grating, each wavelength emerges at a slightly different angle and can be focused into a receiving fiber.
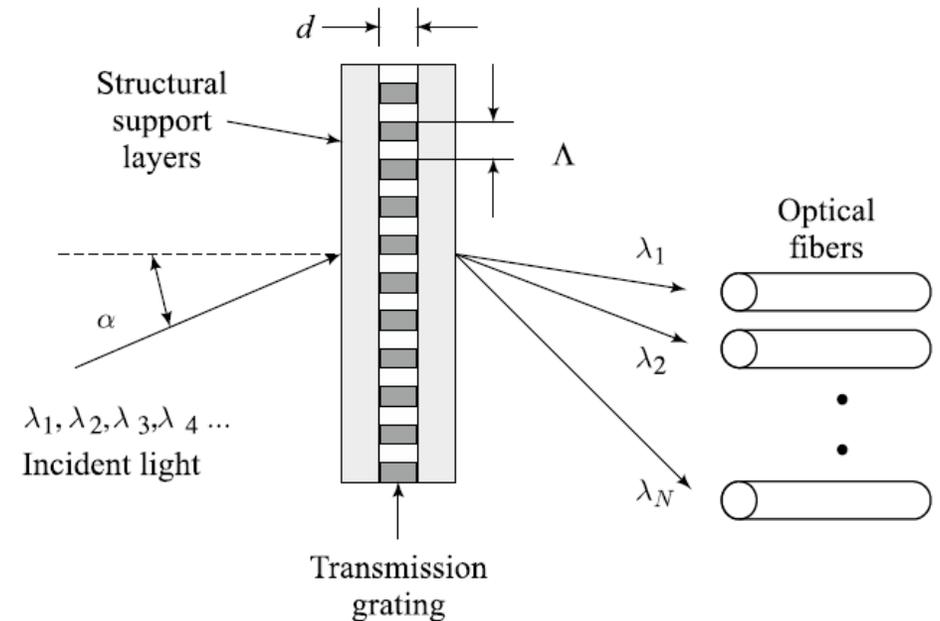
Fig. 10.33 Each wavelength emerges at a slightly different angle after passing through a transmission grating

Reference

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