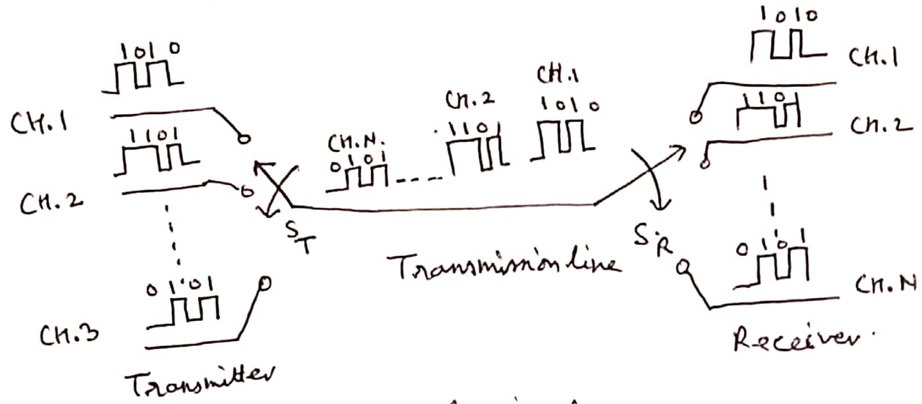
Dr. R. K. SHUKLA.
Department of Physics.
University of Lucknow.

TDM, OTDM, WDM, OFDM

Time - Division Multiplexing (TDM) :- TDM allows a number of digitized messages to timeshare the same transmission line. Unlike WDM systems, which propagate several messages simultaneously, TDM interleaves bits or groups of bits (words or characters) belonging to different messages prior to transmission. At the receiver, the process reverses. Pulses belonging to the individual messages are separated and routed to their appropriate destination. Figure schematically illustrates TDM.



(1)

Switches S_T and S_R are synchronized.

In above figure, the system interleaves four-bit words belonging to N-channels (N messages). The switch S_T sequentially samples each channel and then starts over again, producing a single frame of N four-bit words for each cycle. A group of bits are distinguished from other group bits by adding a Frame synchronizing bit after every group. *

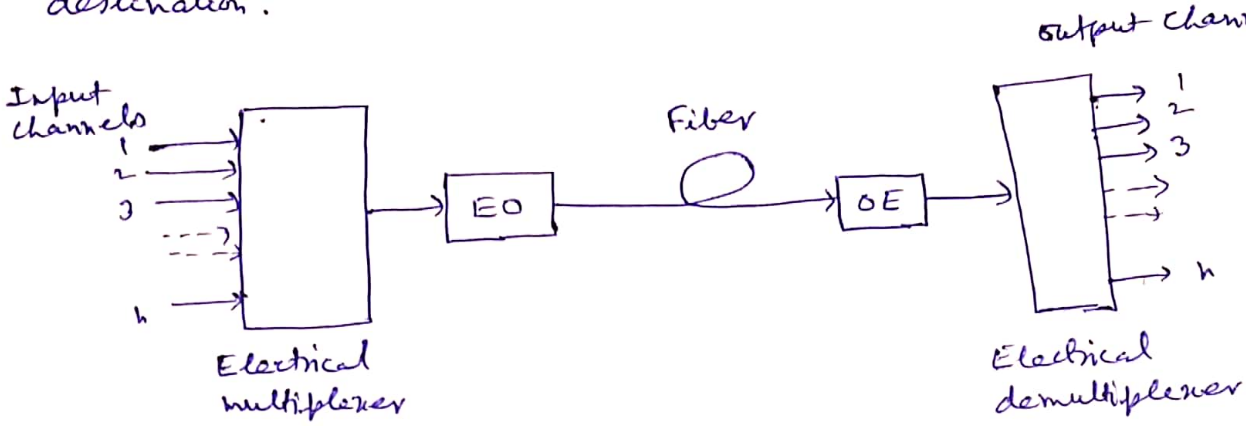
The telephone system provides an excellent practical example of TDM. The voice messages are sampled 8000 times ($2\times4000=8000$) a second and that an eight-bit word represent the amplitude of each sample. Eight bits can describe $2^8 = 256$ unique levels. That is, the amplitude of the voice waveform is quantized into 256 levels. The data rate for a single voice message is $8\times8000 = 64{,}000$ b/sec. Fibers can easily transmit at much higher rates. Sending only 64 kb/s would be wasteful. Time-division multiplexing results in better utilization of the fiber's available bandwidth.

