

WDM Concepts and Components

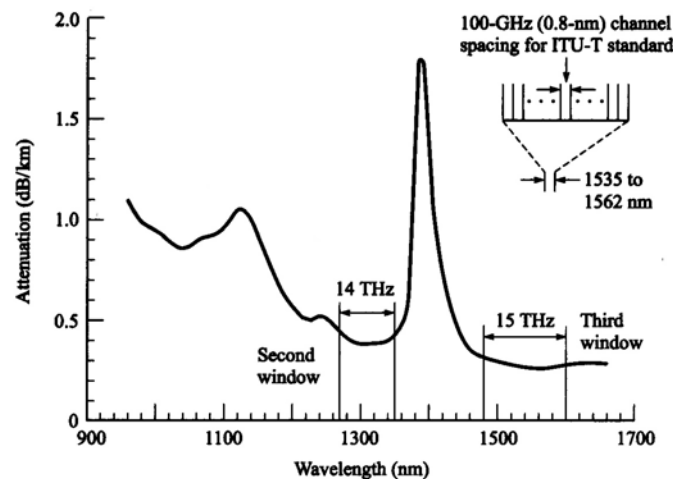
A powerful aspect of an optical communication link is that many different wavelengths can be sent along the fibre simultaneously. The technology of combining a number of wavelengths onto the same fibre is known as *wavelength-division multiplexing* or **WDM**. The key system features of **WDM** are as follows:

- *Capacity upgrade.* WDM can increase the capacity of a fibre network dramatically.
- *Transparency.* An important aspect of WDM is that each optical channel can carry any transmission format
- *Wavelength routing.* The use of wavelength-sensitive optical routing devices makes it possible to use wavelength as another dimension in designing communication network and switches.
- *Wavelength switching.* Whereas wavelength-routed networks are based on a rigid fibre infrastructure, wavelength-switched architectures allow reconfigurations of the optical layer.

WDM Concepts and Components

Operational Principles of WDM

In a standard point-to-point links, signals from different light sources use separate and uniquely assigned optical fibres. Since an optical source has a narrow linewidth, this type of transmission makes use of only a very narrow portion of the transmission bandwidth capability of a fibre. This can be seen from figure below, which depicts the attenuation of light in a silica fibre as a function of wavelength.

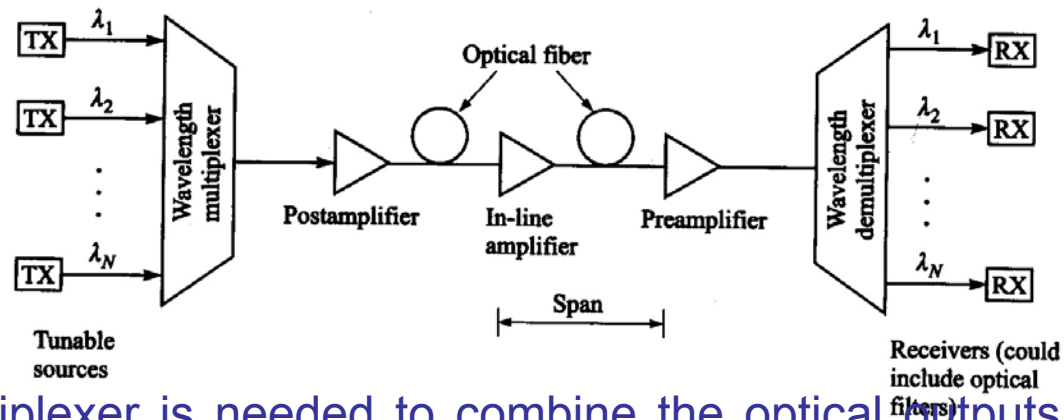


By using a number of light sources, each emitting at a different peak that is sufficiently spaced from its neighbour, the integrities of the independent message from each source are maintained.

WDM Concepts and Components

Operational Principles of WDM

The implementation of WDM network requires a variety of passive and/or active devices to combine, distribute, isolate, and amplify optical power at different wavelength. Figure below shows the use of such components in a typical WDM link.



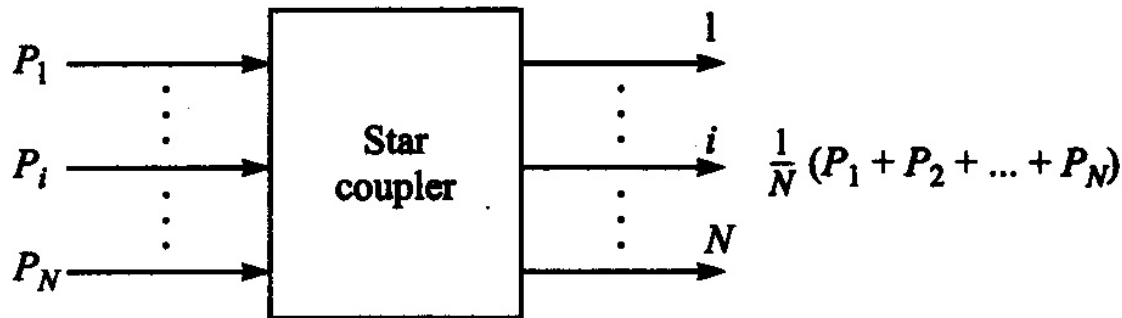
Here, a multiplexer is needed to combine the optical outputs into a serial spectrum of closely spaced wavelength signals and couple them onto a single fibre. At the receiving end, a demultiplexer is required to separate the optical signals into appropriate detection channels for signal processing.

WDM Concepts and Components

Passive Components

Passive devices operate completely in the optical domain to split and combine light streams. They include $N \times N$ couplers (with $N \geq 2$), power splitters, power taps, and star couplers.

