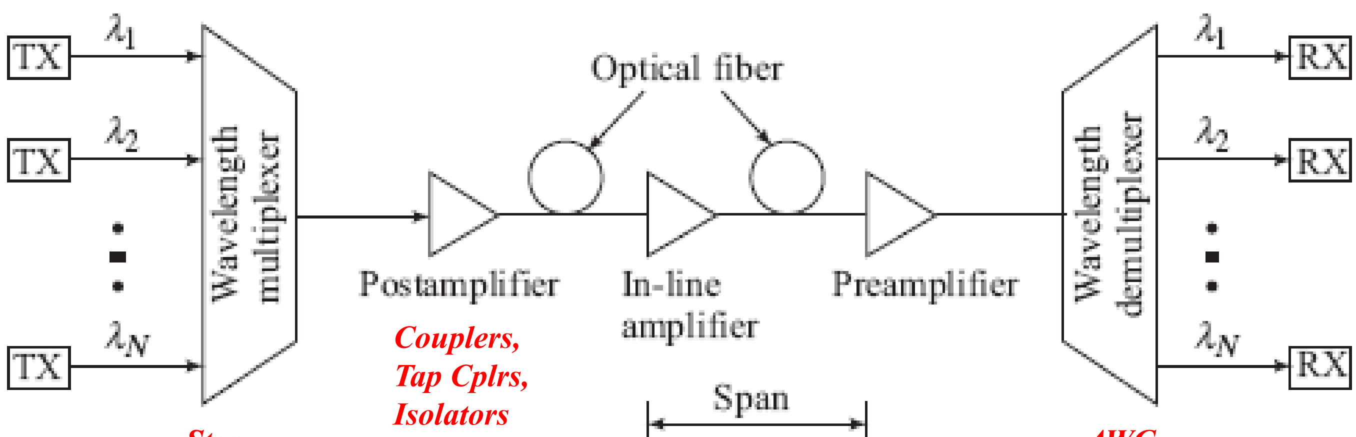
Optical Fiber Communications

Chapter 10

WDM Concepts and Components

Overview of WDM

- **A characteristic of WDM is that the *discrete wavelengths form an orthogonal set of carriers* that can be separated, routed, and switched without interfering with each other.**
- **WDM networks require a variety of *passive and active devices* to *combine, distribute, isolate, and amplify optical power at different wavelengths*.**



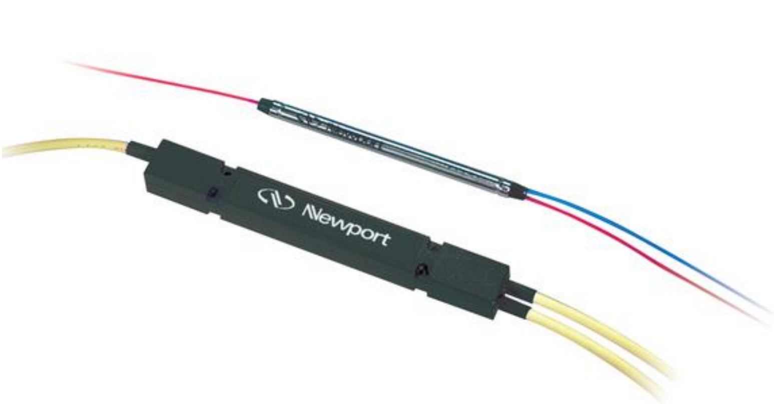
Isolators

Star Couplers

AWG
FBG,
Optical Filters

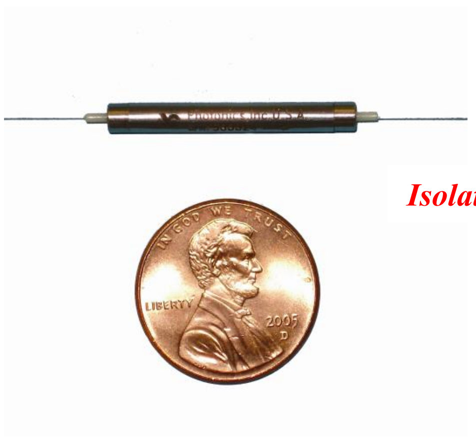
PASSIVE DEVICES BEING USED

Optical Passive Components



1 x 2
Coupler

Circulator



Isolators

1 x 8
Star Coupler

Optical Add/Drop Multiplexing

- An ***optical add/drop multiplexer* (OADM)** allows the insertion or extraction of one or more wavelengths from a fiber at a network node.
- **Most OADMs are constructed using WDM elements** such as a series of dielectric thin-film filters, an AWG, a set of liquid crystal devices, or a series of fiber Bragg gratings used in conjunction with optical circulators.
- **The OADM architecture** depends on factors such as the number of wavelengths to be dropped/added, the OADM modularity for upgrading flexibility, and what groupings of wavelengths should be processed.

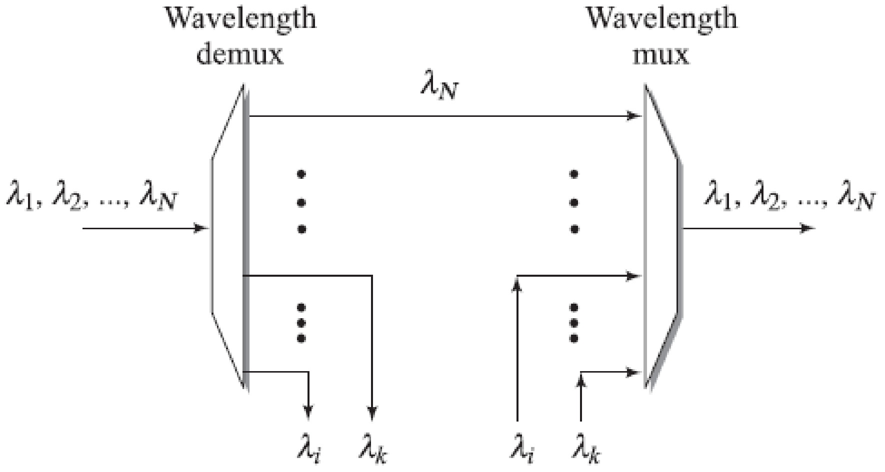


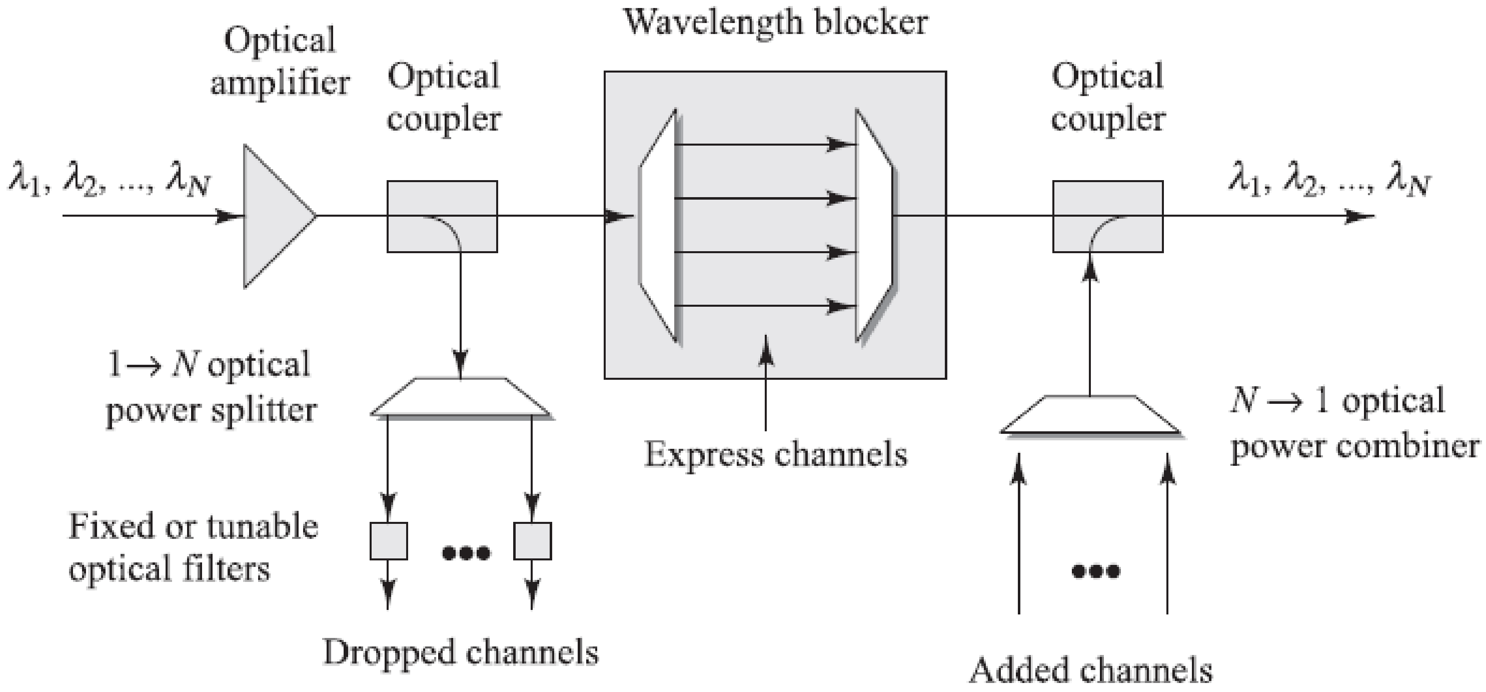
Fig. 13.21 *Simple passive optical add/drop multiplexer*