* The electrical TDM becomes difficult to implement at bit rates above 10 Gb/s because of the limitations imposed by high-speed electronics. A solution is offered by the optical TDM (OTDM), a scheme that can increase the bit rate of a single optical carrier to values above 1 Tb/sec. Its commercial deployment requires new types of optical transmitter and receivers based on all optical multiplexing and demultiplexing techniques.

Limitation of TDM:- As we divide the sampling time, more data can be send through fiber, but each bit has certain width that is why we have certain limit over which we cannot reduce the multiplexing division time.

*

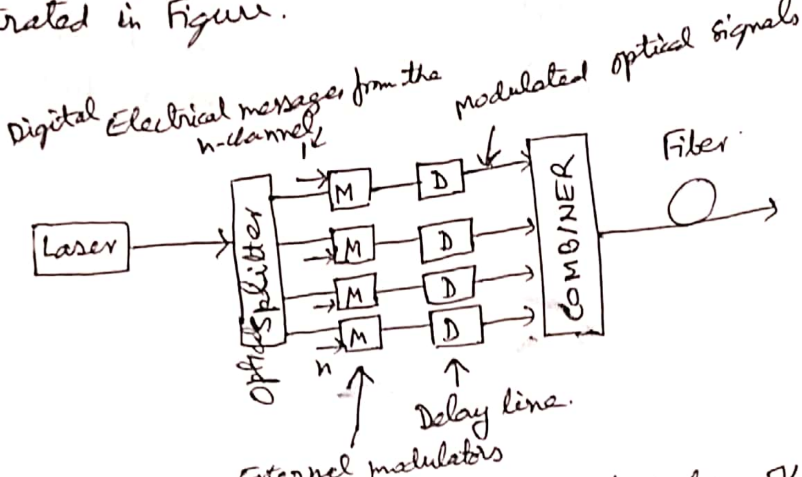
In electrical TDM, the messages are multiplexed in the electrical domain as shown in above figure. Next, the multiplexed electrical signal modulates an optical source (a laser diode) in the EO (electrical to-optical) converter. The multiplexed signal, now in the optical domain, propagates down the fiber. ~~It travels~~ to the receiver, where it is detected (i.e. converted back to ~~an~~ optical to electrical signal) in the OE (optical-to-electrical) converter. The multiplexed signal is then electronically demultiplexed, sending each of the electrical messages to its intended destination.



EO – Electrical to optical converter
OE – Optical to electrical converter

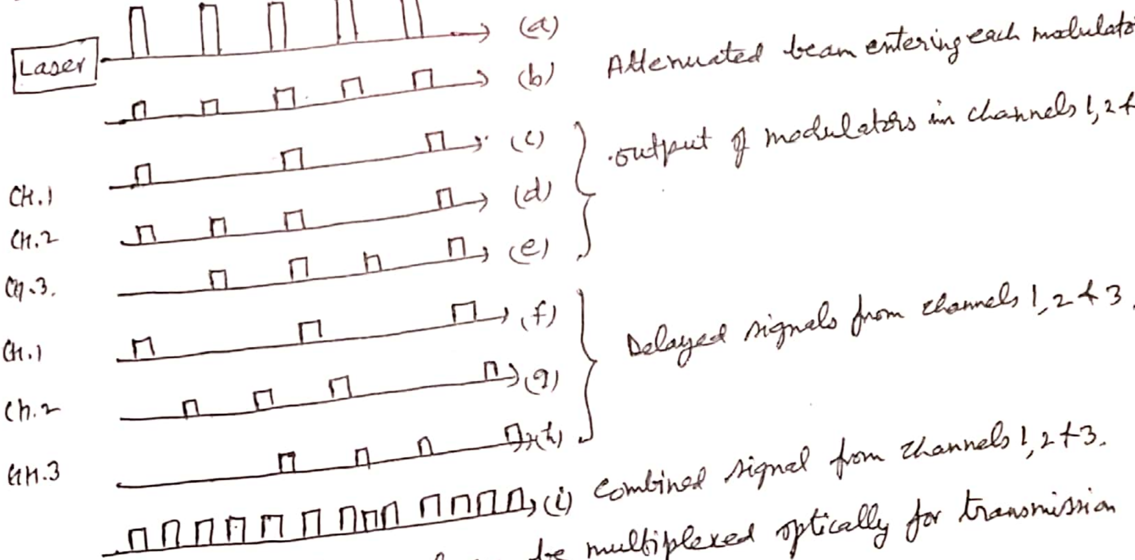
Optical Time – Division Multiplexing :- The electrical TDM becomes difficult to implement at bit rates above 10 Gb/sec because of the limitation imposed by electronic circuits cannot be built to respond at high enough speeds.