Basically, most passive WDM devices are variations of a star-coupler concept. Figure below shows a generic star coupler, which can perform both power combining and splitting.



In the broadest application, star couplers combine the light streams from two or more input fibres and divide them among several output fibres. In the general case, the splitting is done uniformly for all wavelengths.

WDM Concepts and Components

Passive Components

A common fabrication method for an $N \times N$ splitter is to fuse together the core of N single-mode fibres over a length of few millimetres.

The optical power inserted through one of the N fibre entrance ports gets divided uniformly into the cores of the N output fibres through evanescent power coupling in the fused region.

Couplers with 64 inputs and outputs are possible, although, more commonly, the size tends to be less than 10.

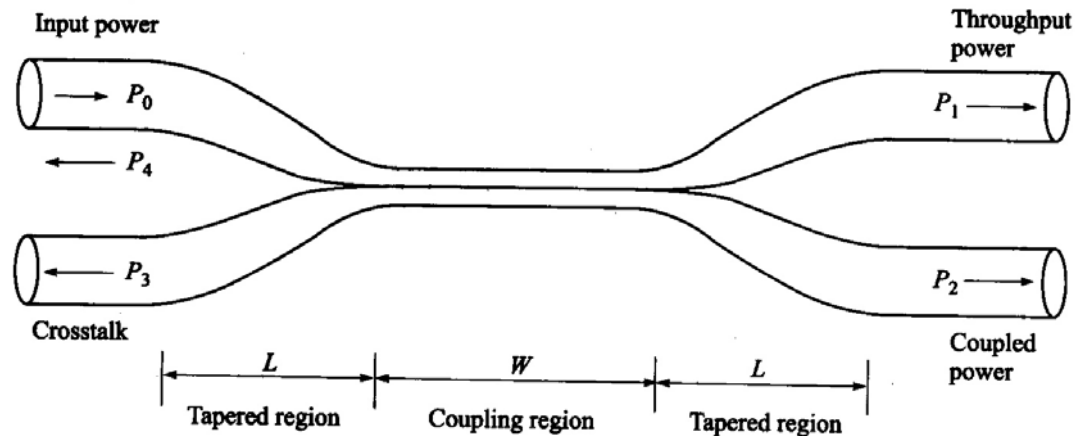
The three fundamental technologies for making passive components are based on optical fibres, integrated optical waveguides, and bulk micro-optics

WDM Concepts and Components

Passive Components

- The 2 x 2 fibre coupler

The 2 x 2 coupler is fabricated by twisting together, melting, and pulling two single-mode fibres so they get fused together over a uniform section of length W , as shown in figure below.

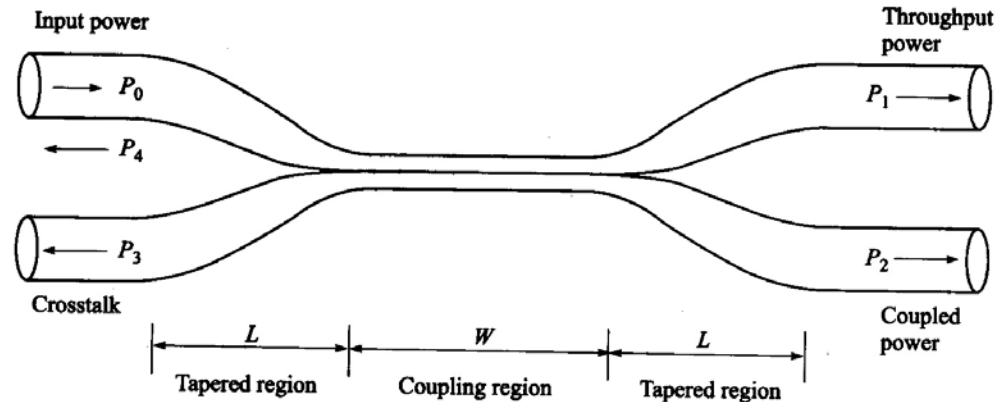


Each input draw length is $\mathcal{L} = 2L + W$. This device is known as a *fused biconical tapered coupler*.

WDM Concepts and Components

Passive Components

- The 2 x 2 fibre coupler



P_0 is the input power, P_1 is the throughput power, and P_2 is the power coupled into the second fibre. The parameters P_3 and P_4 are extremely low signal levels resulting from backward reflections and scattering.

As the input light P_0 propagates along the taper in fibre 1 and into the coupling region W , there is a significant decrease in the V number owing to the reduction in the ratio r/λ , where r is the reduced fibre radius.

As the signal enters the coupling region, an increasingly larger portion of the input field now propagates outside the core of the fibre. Depending on the dimensioning of the coupling region, any desired fraction of this decoupled field can be recoupled into the other fibre. These devices are also known as *directional couplers*.

WDM Concepts and Components

Passive Components

- *The 2 x 2 fibre coupler*

The optical power coupled from one fibre to another can be varied through three parameters:

- The axial length of the coupling region.
- The size of the reduced radius r in the coupling region.
- The difference Δr in the radii of the two fibres in the coupling region.

The coupling length is normally fixed, so that only L and r change as the coupler is elongated. Typical values for W and L are a few millimetres and $\Delta r/r$ is around 0.015.