Reconfigurable OADM (ROADM)

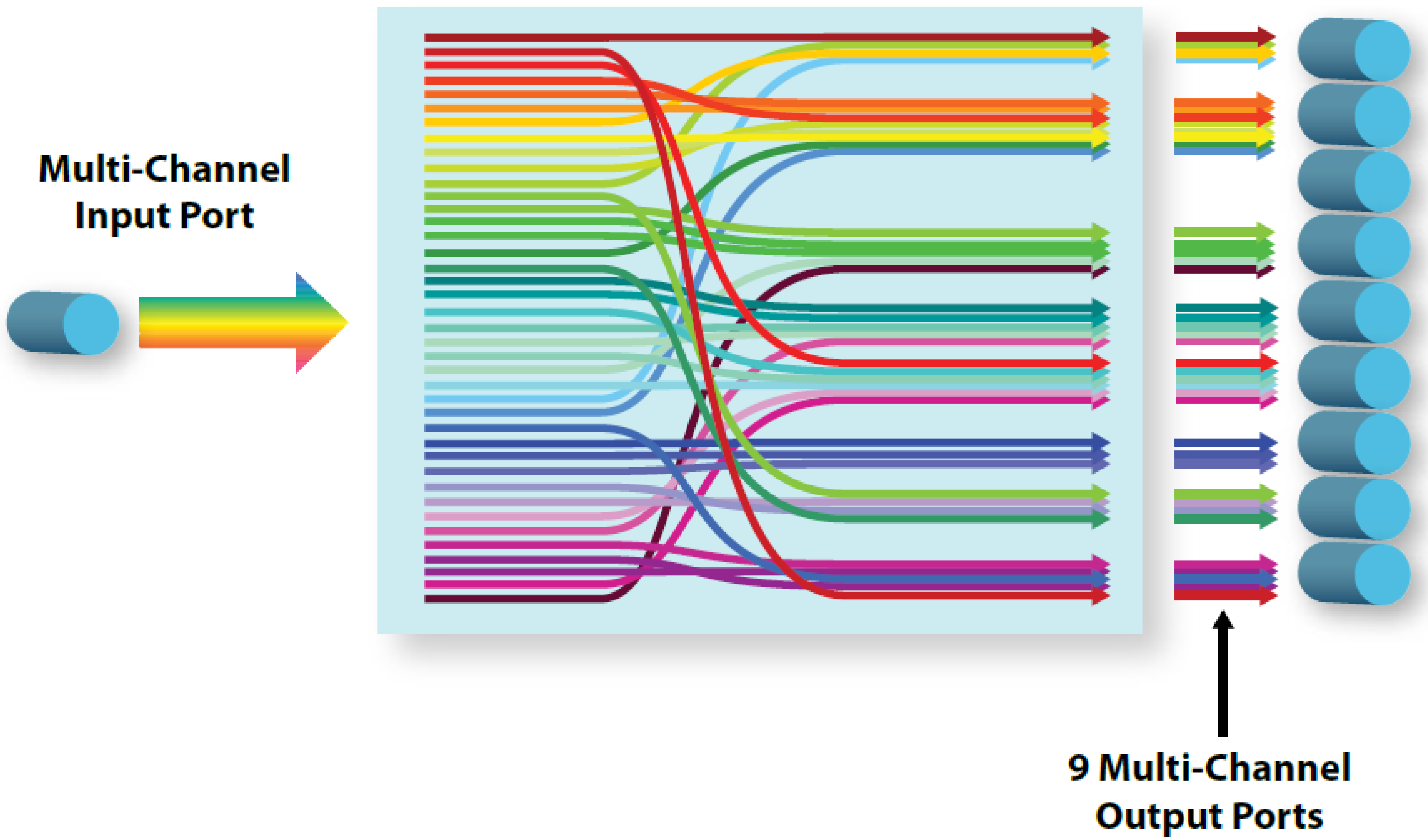
- **ROADMs can be reconfigured by a network operator within minutes from a remote network-management console.**
- **ROADM architectures include *wavelength blockers, arrays of small switches,* and *wavelength-selective switches*.**
- **ROADM features:**
  - **Wavelength dependence*.* When a ROADM is *independent of wavelength*, it is *colorless* or has *colorless ports.***
  - **ROADM degree is the number of bidirectional multiwavelength interfaces the device supports. Example: A degree-2 ROADM has 2 bidirectional WDM interfaces and a degree-4 ROADM supports 4 bidirectional WDM interfaces.**
  - **Express channels allow a selected set of wavelengths to pass through the node without the need for OEO conversion.**

Wavelength Blocker Configuration

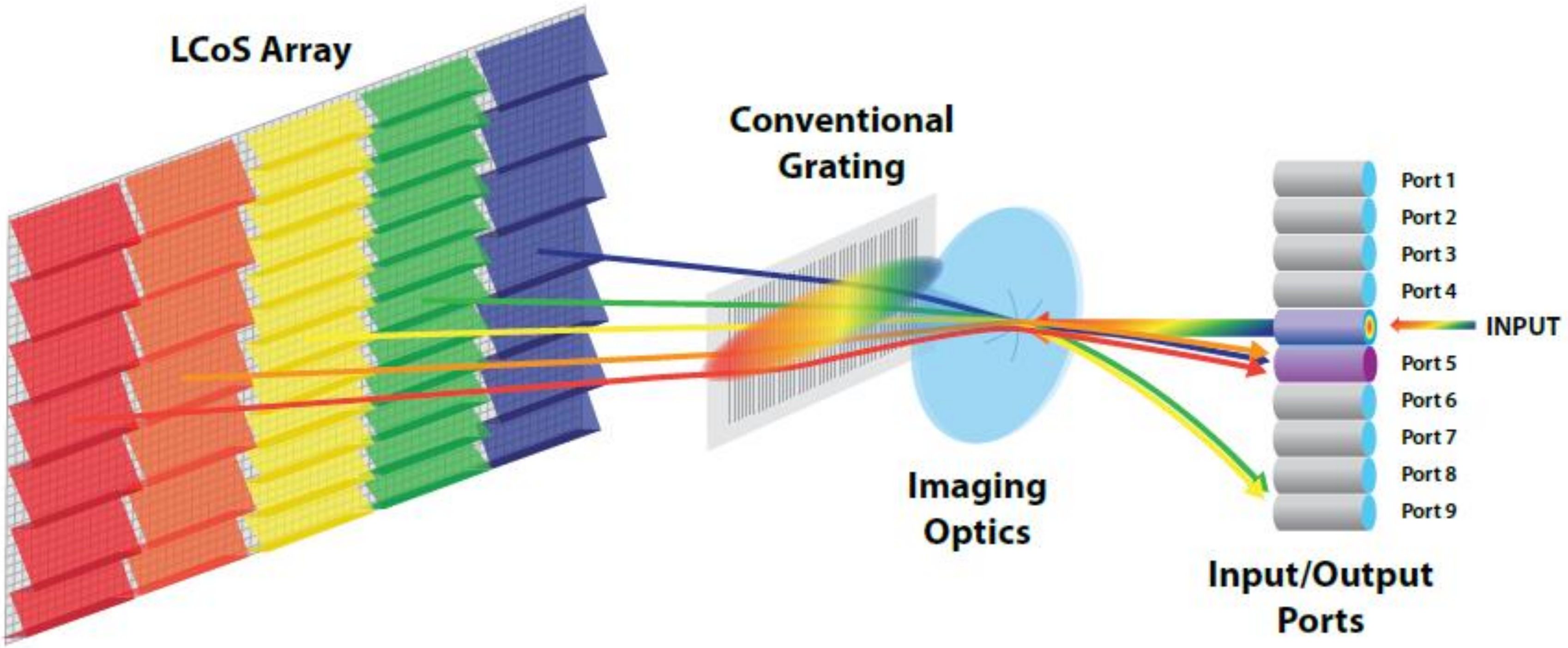
The simplest ROADM configuration uses a *broadcast-and-select approach:*