In order to multiplex several high speed channels, each operating at or above 10 Gb/sec, it is necessary to do in the optical domain. The OTDM is illustrated in Figure.



(3)

In above figure, a laser emits a train of short pulses. The pulse train appears in part (a). The optical splitter divides the power among the n-channels of the OTDM system. Entering each of the n external modulators (M) have the repetitive pulse train and the electrical digital information signal from one of the channels. The digital electrical signal modulates the pulse train. It allows passage of pulses representing binary 1s and blocks pulses representing binary 0s. Exiting each of the n modulators are the modulated optical beams part c, d and e. The beams enter delay lines (D) constructed such that the pulse train for each channel exists with a different time shift part f, g and h. The beams are ~~reassa~~ reassembled in the optical combiner. The output of the combiner has the data from n channels sequenced in time, as demonstrated in part i.



Thus, the information from several channels can be multiplexed optically for transmission along a single fiber.

Demultiplexing of the OTDR signal can also be done optically.

In part (i) for RZ modulation one extra pulse are inserted to remove ~~intersy~~ intersymbol interference between adjacent channels.

P.T.O.

In this scheme, the laser output pulses must meet certain requirements. The pulse rate must be the same as the rate of the individual channels. The pulse width must be narrower then the period of the combined signals.

Example :- If each channel is to operate at 10 Gb/sec and if 20 channels are to be multiplexed, the system bit rate will be 200 Gb/sec and the period of the OTDM signal will be.

$$T = \frac{1}{200 \times 10^9} = 5 \times 10^{-12} \text{ sec}$$

Thus, the laser must operate a pulse rate of 10 Gb/sec and produce pulses somewhat less than 5 psec long, to allow for some transmission pulse spreading.

Wavelength-Division Multiplexing :- (1) (A powerful aspect of an optical communication link is that many different wavelengths can be sent along a single fiber simultaneously in the 1300-to-1600 nm spectral band. The technology of combining a number of wavelengths onto the same fiber is known as wavelength-division multiplexing or WDM.)

× WDM scheme is the same as frequency-division multiplexing (FDM) used in microwave radio and satellite systems.
WDM must be properly spaced to avoid interchannel interference.

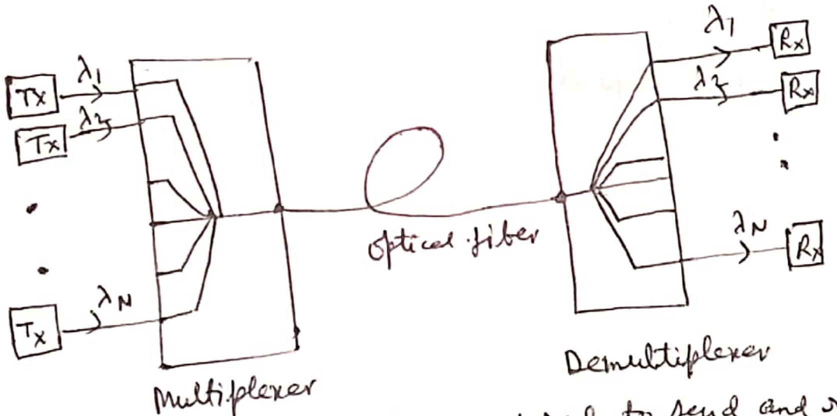
(2) In WDM scheme in which multiple optical carriers at different wavelengths are modulated by using independent electrical bit streams and are then transmitted over the same fiber. The optical signal at the receiver is demultiplexed into separate channels by using an optical technique. WDM has the potential for exploiting the large bandwidth offered by optical fibers. For example, hundreds of 10-Gb/s channels can be transmitted over the same fiber when channel spacing is reduced to below 100 GHz. * P.T.O.