WDM Concepts and Components

Passive Components

- *The 2 x 2 fibre coupler*

Assuming that the coupler is lossless, the expression for the power P_2 coupled from one fibre to another over an axial distance z is

$$P_2 = P_0 \sin^2(kz)$$

where k is the coupling coefficient describing the interaction between the fields in the two fibres. By conservation of power, for identical-core fibres we have

$$P_1 = P_0 - P_2 = P_0 [1 - \sin^2(kz)] = P_0 \cos^2(kz)$$

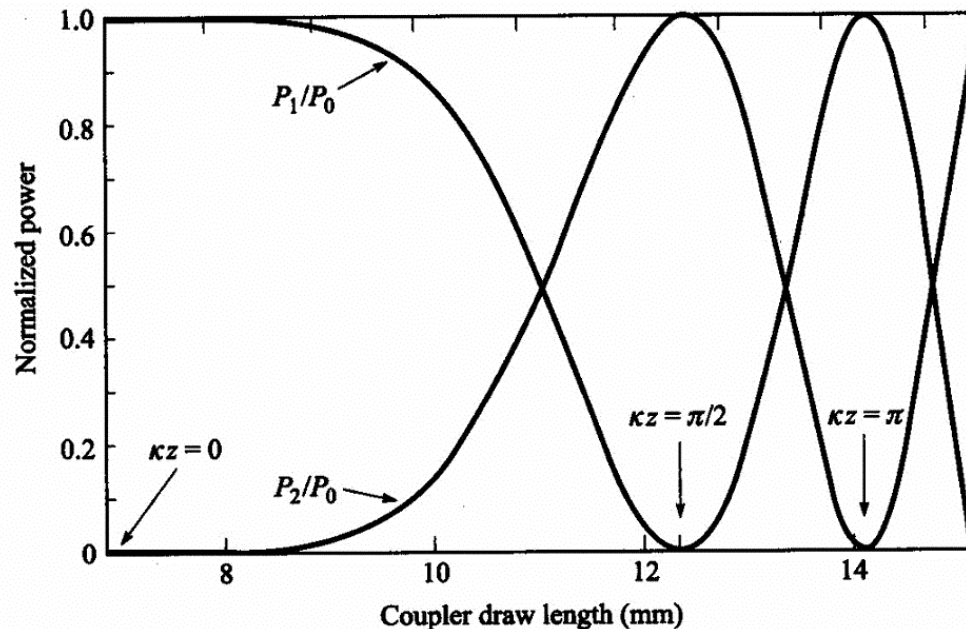
This shows that the phase of the driven fibre always lags 90° behind the phase of the driving fibre.

WDM Concepts and Components

Passive Components

- The 2 x 2 fibre coupler

Figure below shows the relation between the phase of the driven and the driving fibres.



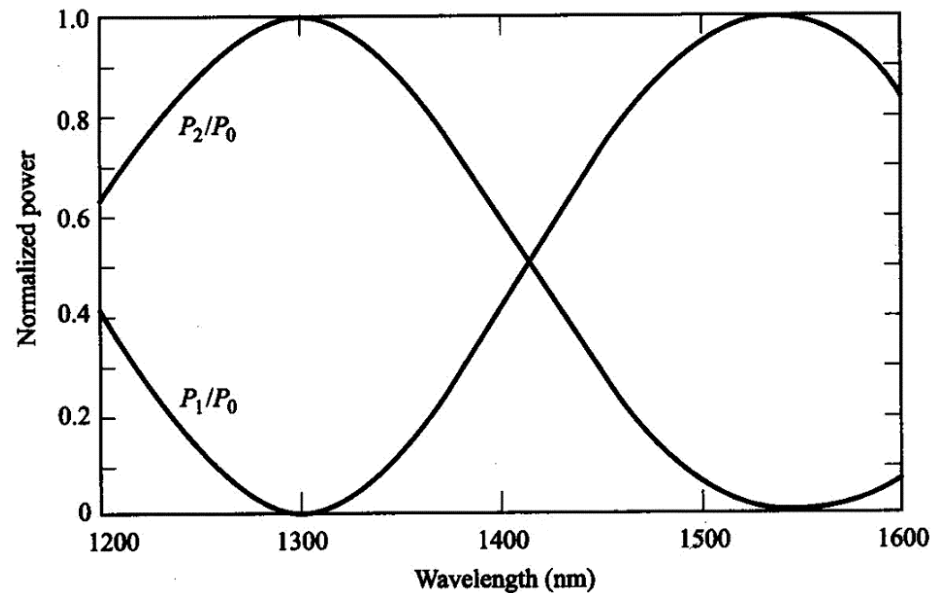
As a result of this phase relationship, the 2 x 2 coupler is a *directional coupler*. That is, no energy can be coupled into a wave travelling backward in the negative-z direction in the driven waveguide.

WDM Concepts and Components

Passive Components

- *The 2 x 2 fibre coupler*

Figure below shows how k varies with wavelength for the final 15 mm long coupler.



Thus, different performance couplers can be made by varying the parameters W , L , r , and Δr for a specific wavelength.

WDM Concepts and Components

Passive Components

- *The 2 x 2 fibre coupler*

In specifying the performance of an optical coupler, one usually indicates the percentage division of optical power between the output ports by means of the *splitting ratio* or *coupling ratio*.

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

A coupler could also be made in which almost all the optical power at 1500 nm goes to one port and almost all the energy around 1300 nm goes to the other port.

WDM Concepts and Components

Passive Components

- *The 2 x 2 fibre coupler*

In the previous analysis, we have assumed for simplicity, that the device is lossless. However, in any practical coupler there is always some light that is lost when a signal goes through it. The two basic losses are

- *Excess loss*

It is defined as the ratio of the input power to the total output power

Excess loss =

$$10\log\left(\frac{P_0}{P_1 + P_2}\right)$$

- *Insertion loss*

It refers to the loss for a particular port-to-port path. For the path from input port i to output port j

Insertion loss =

$$10\log\left(\frac{P_i}{P_j}\right)$$

WDM Concepts and Components

Passive Components

- *The 2 x 2 fibre coupler*

Another performance parameter is *crosstalk*, which measure the degree of isolation between the input at one port and the optical power scattered or reflected back into the other input port.