WSS (Wavelength Selective Switch)



WSS (Wavelength Selective Switch)

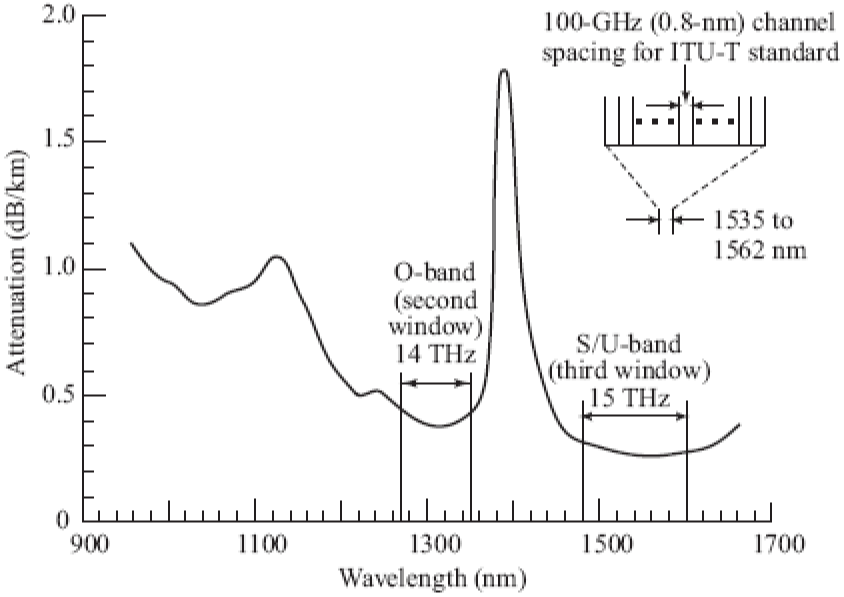


WSS (Wavelength Selective Switch)

WDM Spectral Bands

- Many independent narrowband regions in the O- through L-bands can be used simultaneously.
- These regions are designated either in terms of ***spectral width*** or ***optical bandwidth***.
- The optical bandwidth $\Delta\nu$ related to a particular spectral width $\Delta\lambda$ is found by differentiating $c = \lambda\nu$; for $\Delta\lambda \ll \lambda^2$

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



WDM Standards

- ITU-T Recommendation G.694.1 specifies DWDM operation in the S-, C-, and L-bands for frequency spacing of 100 to 12.5 GHz (or, equivalently, 0.8 to 0.1 nm at 1550 nm).
- **The number NM is used by ITU-T to designate a specific 19N.M-THz C-band 100-GHz channel, e.g., the frequency 194.3 THz is ITU channel 43.**

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

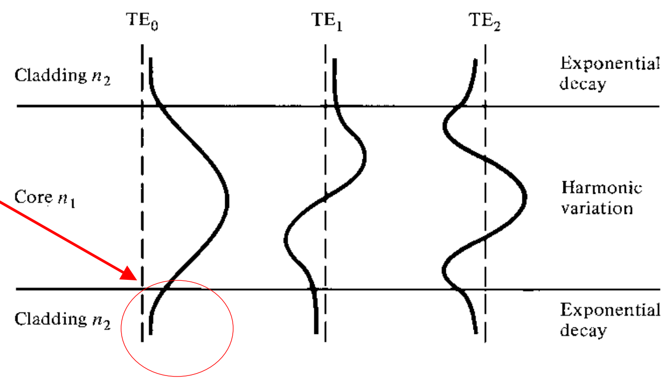
10.2 Passive Optical Couplers

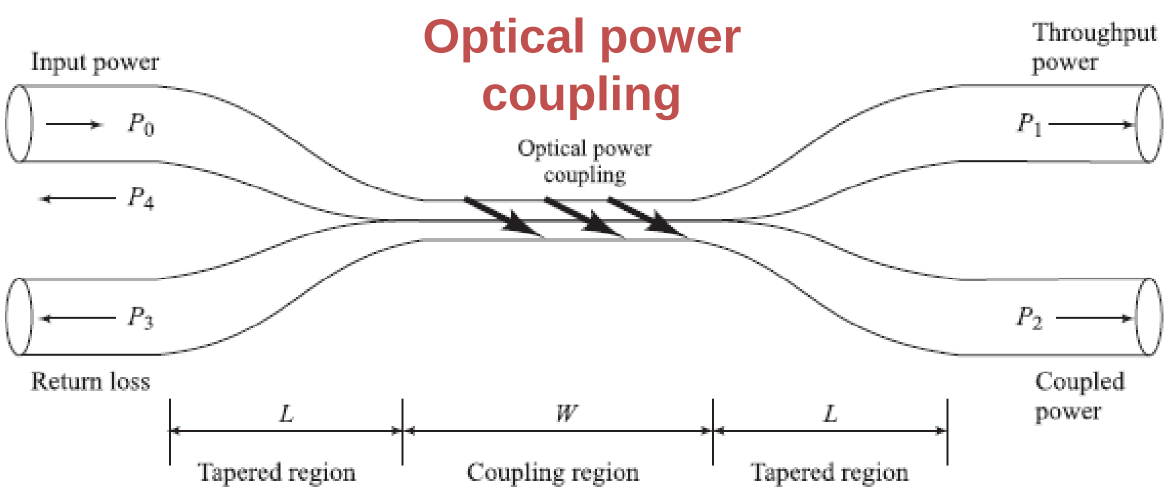
- **Passive devices operate completely in the optical domain to split and combine light streams.**
- **They include N × N couplers (with N ≥ 2), power splitters, power taps, and star couplers.**
- **They can be fabricated either from optical fibers or by means of planar optical waveguides using material such as LiNbO3, InP, silica, silicon oxynitride, or various polymers.**

The 2 × 2 Fiber Coupler

- P_0 is the input power, P_1 is the throughout power, and P_2 is the power coupled into the second fiber.
- P_3 and P_4 are extremely low signal levels (-50 to -70 dB below the input level) resulting from backward reflections and scattering in the device

The evanescent tail from one fiber core couples into another closely spaced fiber core





Performance of an Optical Coupler

$$\text{Splitting ratio} = \left(\frac{P_2}{P_1 + P_2}\right) \times 100\%$$

- **3-dB coupler: $P_1 = P_2 = 0.5\ P_0$**
- **Tap coupler: $P_2 = 0.005\ P_0$ (- 23 dB)**

$$\text{Excess loss} = 10\log\left(\frac{P_0}{P_1 + P_2}\right)$$

$$\text{Insertion loss} = 10\log\left(\frac{P_i}{P_j}\right)$$

$$\text{Return loss} = 10\log\left(\frac{P_3}{P_0}\right)$$

Example Coupler Performance

Example 10.4 A 2 × 2 biconical tapered fiber coupler has an input optical power level of $P_0 = 200\ \mu W$. The output powers at the other three ports are $P_1 = 90\ \mu W$, $P_2 = 85\ \mu W$, and $P_3 = 6.3$ nW. What are the coupling ratio, excess loss, insertion losses, and return loss for this coupler?