× Low-loss transmission windows of optical fibers centered near 1.3 and 1.55 μm.
If OH^- peak can be eliminated using dry fibers, the total capacity of a WDM system can ultimately exceed 30 Tb/s.
The role of WDM is simply to increase the total bit rate.

(3) (Figure shows schematically such a point-to-point, high capacity, WDM link.) *(4)
The output of several transmitter, each operating at its own carrier frequency (or wavelength), is multiplexed together. The multiplexed signal is launched into the optical fiber for transmission to the other end, where a demultiplexer sends each channel to its own receiver.

✓ When N channels at bit rates B_1, B_2, --- and B_N are transmitted simultaneously over a fiber of length L, the total bit rate-distance product, BL, becomes.

$$BL = (B_1 + B_2 + \cdots + B_N) \cdot L$$



(4)

Separate transmitter-receiver pairs are used to send and receive the signal at different wavelengths.

(5)
* ~~When channel spacing less than~~ ...
* When channel separated by a nm or less, then these WDM are called dense wavelength division multiplexing (DWDM). (Channel spacing not more than 200 GHz)
If there are just a few channels (eight or so) and they are spaced more widely (say 10 nm or more apart), we say coarse-wavelength-division multiplexing (CWDM) systems.
Narrow band WDMs combine and separate wavelength channels with centre to centre spacing greater than 200 GHz.

2* WDM Channel Spacing

Δf (GHz)	Δλ (nm)	C-Band channels (1530 – 1565 nm) ≈ 35 nm
25	0.2	175 nm
50	0.4	87 nm
100	0.8	43 nm
200	1.6	21 nm

$\frac{35}{0.2} = 175$

If $\Delta f = 100\ GHz$, for $\lambda = 1550\ nm$;

$$\Delta\lambda = \lambda^2 \frac{\Delta f}{c}$$

$$= \frac{1550 \times 1550 \times 100 \times 10^{-9-9+9}}{3 \times 10^8}$$

$$= 800833.333 \times 10^{-9-8+2}$$

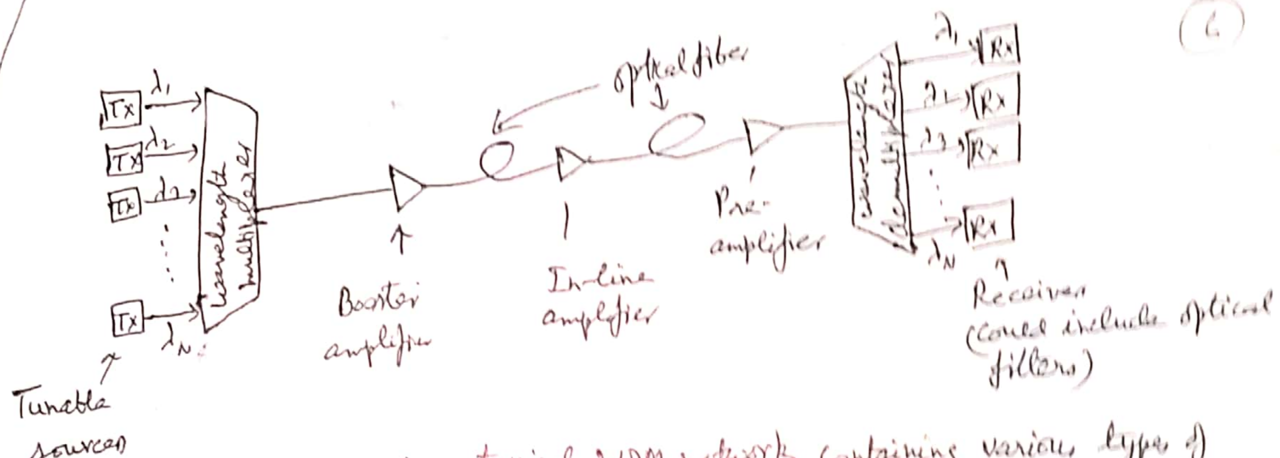
$$= 800833 \times 10^{-6} \times 10^{-9}$$

$$\boxed{\Delta\lambda = .8\ nm}$$

Channel Spacing in a WDM system.