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

WDM Concepts and Components

Passive Components

- *The 2 x 2 fibre coupler*

Example

A 2 x 2 biconical tapered fibre coupler has an input power level $P_0 = 200 \mu\text{W}$. The output powers at the three ports are $P_1 = 90 \mu\text{W}$, $P_2 = 85 \mu\text{W}$, and $P_3 = 6.3 \text{ nW}$. Calculate the coupling ratio, the excess loss, the insertion loss (port 0 to port 1, and port 0 to port 2), and the crosstalk.

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

$$\text{Excess loss} = 10 \log \left(\frac{200}{90 + 85} \right) = 0.85 \text{ dB}$$

$$\text{Insertion loss (port 0 to port 1)} =$$

$$10 \log \left(\frac{200}{90} \right) = 3.47 \text{ dB}$$

$$\text{Insertion loss (port 0 to port 2)} =$$

$$10 \log \left(\frac{200}{85} \right) = 3.72 \text{ dB}$$

$$\text{Crosstalk} =$$

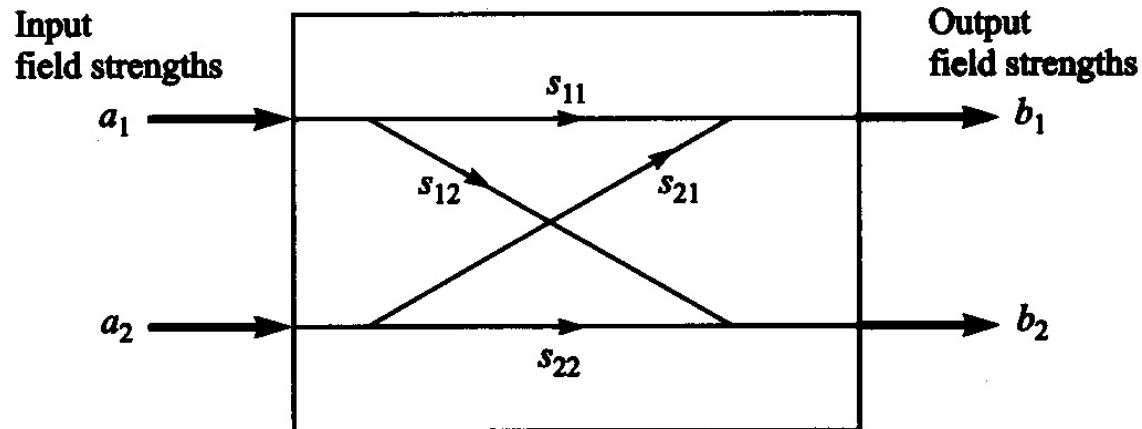
$$10 \log \left(\frac{6.3 \times 10^{-3}}{200} \right) = -45 \text{ dB}$$

WDM Concepts and Components

Passive Components

- Scattering Matrix Representation

One can also analyse a 2 x 2 guided-wave coupler as a four-terminal device that has two inputs and two outputs, as shown in figure.



Either all-fibre or integrated-optics devices can be analysed in terms of *scattering matrix* \mathbf{S} , which defines the relationship between the two input field strengths a_1 and a_2 , and the two output field strengths b_1 and b_2 .

WDM Concepts and Components

Passive Components

- *Scattering Matrix Representation*

By definition

$$\mathbf{b} = \mathbf{S}\mathbf{a}$$

where

$$\mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}, \quad \mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \quad \mathbf{S} = \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix}$$

Here, $s_{ij} = |s_{ij}| \exp(j\phi_{ij})$ represents the coupling coefficient of optical power transfer from input port i to output port j , with $|s_{ij}|$ being the magnitude of s_{ij} and ϕ_{ij} being its phase at port j relative to port i .

WDM Concepts and Components

Passive Components

- *Scattering Matrix Representation*

For an actual physical device, two restrictions apply to the scattering matrix \mathbf{S}

- One is a result of the reciprocity condition arising from the fact that Maxwell's equations are invariant for time inversion; that is they have two solutions in opposite propagating directions through the device, assuming single-mode operation.
- The other restriction arises from energy-conservation principles under the assumption that the device is lossless.

From the first condition

From the second condition $S_{12} = S_{21}$

$I_0 = b_1^* b_1 + b_2^* b_2 = I_i = a_1^* a_1 + a_2^* a_2$ or $b^+ b = a^+ a$
where “*” means the complex conjugate and “+” indicates the transpose conjugate

WDM Concepts and Components

Passive Components

- Scattering Matrix Representation

Substituting last two relations into the *scattering matrix* equation yields the following set of three equations

$$s_{11}^* s_{11} + s_{12}^* s_{12} = 1$$

$$s_{11}^* s_{12} + s_{12}^* s_{22} = 0$$

$$s_{22}^* s_{22} + s_{12}^* s_{12} = 1$$

If we now assume that the fraction $(1-\epsilon)$ of the optical power from input 1 appears at output port 1, with the remainder ϵ going to port 2, then we have

$s_{11} = \sqrt{1-\epsilon}$ which is a real number between 0 and 1. Here, we have

assumed that the electric field at output 1 has zero phase shift relative to the input at port 1; that is, $\phi_{11}=0$. We also make the simplifying assumption that the coupler is symmetric. Then, analogous to the effect at port 1, we have $s_{22} = \sqrt{1-\epsilon}$ with $\phi_{22}=0$. Using these expressions we can determine the

phases $\phi_{12}=0$ of the coupled outputs relative to the input signals and find constraints on the composite outputs when both input ports are receiving signals.