Solution: From Eq. 10.4, the coupling ratio is

$$\text{Coupling ratio} = \left(\frac{85}{90 + 85}\right) \times 100\% = 48.6\%$$

From Eq. 10.5, the excess loss is

$$\text{Excess loss} = 10 \log\left(\frac{200}{90 + 85}\right) = 0.58 \text{ dB}$$

Using Eq. 10.6, the insertion losses are

$$\text{Insertion loss (port 0 to port 1)} = 10 \log\left(\frac{200}{90}\right) = 3.47 \text{ dB}$$

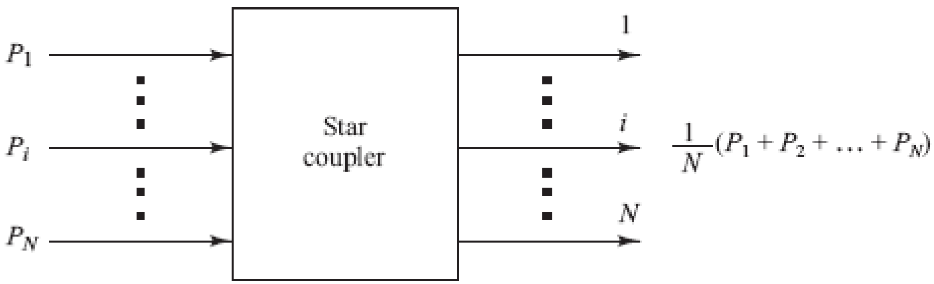
$$\text{Insertion loss (port 0 to port 2)} = 10 \log\left(\frac{200}{85}\right) = 3.72 \text{ dB}$$

The return loss is given by Eq. 10.7 as

$$\text{Return loss} = 10 \log\left(\frac{6.3 \times 10^{-3}}{200}\right) = -45 \text{ dB}$$

Star Couplers

- **In general, an N × M coupler has N inputs and M outputs**



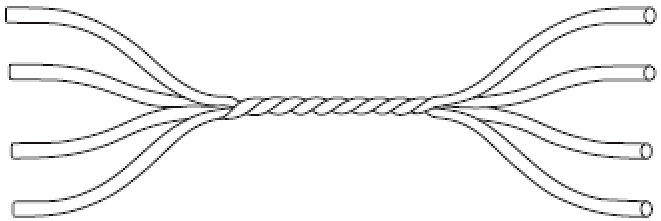


Fig. 10.13 *Generic 4 × 4 fused-fiber star coupler fabricated by twisting, heating, and pulling on four fibers to fuse them together*

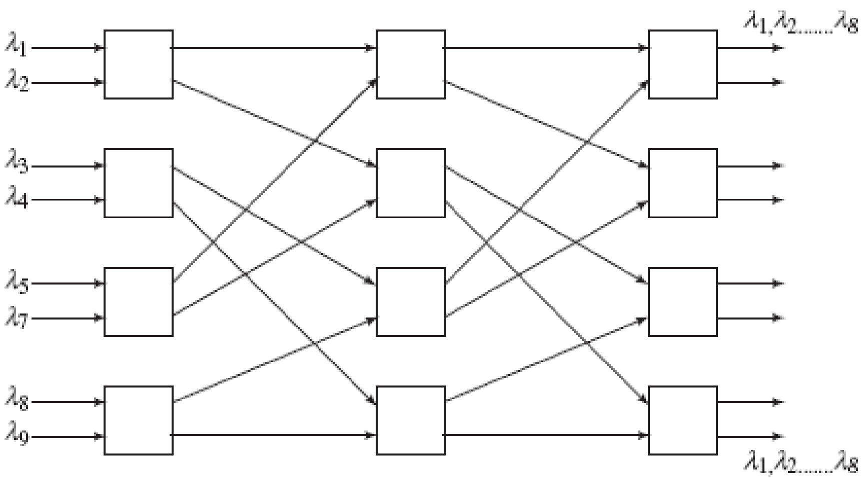
$$\text{Splitting loss} = -10\log\left(\frac{1}{N}\right) = 10\log N$$

$$\text{Fiber star excess loss} = 10\log\left(\frac{P_{in}}{\sum_{i=1}^{N} P_{out,\,i}}\right)$$

N × N Star Coupler

- Can construct star couplers by cascading 3-dB couplers
- The number of 3-dB couplers needed to construct an N × N star is

$$N_c = \frac{N}{2}\log_2 N = \frac{N}{2}\frac{\log N}{\log 2}$$



Example of an 8 × 8 star coupler formed by interconnecting twelve 2 × 2 couplers

Example 10.8 A device engineer wants to construct a 32 × 32 coupler from a cascade of 2 × 2 3-dB single-mode fiber couplers. How many 2 × 2 elements are needed for this?

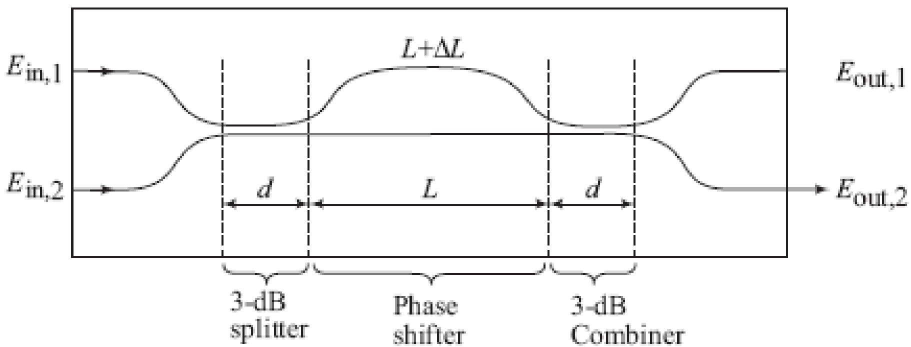
Solution: In this case there will be 16 coupler elements in the vertical direction. From Eq. (10.26), we find how many 2 × 2 elements are needed:

$$N_c = \frac{32}{2}\frac{\log 32}{\log 2} = 80$$

Mach-Zehnder Interferometer Multiplexers

- **By splitting the input beam and introducing a phase shift in one of the paths, the recombined signals will interfere constructively at one output and destructively at the other.**
- **In the central region, when the signals in the two arms come from the same light source, the outputs from these two guides have a phase difference**

$$\Delta\phi = \frac{2\pi n_1}{\lambda} L - \frac{2\pi n_2}{\lambda}(L + \Delta L)$$



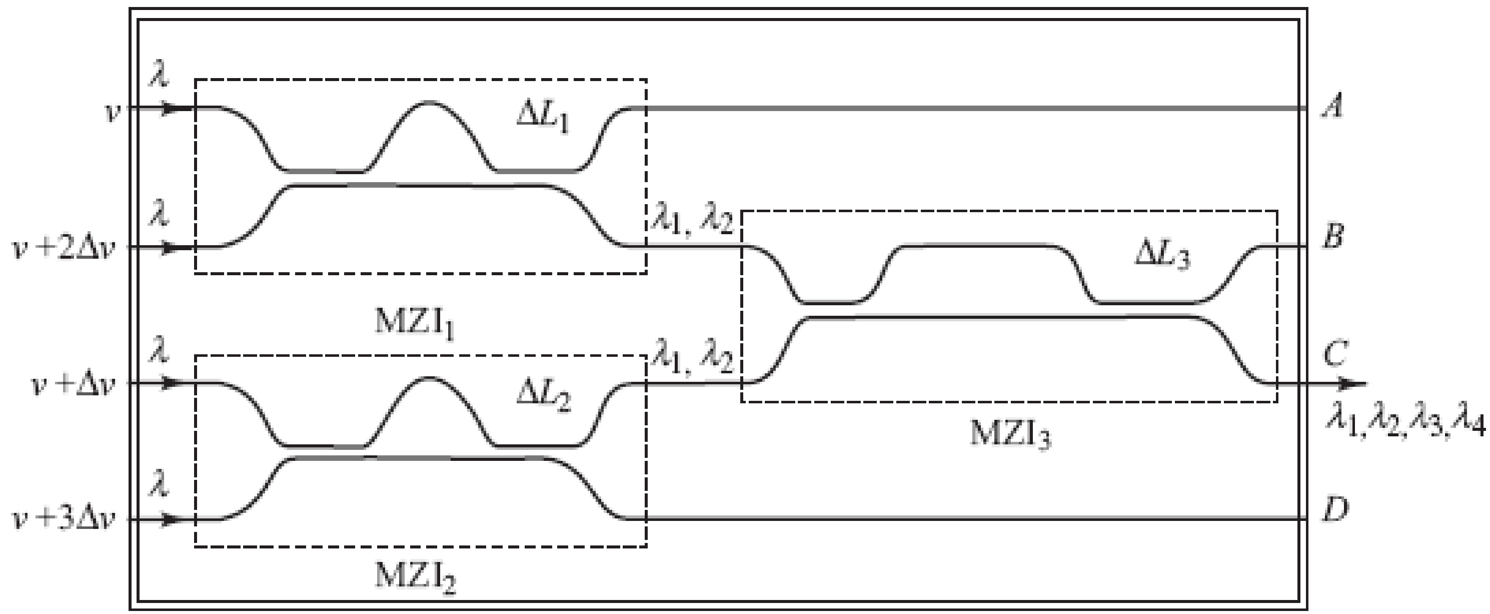
Example 10.10 (*a*) Assume that the input wavelengths of a 2 × 2 silicon MZI are separated by 10 GHz (i.e., $\Delta\lambda = 0.08$ nm at 1550 nm). With $n_{eff} = 1.5$ in a silicon waveguide, we have from (Eq. 10.41) that the waveguide length difference must be