WDM :- The implementation of WDM networks requires a variety of passive and/or active devices to combine, distribute, isolate and amplify optical power at different wavelengths. Passive devices require no external control for their operation, so they are somewhat limited in their application in WDM networks. These components are mainly used to split and combine or tap off optical signals. The performance of active devices can be controlled electronically, thereby providing a large degree of network flexibility. Active WDM components include tunable optical filters, tunable sources and optical amplifiers.

Figure shows the use of such components in a typical WDM link containing various types of optical amplifiers. At the transmitting end, there are several independently modulated light sources, each emitting signals at a unique wavelength. Multiplexer is needed to combine these optical outputs into a serial spectrum of closely spaced wavelength signals and couple them onto a single fiber. At the receiving end, a demultiplexer is required to separate the optical signals into appropriate detection channels for signal processing.

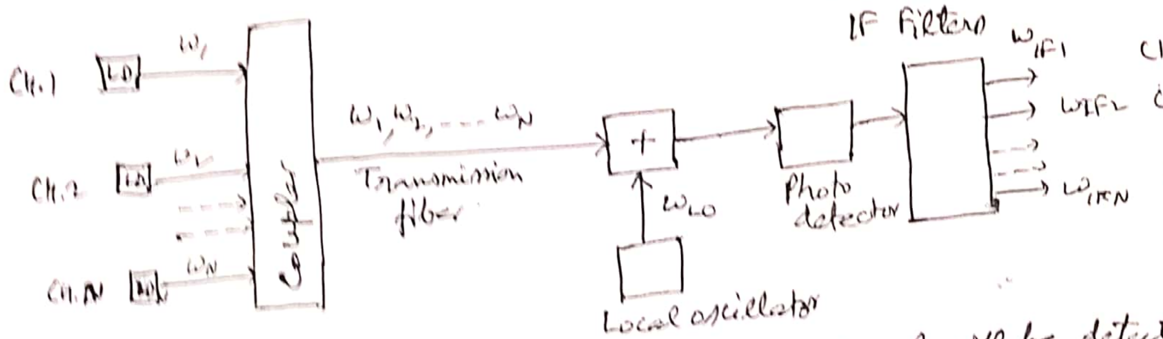


Implementation of a typical WDM network containing various types of optical amplifier.

To prevent spurious signals from entering a receiving channel (i.e. to give good channel isolation of the different wavelengths being used), the demultiplexer must exhibit narrow spectral operation, or very stable optical filters with sharp wavelength cutoffs must be used.

In principle, any optical demultiplexer can also be used as a multiplexer.

Optical-Frequency-Division Multiplexing :- Several messages can be simultaneously transmitted along the fiber by optic frequency division multiplexing (OFDM) combined with heterodyne detection. N identical laser diodes are temperature-tuned to emit at slightly different frequencies, $\omega_1, \omega_2, \ldots \omega_N$. The diodes are modulated with the desired messages. The output of each diode is coupled to a fiber, and the multiple fibers are coupled (by fusion) to the transmission fiber. At the receiver, light from a single local oscillator mixes with each transmitted beam, producing a different IF frequency for each channel. The IF frequencies, $\omega_{IF1}, \omega_{IF2}, \ldots, \omega_{IFN}$, are electronically sorted by filters. The speed of the photodetector and of the receiving circuit determine the maximum allowable IF frequency. In a OFDM arrangement, a tunable local oscillator replaces the fixed one as shown in figure.



In addition, only one IF filter is needed. A given channel will be detected when its optical carrier frequency differs from that of the LO by an amount equal to the IF frequency. In this case, all other channels will produce IF frequencies outside the passband of the IF filter. To receive a different channel, the LO frequency is changed. In this system, a station can tune into any of the transmitted channels. Optic-frequency-division multiplexing and wavelength-division-multiplexing are somewhat similar. They both use separate optic sources for each channel. Their differences are import, however.