WDM Concepts and Components

Passive Components

- Scattering Matrix Representation

Inserting the expressions for s_{11} and s_{22} into letting $s_{12} = |s_{12}| \exp(j\phi_{12})$ we have

$$s_{11}^* s_{12} + s_{12}^* s_{22} = 0 \quad \text{and}$$

$$\exp(j2\phi_{12}) = -1$$

where

- $|s_{12}|$ is the magnitude of s_{12}
- ϕ_{12} is the phase of s_{12}

which holds when

$$\phi_{12} = (2n+1) \frac{\pi}{2} \quad \text{where } n = 0, 1, 2, \dots$$

so that the scattering matrix becomes

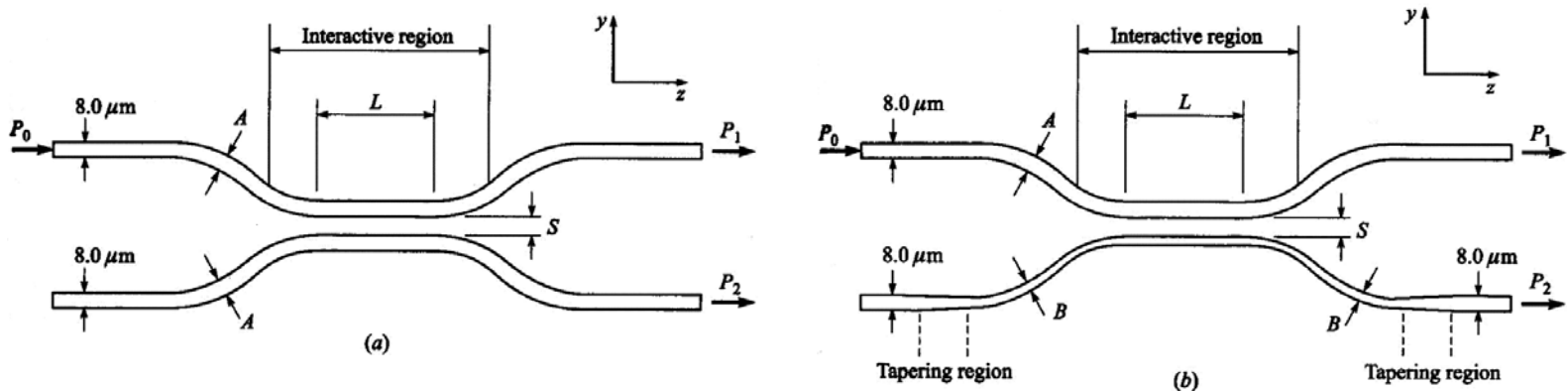
$$S = \begin{bmatrix} \sqrt{1-\varepsilon} & j\sqrt{\varepsilon} \\ j\sqrt{\varepsilon} & \sqrt{1-\varepsilon} \end{bmatrix}$$

WDM Concepts and Components

Passive Components

- The 2 x 2 waveguide coupler

Figure below shows two type of 2 x 2 waveguide couplers.



(a) uniformly symmetric directional waveguide coupler, (b) uniformly asymmetric directional coupler

Analogous to fused-fibre couplers, waveguide devices have an intrinsic wavelength dependence in the coupling region, and the degree of interaction between the guides can be varied through the guide width w , the gap s between the guides, and the refractive index n_f between the guides.

WDM Concepts and Components

Passive Components

- *The 2 x 2 waveguide coupler*

In real waveguides, with absorption and scattering losses, the propagation constant β_z is a complex number given by

$$\beta_z = \beta_r + j\frac{\alpha}{2}$$

where

- β_r is the real part of the propagation constant
- α is the optical loss coefficient in the guide

Hence, the total power contained in both guides decreases by a factor $\exp(-\alpha z)$ along their length.

WDM Concepts and Components

Passive Components

- *The 2 x 2 waveguide coupler*

The transmission characteristics of the symmetric coupler can be expressed through the coupled-mode theory approach to yield

$$P_2 = P_0 \sin^2(kz) e^{-\alpha z}$$

where the coupling coefficient is

$$k = \frac{2\beta_y^2 q e^{-qs}}{\beta_z w (q^2 + \beta_y^2)}$$

This is a function of the waveguide propagation constant β_y and β_z , the gap width and separation, and the extinction coefficient q in the y direction outside the waveguide, which is