$$\Delta L = \frac{3 \times 10^8 \text{ m/s}}{2(1.5)10^{10}\text{/s}} = 10 \text{ mm}$$

(*b*) If the frequency separation is 130 GHz (i.e., $\Delta\lambda = 1$ nm), then ΔL, = 0.77 mm.

Cascaded MZIs

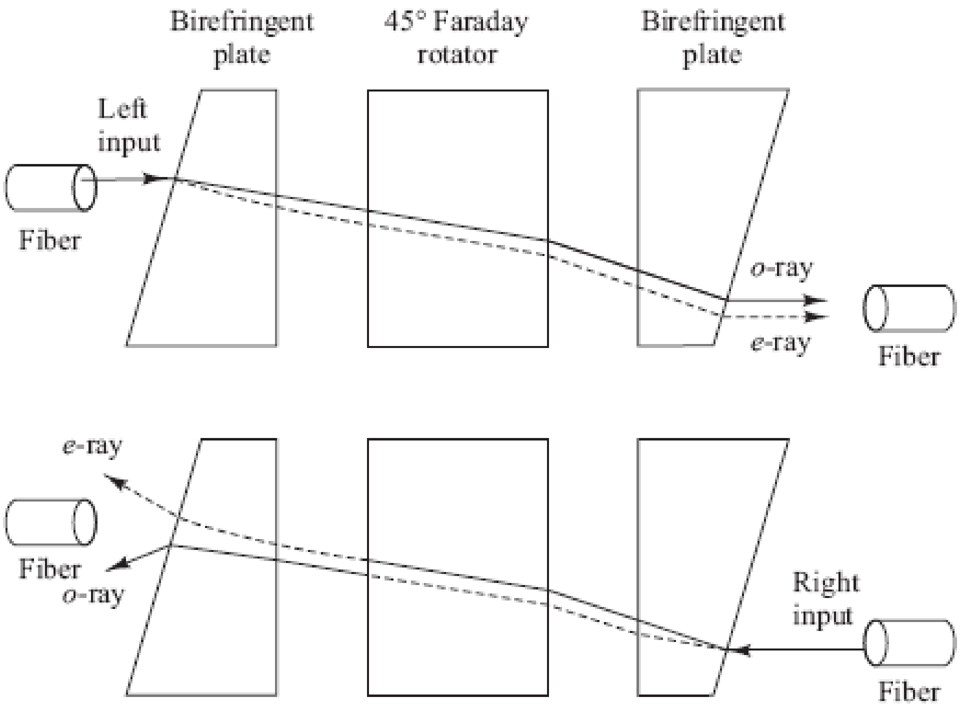
- Using basic 2 × 2 MZIs, any size N × N multiplexer (with $N = 2^n$) can be constructed.
- Each module i has a different ΔL_i in order to have all wavelengths exit at port C



Optical Isolators

Optical isolators allow light to pass in only one direction.

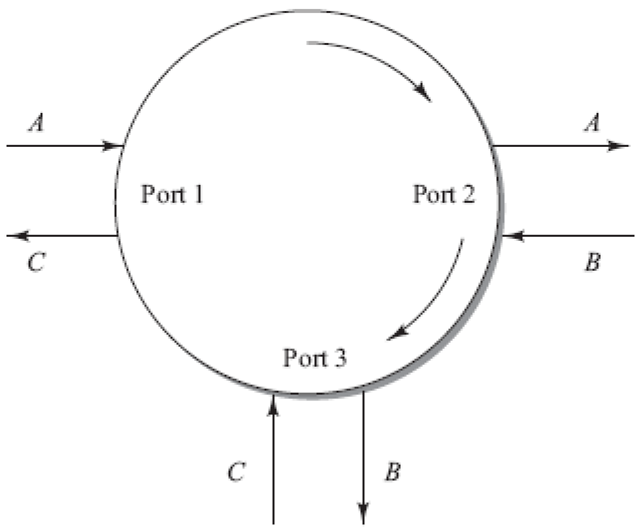
- **This prevents scattered or reflected light from traveling in the reverse direction.**
- **E.g., can keep backward-traveling light from entering a laser diode and possibly causing instabilities in the optical output.**



Polarization-independent isolator made of three miniature optical components

Optical Circulators

- **An *optical circulator* is a nonreciprocal multiport passive device that directs light sequentially from port to port in only one direction.**
- **In the 3–port example, an input on port 1 is sent out on port 2, an input on port 2 is sent out on port 3, and an input on port 3 is sent out on port 1.**



Isolator and Circulator Parameters

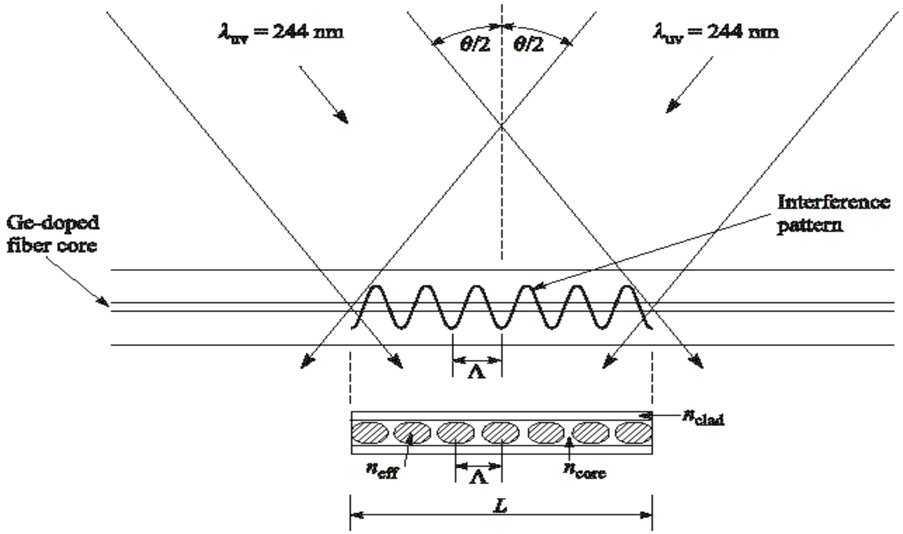
Table 10.3 *Typical parameter values of commercially available optical isolators*

Parameter	*Unit*	*Value*
Central wavelength λc	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

Table 10.4 *Typical parameter values of commercially available optical circulators*

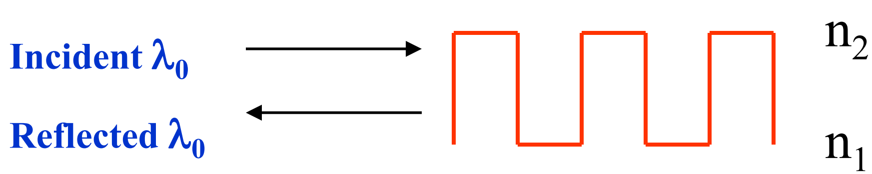
Parameter	*Unit*	*Value*
Wavelength band	nm	C-band: 1525–1565 L-band: 1570–1610
Insertion loss	dB	< 0.6
Channel isolation	dB	> 40
Optical return loss	dB	> 50
Operating power	mW	< 500
Polarization-dependent loss	dB	< 0.1
Polarization-mode dispersion	ps	< 0.1
Size (diameter × length)	mm	5.5 × 50

Fiber Bragg Grating (FBG)



Example formation:
Two ultraviolet beams will create a permanent interference pattern in a GeO_2-doped silica fiber to form a periodic index variation along the axis.

