Fiber Optic Communications

Ch 6. Multichannel Systems

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Multichannel systems

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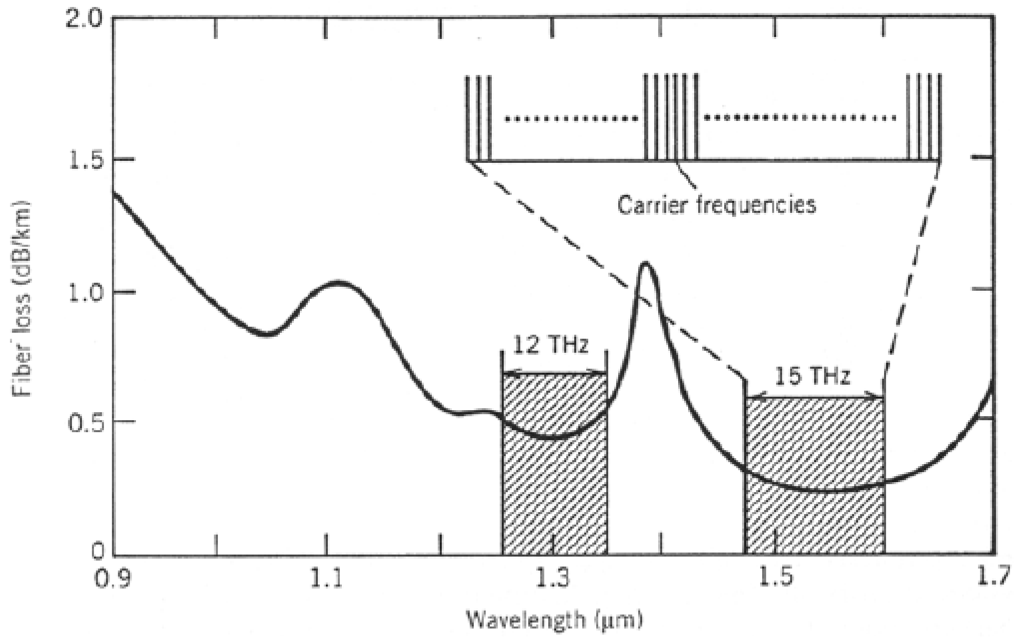
Fiber bandwidth

The bandwidth of fibers is huge

- Potential bit rate is >> 1 Tbit/s

In practice, electronics, dispersion, etc. is a bottle neck

- Limits the OOK bit rate to ~40 Gbit/s



Simultaneous transmission of many channels offers the simplest way to make better use of the available bandwidth

Multichannel approaches

Frequency Division Multiplexing (FDM)

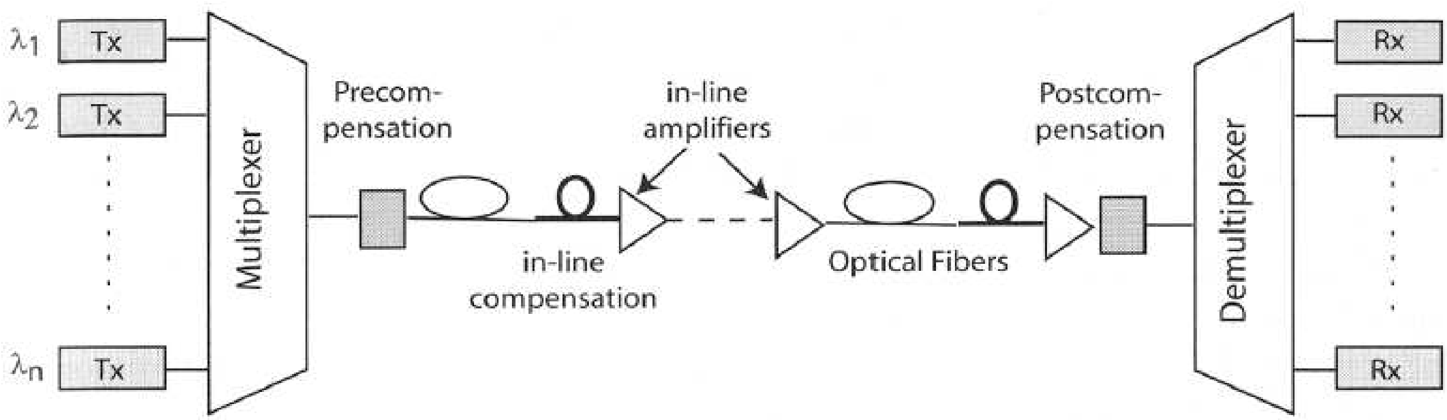
- Optical FDM [Wavelength DM (WDM)]
  - Multiple optical carriers are modulated with independent bit streams
  - The optical data is combined optically into the same fiber
  - 100's of channels can be transmitted this way
- Electrical FDM [subcarrier multiplexing (SCM)]
  - Modulating different microwave sub-carriers which are combined to modulate a single optical carrier