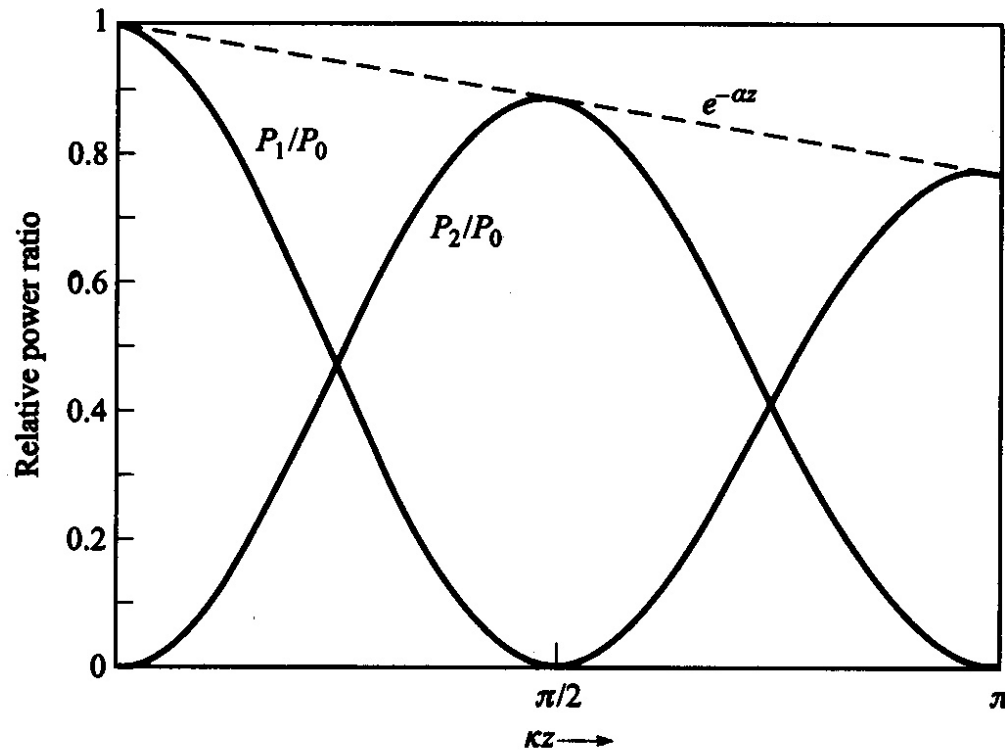
$$q^2 = \beta_y^2 - k_1^2$$

WDM Concepts and Components

Passive Components

- *The 2 x 2 waveguide coupler*

The theoretical power distribution as a function of the guide length is as shown in figure below, where we have used $k = 0.6 \text{ mm}^{-1}$ and $\alpha = 0.02 \text{ mm}^{-1}$.



WDM Concepts and Components

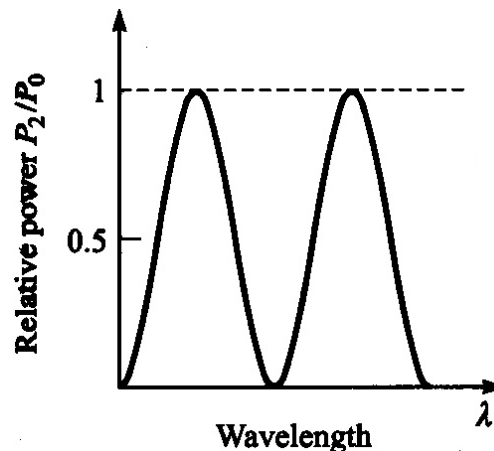
Passive Components

- *The 2 x 2 waveguide coupler*

Analogous to the fused-fibre coupler, complete power transfer to the second guide occurs when the guide length L is

$$L = \frac{\pi}{2k}(m+1) \quad \text{with } m = 0, 1, 2, \dots$$

Since k is found to be almost monotonically proportional to wavelength, the coupling ratio P_2/P_0 rises and falls sinusoidally from 0 to 100 percent as a function of wavelength, as figure below illustrates generically (assuming here, for simplicity, that the guide loss is negligible).



WDM Concepts and Components

Passive Components

- *The 2 x 2 waveguide coupler*

Example

A symmetric waveguide coupler has a coupling coefficient $k=0.6\text{mm}^{-1}$. Find the coupling length for $m=1$.

Using $L = \frac{\pi}{2k}(m+1)$ we find $L = 5.24 \text{ mm}$

WDM Concepts and Components

Passive Components

- *The 2 x 2 waveguide coupler*

When the two guides do not have the same widths the amplitude of the coupled power is dependent on wavelength, and the coupling ratio becomes

$$\frac{P_2}{P_0} = \frac{k^2}{g^2} \sin^2(gz) e^{-\alpha z}$$

where

$$g^2 = k^2 + \left(\frac{\Delta\beta}{2} \right)^2$$

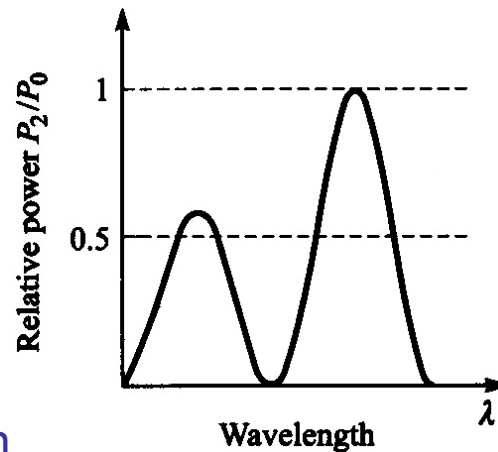
with $\Delta\beta$ being the phase difference between the two guides in the z direction.

WDM Concepts and Components

Passive Components

- *The 2 x 2 waveguide coupler*

With this type of configuration, one can fabricate devices that have a flattened response in which the coupling ratio is less than 100 percent in a specific desired wavelength range, as shown in figure below.



The main cause of the response at the lower wavelength results from suppression by the amplitude term k^2/g^2 . This asymmetric characteristic can be used in a device where only a fraction of power from a specific wavelength should be tapped off.

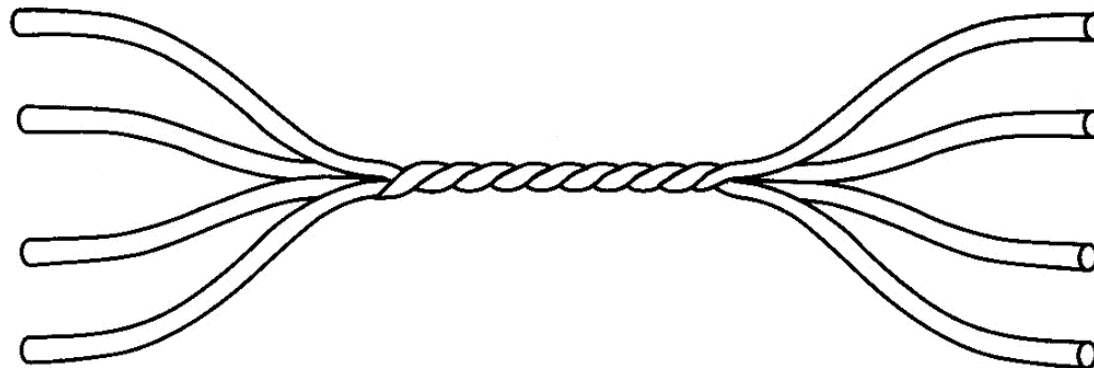
WDM Concepts and Components

Passive Components

- *Star Couplers*

The principal role of all star couplers is to combine the powers from N inputs and divide them equally among M output ports. Techniques for creating star couplers include fused fibres, gratings, micro-optic technologies, and integrated-optics schemes. The fibre-fusion technique has been a popular construction method for $N \times N$ star couplers.