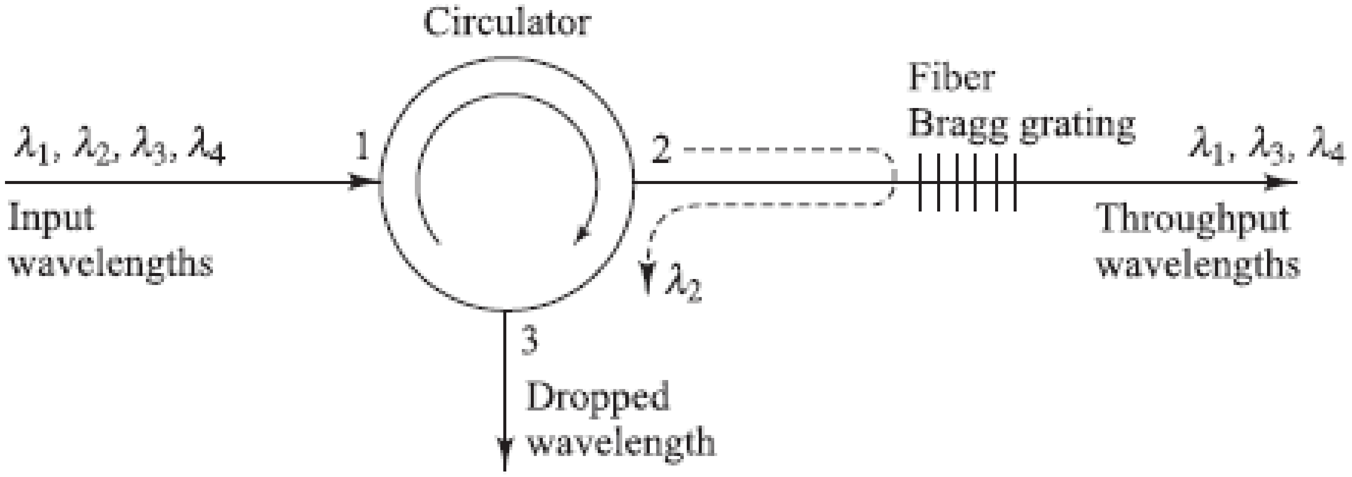
Operating Principle: Incident optical wave at λ_0 will be reflected back if the following grating condition is met: $\lambda_0 = 2n_{eff}\Lambda$, where n_{eff} is average weighting of n_1 and n_2 and Λ = grating period (periodicity of index variation)



Fiber Bragg Grating Application

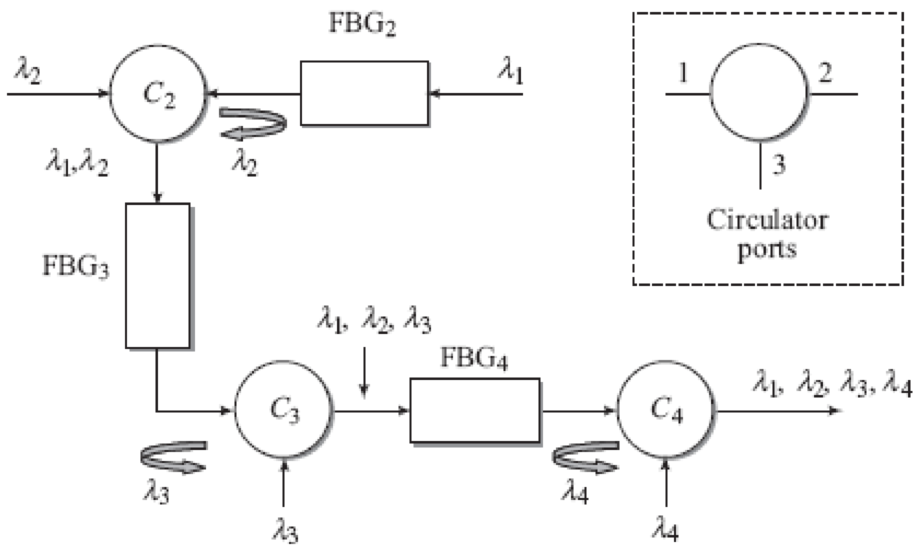
<u>**Demultiplexing (wavelength dropping) process:**</u>

- Consider 4 wavelengths entering a circulator at port 1.
- All wavelengths exit from port 2.
- The fiber Bragg grating is designed to reflect λ_2 and pass all other wavelengths.
- After reflection, λ_2 enters port 2 and comes out of port 3.



Multiplexing of Four Wavelengths

- One needs to cascade N-1 FBGs and N-1 circulators for combining or separating N wavelengths.
- Example for multiplexing four wavelengths using three FBGs and three circulators (labeled C2, C3, and C4). The fiber grating filters labeled
- FBG2, FBG3, and FBG4 are constructed to reflect wavelengths λ_2, λ_3, and λ_4, respectively, and to pass all others.

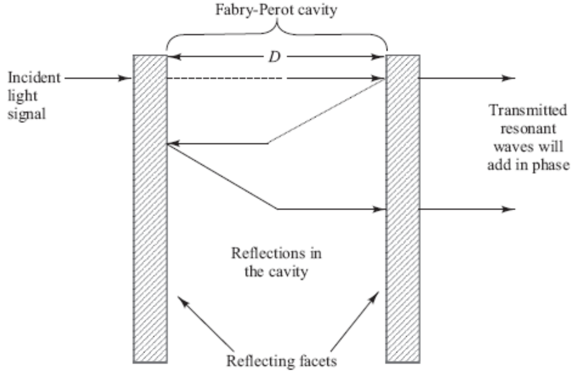


Etalon Theory

- **A dielectric thin-film filter (TFF) is used as an optical bandpass flter.**
- **It allows a very narrow wavelength band to pass straight through it and reflects all other wavelengths.**
- **The basis of these devices is a reflective mirror surfaces called *a Fabry-Perot interferometer* or an *etalon.***
- **The transmission T of an ideal etalon in which there is no light absorption by the mirrors is an Airy function**

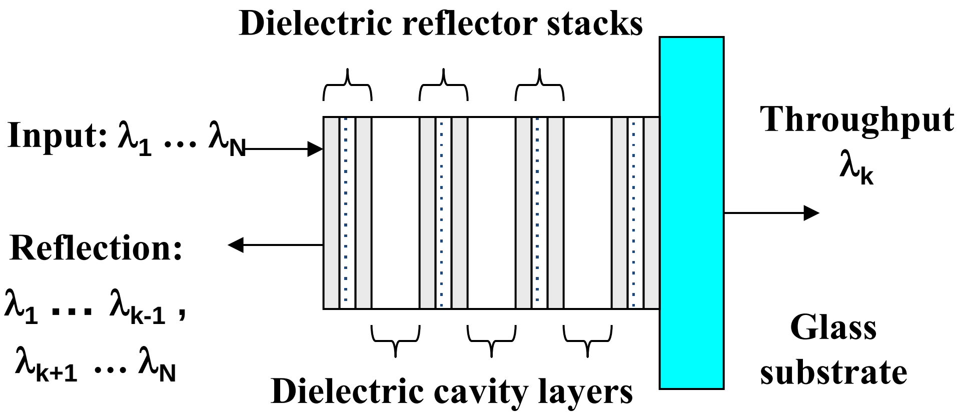
$$T = \left[1 + \frac{4R}{(1-R)^2}\sin^2\left(\frac{\phi}{2}\right)\right]^{-1}$$