Imp
(1) OFDM requires heterodyne detection, whereas WDM uses direct detection.
(2) WDM system sort the channels in the optic domain, whereas OFDM systems separate them electronically (after photodetection).
(3) Electrical separation at radio frequencies is much more selective than optic separation, so adjacent channels can be closer together in OFDM systems than in WDM systems. (4) Closer spacing allows transmission of more channels of information in the wavelength regions where fiber losses are low.

Comparison of WDM and OFDM :- OFDM and WDM are somewhat similar. They both use separate optic sources for each channel. Their differences are given below

1. OFDM requires heterodyne detection whereas, WDM requires direct detection.
2. OFDM system separates the channels electrically (after photodetection) whereas, WDM systems sort the channels in the optic domain (before photo-detection).
3. Electrical separation at radio frequencies is much more selective than optic separation, so adjacent channels can be closer together in OFDM systems than in WDM systems.
4. Due to closer spacing more channels of information in wavelength region can be transmitted in OFDM than in WDM.
5. WDM have less bandwidth and OFDM have more bandwidth.
6. WDM have less link length and OFDM have larger link length.
7. In WDM circuitry is less complicated and cost is small whereas in OFDM the circuitry is complex.

Four-Wave Mixing in WDM:- In describing WDM, we assumed that different carriers propagate along the fiber without affecting one another. This is a good approximation if the waves do not have much power. However, at higher power levels, the carriers in a WDM system exchange energy by four-wave mixing (FWM). This is caused by the nonlinear vibrations of the atoms and molecules in the fiber in response to the incident waves. Because it is a second order effect, FWM is not noticeable at low power levels. In WDM systems, the power levels become greater than those in single-carrier systems as each carrier adds power.

A partial spectrum of a WDM signal appears in below figure. The FWM nonlinearity results in a mixing of the carriers to produce new waves at wavelengths

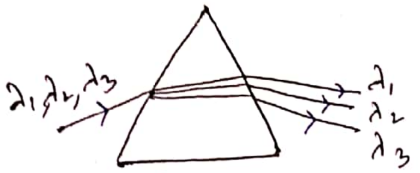
$$\lambda_{x,y,z} = \lambda_x + \lambda_y - \lambda_z$$

where x, y and z can take on any of the subscripts 1, 2 and 3.
As an example, if the carriers are equally spaced by an amount Δλ and we set x=1, y=3, and z=2, there is an output at wavelength

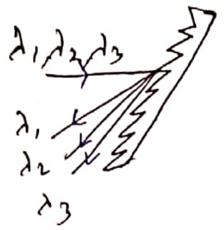
$$\lambda_{out} = \lambda_1 + \lambda_3 - \lambda_2 = (\lambda_2 - \Delta\lambda) + (\lambda_2 + \Delta\lambda) - \lambda_2 = \lambda_2$$

The result is a contribution to the power in channel 2 (λ_2) from signals originating in channels 1 (λ_1) and 3 (λ_3). This effect results in both crosstalk and a loss in power in channels 1 and 3.
To avoid this situation, it limits the amount of power that can be launched into a WDM system ultimately limiting the length of the fiber link.
The nonlinear phenomenon of FWM requires phase matching. It becomes a major source of nonlinear crosstalk whenever the channel spacing and fiber dispersion are small enough to satisfy the phase-matching condition.
The physical origin of FWM-induced crosstalk and the resulting system degradation can be understood by noting that FWM generates a new wave at the frequency $\omega_{ijk} = \omega_i + \omega_j - \omega_k$, whenever three waves at frequencies ω_i, ω_j and ω_k copropagate inside the fiber. For an N-channel system i, j, and k can vary from 1 to N, resulting in a large combination of new frequencies generated by FWM.
In the case of equally spaced channels, the new frequencies coincide with the existing frequencies, leading to coherent in-band crosstalk.
When channels are not equally spaced, most FWM components fall in between the channels and lead to incoherent out-of-band crosstalk. In both cases, the system performance is degraded because of a loss in the channel power, but the coherent crosstalk degrades system performance much more severely.
The FWM process in optical fibers is governed by a set of four coupled equations whose general solution requires a numerical approach.