However, large-scale fabrication of these devices for $N > 2$ is limited because of the difficulty in controlling the coupling response between the numerous fibres during the heating and pulling process. Figure below shows a generic 4×4 fused-fibre star coupler.



WDM Concepts and Components

Passive Components

- *Star Couplers*

The total loss of the device consists of its splitting loss plus the excess loss in each path through the star. The splitting loss is given in decibels by

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

For a single input power P_{in} and N output powers, the excess loss in decibels is given by

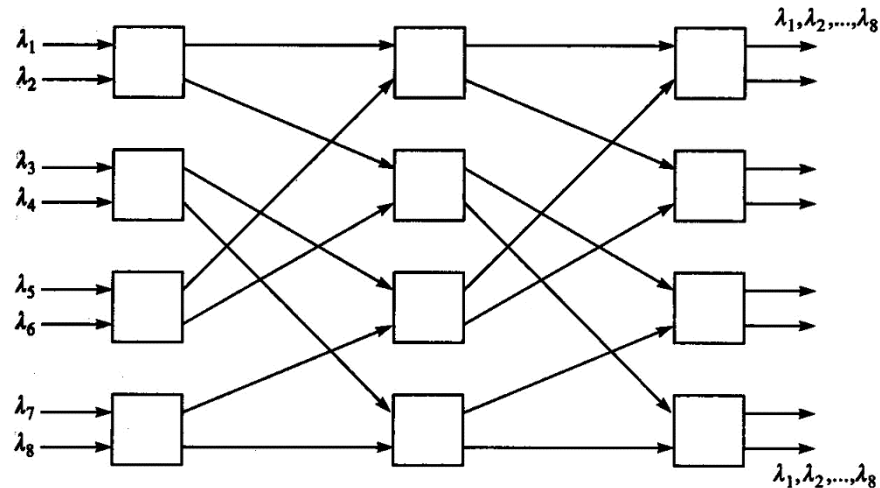
$$\text{Fibre star excess loss} = 10\log\left(\frac{P_{in}}{\sum_{i=1}^N P_{out,i}}\right)$$

WDM Concepts and Components

Passive Components

- Star Couplers

An alternative is to construct star couplers by cascading 3-dB couplers. Figure below shows an example for an 8 x 8 device formed by using twelve 2 x 2 couplers.

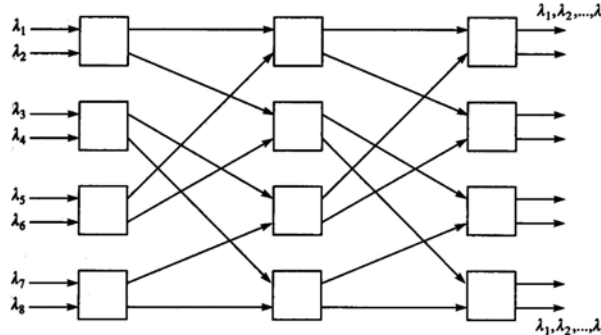


A fraction $1/N$ of the launched power from each input port appears at all output ports. A limitation to the flexibility or modularity of this technique is that N is a multiple of 2; that is, $N = 2^n$ with the integer $n \geq 1$. The consequence is that if an extra node needs to be added to a fully connected $N \times N$ network, the $N \times N$ star needs to be replaced by a $2N \times 2N$ star, thereby leaving $2(N - 1)$ new ports being unused.

WDM Concepts and Components

Passive Components

- Star Couplers



As can be deduced from figure above, the number of 3-dB couplers needed to construct an $N \times N$ star is

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

since there are $N/2$ elements in the vertical direction and $\log_2 N = \log N / \log 2$ elements horizontally.

If the fraction of power traversing each 3-dB coupler element is F_T , with $0 \leq F_T \leq 1$, then the excess loss in decibels is

Excess loss =

$$-10 \log \left(F_T^{\log_2 N} \right)$$

WDM Concepts and Components

Passive Components

- *Star Couplers*

The total loss experienced by a signal as it passes through the $\log_2 N$ stages of the $N \times N$ star and gets divided into N outputs is, in decibels,

$$\begin{aligned} \text{Total loss} &= \text{splitting loss} + \text{excess loss} = -10 \log \left(\frac{F_T^{\log_2 N}}{N} \right) \\ &= -10 \left(\frac{\log N \log F_T}{\log 2} - \log N \right) = -10(1 - 3.322 \log F_T) \log N \end{aligned}$$

This shows that the loss increases logarithmically with N .

WDM Concepts and Components

Passive Components

- *Star Couplers*

Example

Consider a commercially available 32 x 32 single-mode coupler made from a cascade of 3-dB fused-fibre 2 x 2 couplers, where 5 percent of the power is lost in each element. Calculate the excess loss, the splitting loss, and the total loss.

$$\text{Excess loss} = -10\log\left(0.95^{\log 32 / \log 2}\right) = 1.1\text{dB}$$

$$\text{Splitting loss} = 10\log 32 = 15\text{dB}$$

$$\text{Total loss} = \text{excess loss} + \text{splitting loss} = 16.1\text{dB}$$

WDM Concepts and Components

Passive Components

- *Tunable Sources*

Many different laser design have been proposed to generate the spectrum of wavelengths needed for WDM. One can choose from three basic option

- A series of discrete DFB or DBR lasers.
- Wavelength-tunable (or frequency-tunable) lasers.
- A multiwavelength laser array.