Time Division Multiplexing (TDM)

- Optical TDM (OTDM)
  - Several signals with identical bit-rate are combined on the same carrier
  - Only for RZ formats, not yet commercial
- Electrical TDM (ETDM)
  - Channels are combined before modulating a single optical carrier

WDM systems

- WDM system = a single fiber + N transmitters + N receivers + mux/demux
- WDM systems are commercial since 1995
- Spectral efficiency $\eta_s = B/\Delta\nu_{ch}$, today typically $\eta_s < 0.5$ (bit/s)/Hz
  - Standard D(dense)WDM grid spacing ($\Delta\nu_{ch}$) are 200, 100, 50 and 25 GHz
- System limitations include
  - Amplifier gain uniformity and laser wavelength stability
  - Fiber nonlinearities and other interchannel crosstalk
  - Residual dispersion



WDM components

Implementing a WDM system requires several optical components

- Multiplexers
  - Combine the individual WDM channels
- Demultiplexers
  - Separate the WDM channels
- Star couplers
  - Combine signals from multiple origins and sends to multiple destinations
- Tunable optical filters
  - Used to filter out a specific channel
- Wavelength-tunable transmitters
- Add-drop multiplexers/optical routers
  - Used in the transmission path to switch channels to correct destinations
  - Often the term ***reconfigurable optical add-drop multiplexer*** (ROADM) is seen

Tunable optical filters

A ***tunable optical filter*** is used to select one WDM channel while blocking all other channels

- Is a band-pass filter, typically with transmission in multiple bands
- Has adjustable center wavelength
- Is based on diffraction or interference

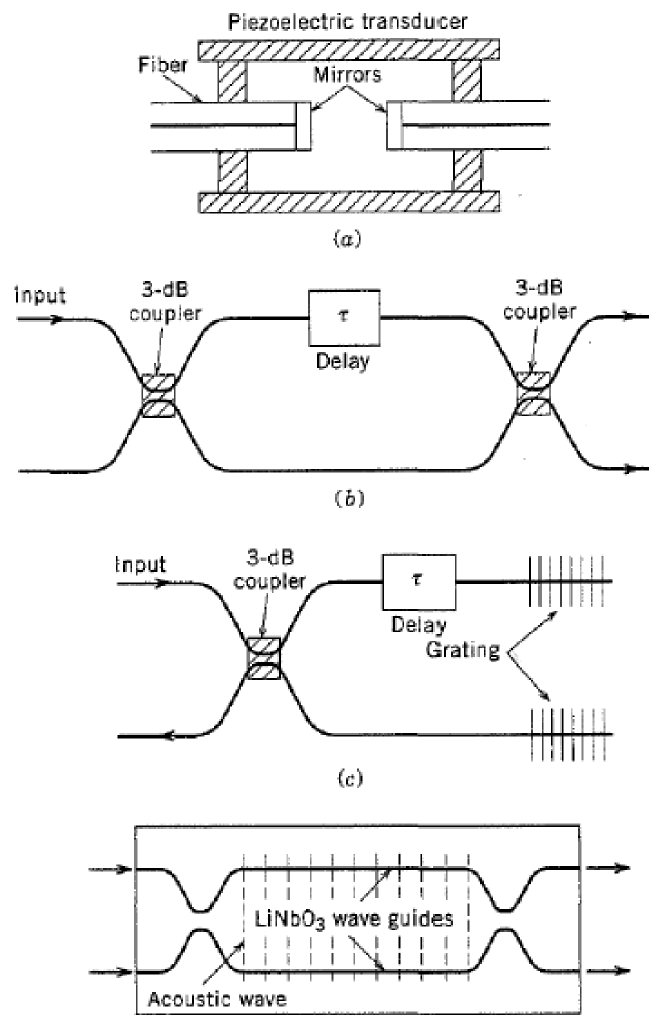
Desirable properties include

- A wide tuning range, allowing processing of many WDM channels
- Negligible crosstalk, close to zero out-of-band transmission
- Fast tuning speed, allowing quick system re-configuration
- Small insertion loss, avoiding need for extra amplification
- Polarization insensitivity, since the signal polarization varies
- Robustness against disturbances like vibrations
- Low price