WDM Devices :-



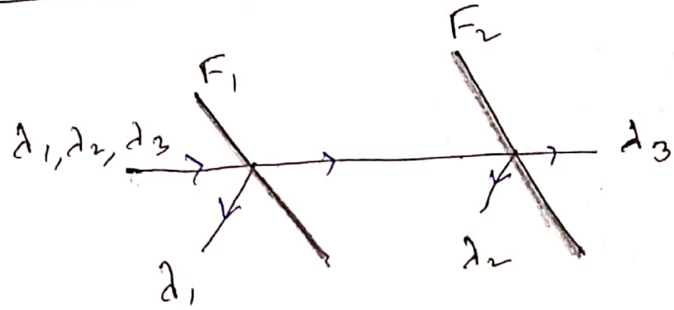
Prism



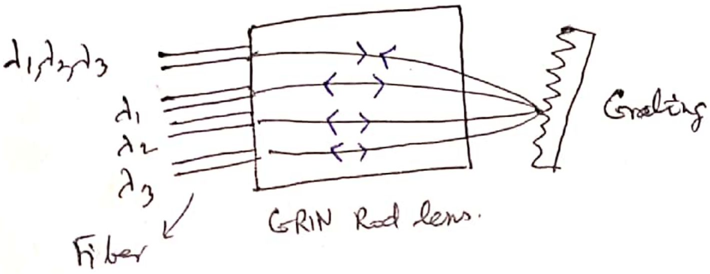
Blazed Reflection Grating

Angular dispersion

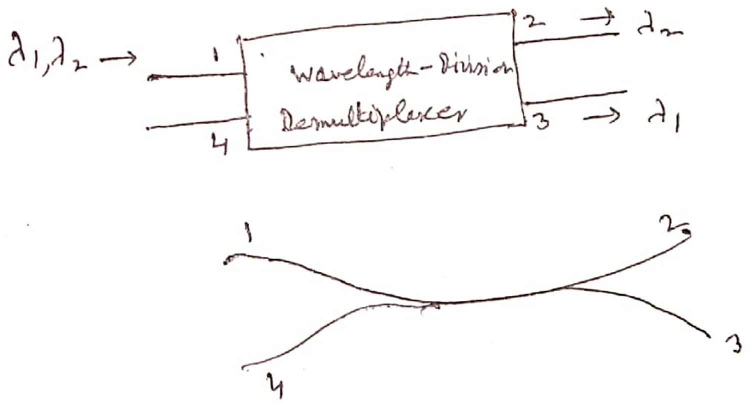
Optical filtering. Filter F_1 reflects λ_1 and transmits λ_2 and λ_3, and filter F_2 reflects λ_2 and transmits λ_3.



Grating multiplexer/ demultiplexer.

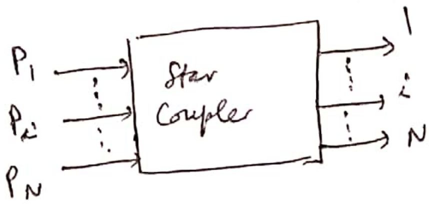


Fused tapered coupler acting as a demultiplexer.



Star Coupler

Basic star coupler concepts for combining or splitting optical powers.



* Generally, multiplexers / demultiplexers have fibers at their input and output ports. It is also possible to replace the input fibers in a multiplexer with optic sources integrated directly into the device. Similarly, photodetectors can replace the output fibers in a demultiplexer.
* Often, the same device can perform as both a multiplexer and a demultiplexer.
* Insertion loss and crosstalk are the important properties of multiplexer/demultiplexer.
* Insertion loss is the attenuation of a wave traveling from the input port to the desired output port. For example, the insertion loss for channel 1 is the fraction of the input power at wavelength λ_1 that reaches the transmitting fiber. A multiplexer/demultiplexer has uniformity when the insertion loss is nearly the same for each channel.
* Crosstalk is the wave attenuation measured at an unintended port. For example, the crosstalk is the fraction of the input power at λ_1 that reaches the output fiber assigned to λ_2. Crosstalk is a problem at the receiver, where mixing of two or more channels can seriously interfere with the desired signal.
* The multiplexer operates in the 1550nm region, where fiber losses are low and where the erbium-doped amplifier works well. Because of this, WDM systems are popular for long, high-capacity transmission paths, such as those encountered in undersea link.