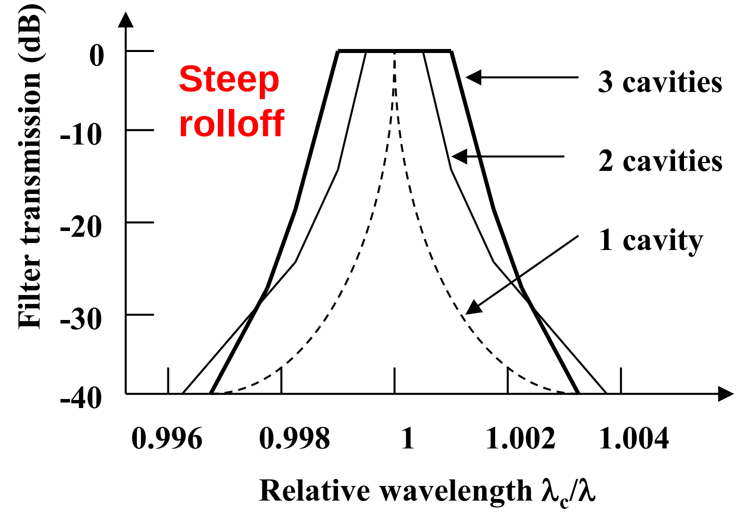
- **The periodicity of the device is called the free spectral range or FSR**



$$\mathrm{FSR} = \frac{\lambda^2}{2nD}$$

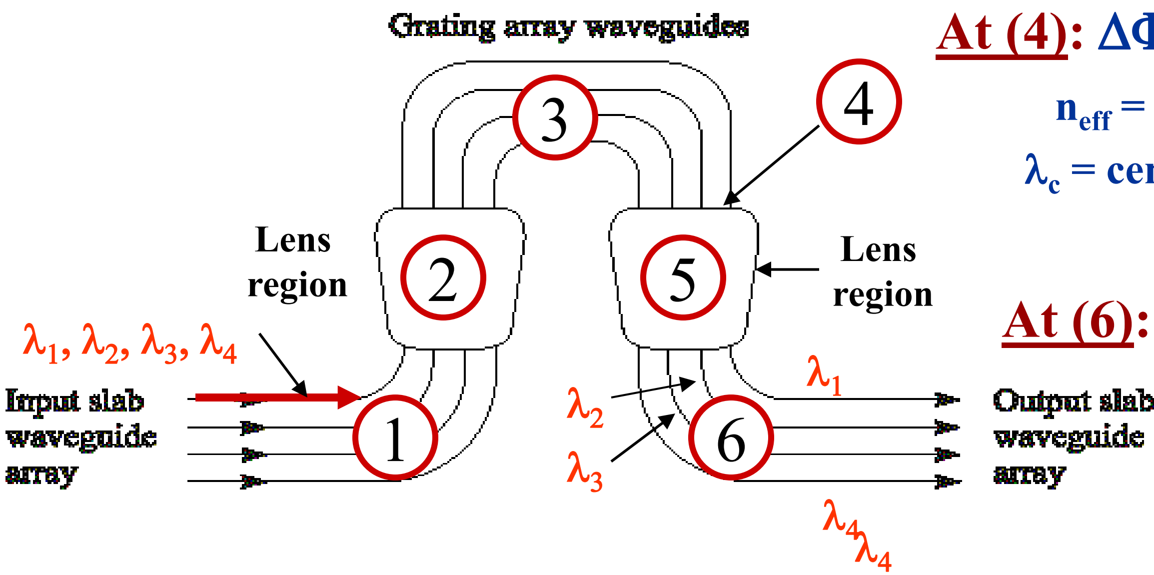
Dielectric Thin-Film Filter





- A **thin-film dielectric resonant cavity filter** is a Fabry-Perot interferometer
- Mirrors surrounding cavity are multiple reflective dielectric thin-film layers
- Cavity length determines a particular wavelength to pass & reflects all others
- Flat passbands with steep rolloffs
- Low insertion loss: 0.5 dB at peak and < 3.5 dB at center frequency ± 10 GHz
- High optical return loss (> 45 dB)
- Thin-film filters with a 50-GHz passband are commercially available

Arrayed Waveguide Grating

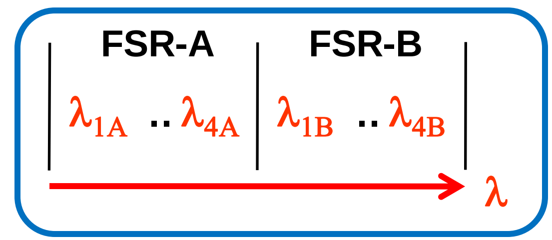


At (4): $\Delta\Phi = 2\pi\, n_{eff}\, \Delta L / \lambda_c$

n_{eff} = effective index

λ_c = center wavelength

At (6): $\Delta\lambda_{FSR} = \lambda_c^2 / (\Delta L\, n_{eff})$



The input waveguides (1) enter a lens region (2)

(2) divides the power among the different waveguides in the grating array (3)

Each grating waveguide has a precise length difference ΔL with its neighbors

Light in each waveguide emerges with different phase delays ΔΦ at (4)

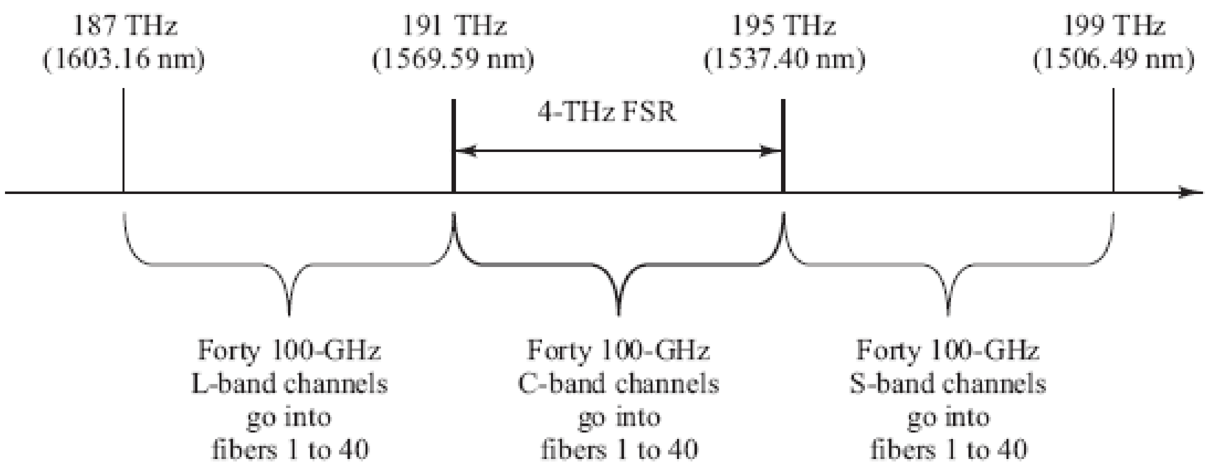
The second lens region (5) refocuses the light from all array waveguides onto the output waveguide array (6) [$\Delta\lambda_{FSR}$ = free spectral range = AWG periodicity]

Each wavelength is focused into a different output waveguide in region (6)

FSR Example

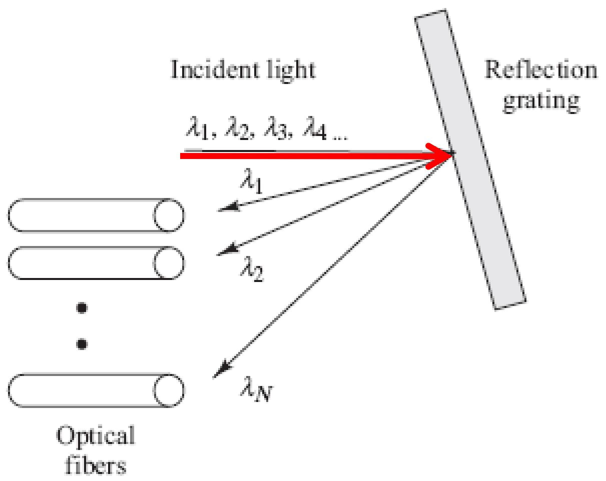
- **The FSR specifies the spectral width that will be separated across the output waveguides of an AWG**