Types of tunable optical filters

There are several types of filters

- A ***Fabry-Perot filter*** (a) is a cavity between mirrors
  - Length is adjustable
  - Transmission at longitudinal modes
- A ***Mach-Zehnder filter*** (b) is an interferometer
  - Uses cascaded Mach-Zehnder interferometers
  - Phase shift is wavelength-dependent
- A ***grating-based Filter*** (c) uses Bragg gratings
  - Reflection is wavelength-dependent
  - Often uses an ***optical circulator***
- An acousto-optic filter (d) forms the grating from acoustic waves
  - ***Photoelastic effect*** ⇒ refractive index is changed
  - Set up dynamically



The Fabry-Perot filter

Typically, several wavelengths can pass an optical band-pass filter

The Fabry-Perot filter is a good example

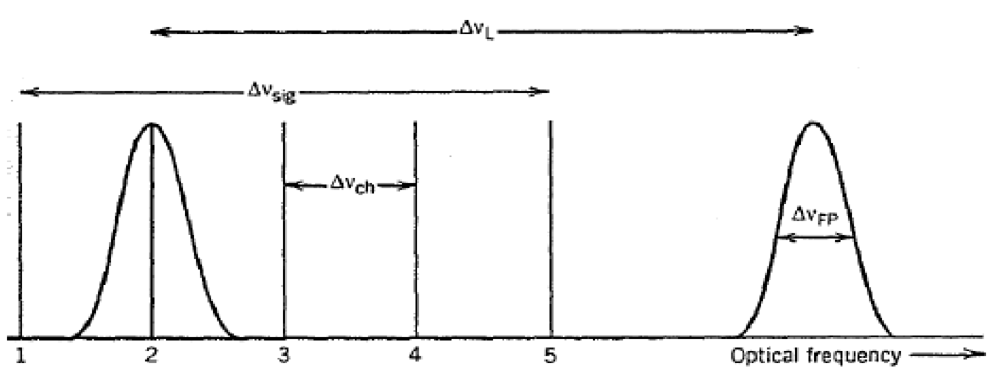
- Transmission of all longitudinal modes of the cavity
- The frequency spacing is known as the ***free spectral range***, given by
  - *L* is cavity length, n_g the group index
  - Signal bandwidth must be smaller than Δv_L

$$\Delta v_L = c/(2n_g L)$$

- The ***finesse***, *F*, is defined as
  - The filter bandwidth is denoted by Δv_{FP}

$$F = \Delta v_L / \Delta v_{FP}$$

The center wavelength is typically adjusted with a piezoelectric actuator

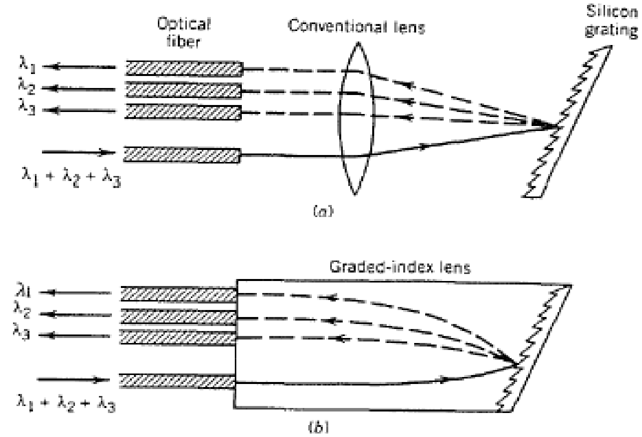


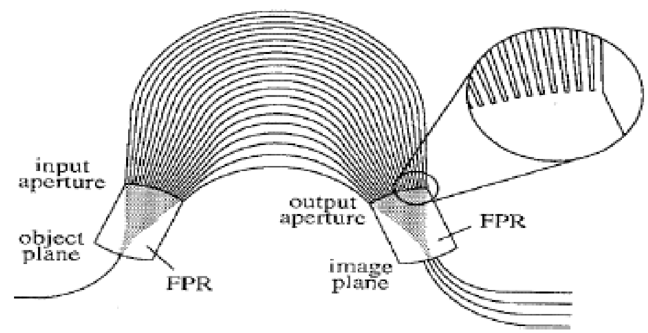
Multiplexers and demultiplexers

A multiplexer with reversed propagation direction is a demultiplexer

(De)multiplexing can be done in several different ways

- A grating-based (de)multiplexer is shown in figure in two different implementation alternatives
- A filter-based (de)multiplexer typically uses MZ filters
- Fiber Bragg gratings can be used to make a all-fiber (de)multiplexer
- An ***arrayed waveguide grating*** (de)multiplexer is seen in lower figure
  - Waveguides have different lengths
  - Phase shifts are wavelength dependent
  - Different channels focus to different outputs
- In a coherent receiver, the channel is selected by tuning the local oscillator frequency