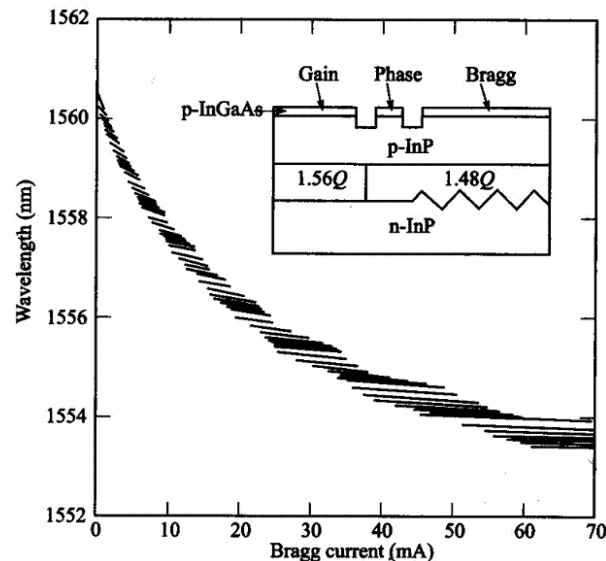
The use of discrete single-wavelength lasers is the simplest method. Here, one hand-select individual sources, each of which operates at a different wavelength. Although it is straightforward, this method can be expensive because of the high cost of individual laser. In addition, the sources must be carefully controlled and monitored to ensure that their wavelengths do not drift with time and temperature into the spectral region of adjacent sources.

WDM Concepts and Components

Passive Components

- *Tunable Sources*

With a frequency-tunable laser, one needs only this one source. These devices are based on DFB or DBR structures, which have a waveguide-type grating filter in the lasing cavity. Frequency tuning is achieved either by changing the temperature of the device, or by altering the injection current into the active (gain) section or the passive section. This results in a change in the effective refractive index, which causes a shift in the peak output wavelength. Figure below illustrates the tuning range of an injection-tunable three-section DBR laser.

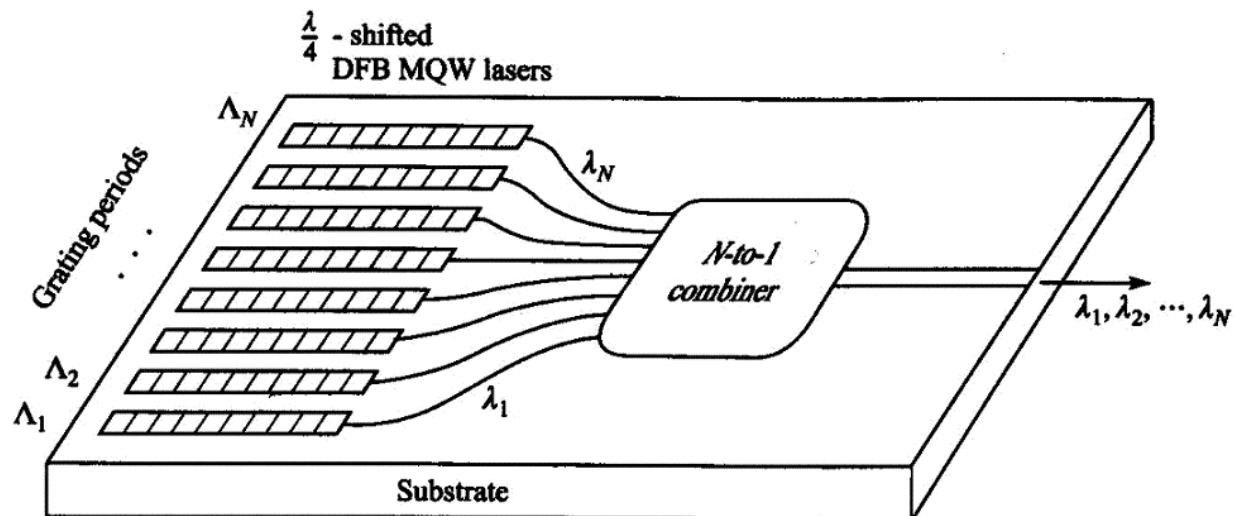


WDM Concepts and Components

Passive Components

- Tunable Sources

An array of tunable lasers provides a more versatile implementation in large WDM networks. Most laser arrays are fabricated from a combination of DFB and MQW architectures. The letters MQW stand for *multiple quantum well*, which is a multilayer structure to enhance the carrier and optical confinement in thin active areas. Basically, MQW allows a low threshold current in the active area and DFB is used for frequency tuning. Figure below shows one possible configuration with several MQW-DFB laser fabricated on the same wafer.



WDM Concepts and Components

Passive Components

- *Tunable Sources*

Other designs utilise an integrated combination of an optical source (either a broadband laser diode or an LED), a waveguide grating multiplexer, and an optical amplifier. In this method, which is known as *spectral slicing*, a broad spectral output (e.g., from an amplified LED) is spectrally sliced by the waveguide grating to produce a comb of precisely spaced optical frequencies, which become an array of constant-output source. These spectral slices are then fed into sequence of individually addressable wavelength channels that can be modulated externally.

Resources

- <http://www.sifamfo.com/datasheets.php?lang=en-gb>
- <http://www.aoctech.com/product1201.htm>