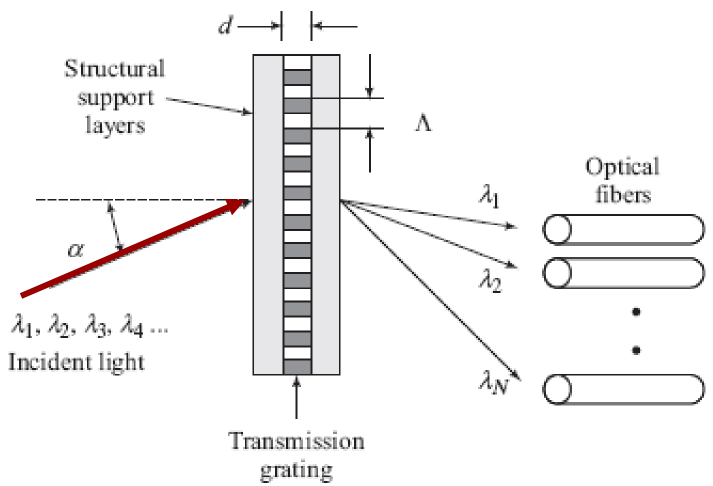
Example 10.13 As shown in Fig 10.29, suppose an AWG is designed to separate light in the 4-THz-wide frequency range in the C-band running from 195.00 THz (1537.40 nm) to 191.00 THz (1569.59 nm) into forty 100-GHz channels. Then it also will separate the next higher-frequency 4-THz spectral segment in the S-band and lower-frequency 4-THz spectral segment in the L-band into the same forty output fibers. The free spectral range $\Delta\lambda_{FSR}$ can be determined from Eq. (10.65). For the 4-THz frequency range denoted here, the center wavelength λ_c is 1550.5 nm, the free spectral range $\Delta\lambda_{FSR}$ should be at least 32.2 nm in order to separate all the wavelengths into distinct fibers, and the effective refractive index n_c is nominally 1.45 in silica. Then the length difference between adjacent array waveguides is $\Delta L = 51.49\ \mu m$.



Diffraction-Grating Couplers

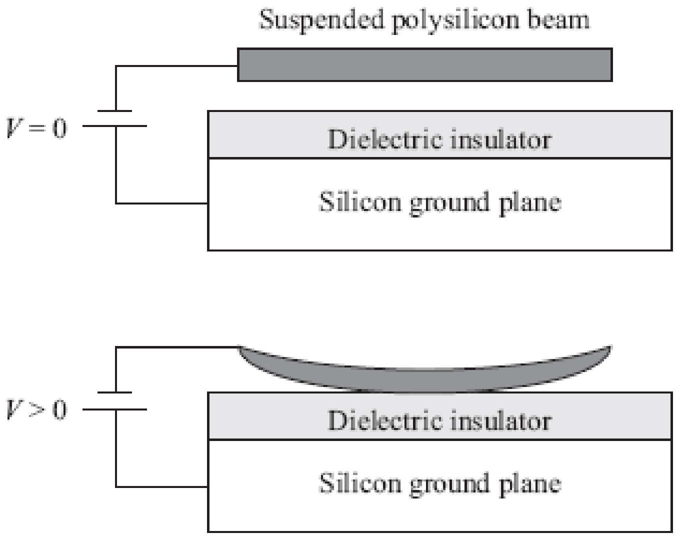
- Diffraction gratings spatially separate λs in a beam
- Reflection gratings are ruled or etched fine parallel lines on a reflective surface
- Transmission gratings have periodic index variations
- Each wavelength will reflect or refract at a different angle



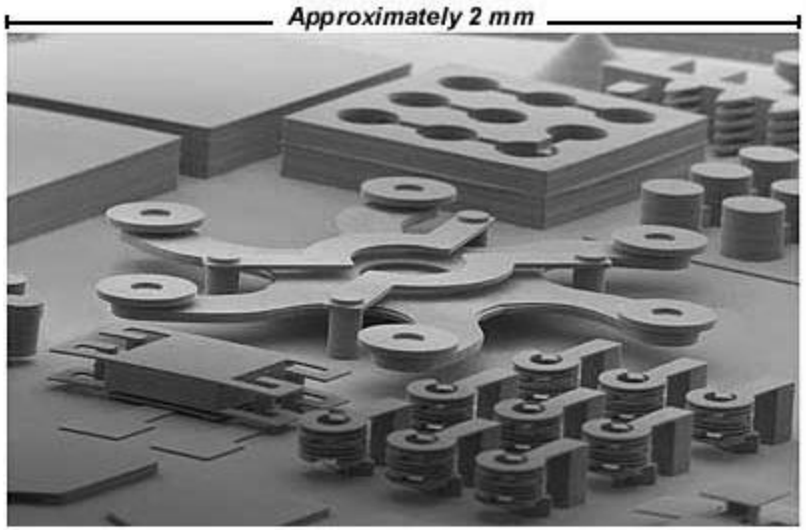


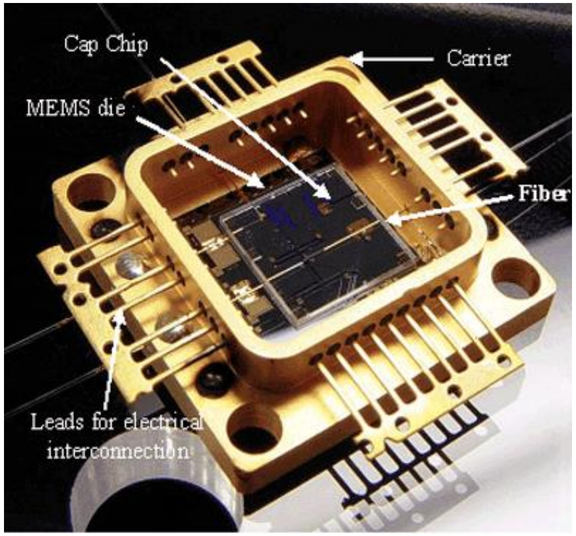
Active Optical Components

- **Active components require some type of external energy either to perform their functions or to be used over a wider operating range than a passive device, thereby offering greater application flexibility**
- **Many active optical components use micro-electrical-mechanical systems or MEMS technology**
- ***A simple example of a MEMS actuation method.***

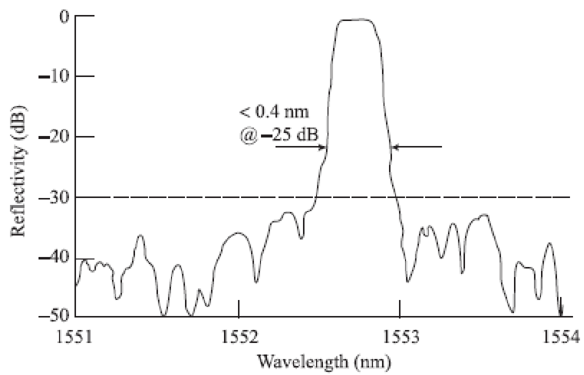


Optical MEMS switch

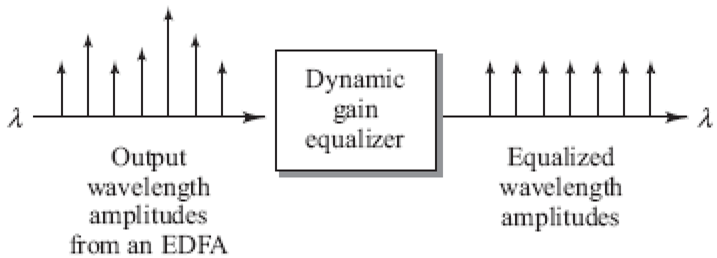




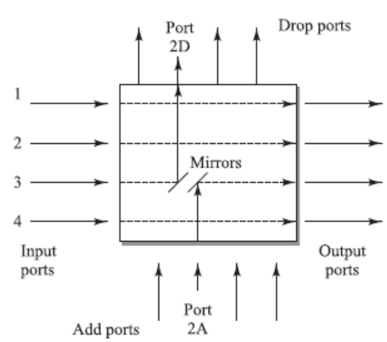
Examples of Active Devices



A tunable optical filter can be varied to select a specific narrow spectral band within a much wider optical band.



A dynamic gain equalizer (DGE) equalizes the gain profile of an erbium-doped fiber amplifier (EDFA)



An *optical add/drop multiplexer (OADM) inserts (adds) or extracts (drops)* wavelengths at a designated point in an optical network.

Tunable Dispersion Compensator

FBG based Tunable Dispersion Compensator

VIPA based Tunable Dispersion Compensator

FP Etalon based Tunable Dispersion Compensator