Multiplexers have been designed to accommodate numerous channels (more than 100), with channels separated by a nm or less. These are dense wavelength-division multiplexing (DWDM) systems.

When there are just a few channels (eight or so) and they are spaced more widely (say 10nm or more apart), this is called coarse-wavelength-division multiplexing (CWDM) systems.

Variation in frequency with small change in wavelength :- If $\Delta\lambda$ is the change / difference in wavelength (say of the order of 3nm or 5nm) then, change in frequency $\Delta\nu$ will be approximately 500 GHz. This may be calculated as :-

$$c = \nu\lambda$$

or $$\nu = \frac{c}{\lambda}$$

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

when λ can be taken to be 1550 nm, 1300nm and 850nm.

let $\Delta\lambda = 3\text{nm} = 3\times10^{-9}\text{m}$, $c = 3\times10^8$ m/sec

let us consider $\lambda = 1300\text{nm} = 1300\times10^{-9}\text{m}$

$$\Delta\nu = \frac{3\times10^8}{(1300\times10^{-9})(1300\times10^{-9})}\times(3\times10^{-9}) \simeq 500\text{ GHz}$$

If $\Delta\lambda = 5\text{nm}$; $\lambda = 1550\text{nm}$, $\Delta\nu = \frac{3\times10^8}{(1550\times10^{-9})^2}\times(5\times10^{-9}) \simeq 6.24\times10^{11} = 600\text{ GHz}$

⇒ For changes in wavelength of only 3nm or 5nm the frequency change is in GHz.

Four-Wave Mixing in WDM:- In describing WDM, we assumed that different carriers propagate along the fiber without affecting one another. This is a good approximation if the waves do not have much power. However, at higher power levels, the carriers in a WDM system exchange energy by four-wave mixing (FWM). This is caused by the nonlinear vibrations of the atoms and molecules in the fiber in response to the incident waves. Because it is a second order effect, FWM is not noticeable at low power levels. In WDM systems, the power levels became greater than those in single-carrier systems as each carrier adds power.

A partial spectrum of a WDM signal appears in below figure. The FWM nonlinearity results in a mixing of the carriers to produce new waves at wavelengths

$$\lambda_{x,y,z} = \lambda_x + \lambda_y - \lambda_z$$

where x, y and z can take on any of the subscripts 1, 2 and 3.

As an example, if the carriers are equally spaced by an amount $\Delta\lambda$ and we set x=1, y=3, and z=2, there is an output at wavelength

$$\lambda_{out} = \lambda_1 + \lambda_3 - \lambda_2 = (\lambda_2 - \Delta\lambda) + (\lambda_2 + \Delta\lambda) - \lambda_2 = \lambda_2$$

The result is a contribution to the power in channel 2 (λ_2) from signals originating in channels 1 (λ_1) and 3 (λ_3). This effect results in both crosstalk and a loss in power in channels 1 and 3.

To avoid this situation, it limits the amount of power that can be launched into a WDM system ultimately limiting the length of the fiber link.

The nonlinear phenomenon of FWM requires phase matching. It becomes a major source of nonlinear crosstalk whenever the channel spacing and fiber dispersion are small enough to satisfy the phase-matching condition.

The physical origin of FWM-induced crosstalk and the resulting system degradation can be understood by noting that FWM generates a new wave at the frequency $\omega_{ijk} = \omega_i + \omega_j - \omega_k$, whenever three waves at frequencies ω_i, ω_j and ω_k copropagate inside the fiber. For an N-channel system i, j, and k can vary from 1 to N, resulting in a large combination of new frequencies generated by FWM.

In the case of equally spaced channels, the new frequencies coincide with the existing frequencies, leading to coherent in-band crosstalk. When channels are not equally spaced, most FWM components fall in between the channels and lead to incoherent out-of-band crosstalk. In both cases, the system performance is degraded because of a loss in the channel power, but the coherent crosstalk degrades system performance much more severely.

The FWM process in optical fibers is governed by a set of four coupled equations whose general solution requires a numerical approach.