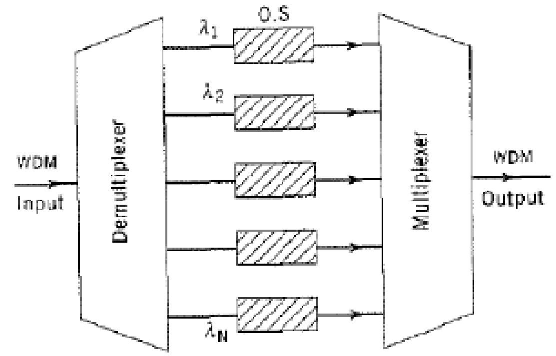


Add-drop multiplexers and filters

During transmission it may be necessary to modify the data content

An ***add-drop multiplexer*** (a) will in principle

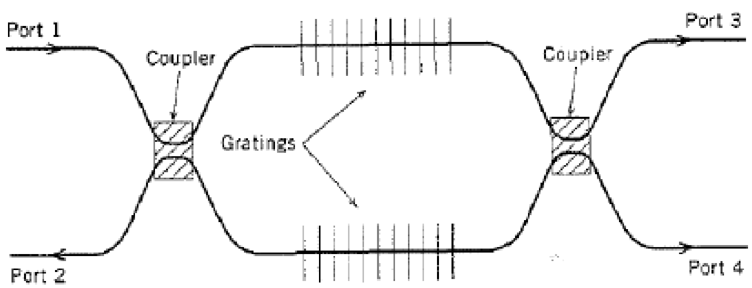
- Demultiplex the incoming signal
- Modify individual channels by passing through, dropping, or adding
- Multiplex individual channels and launch into transmission fiber



(a)

The principle for an ***add-drop filter*** is explained by (b)

- WDM signal is input in port 1
- The channel in the grating stop band is reflected and output in port 2
- A replacement channel can be input in port 3
- Output WDM channel appears in port 4



(b)

WDM components

A ***star-coupler*** combines input signals and divides among the outputs

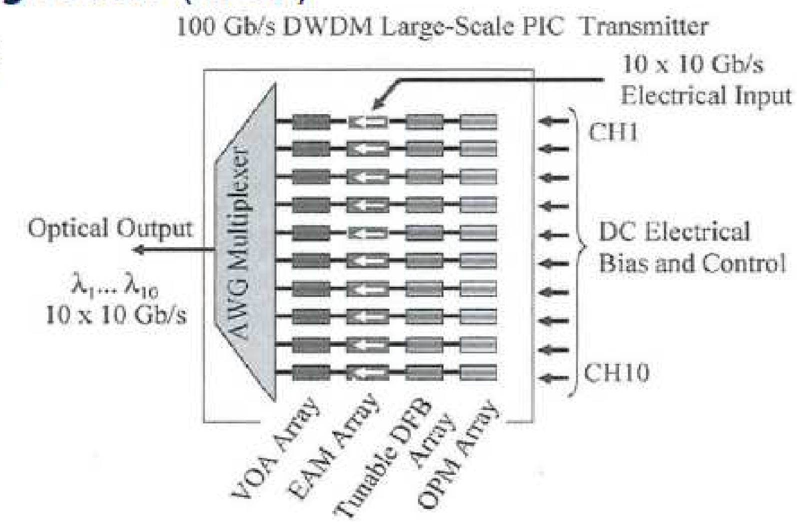
- Are not wavelength-selective
- Can be used for broadcasting
  - Example: Distribution of television to multiple areas

A ***wavelength router*** will redistribute the channels of multiple incoming WDM signals to multiple output fibers

- Different wavelength ⇒ different receiver
- A common design is the ***waveguide-grating router*** (WGR)
  - Like a MZI, but with more than 2 arms

A WDM transmitter can be integrated

- Figure shows a 10 channel system
- OPM = optical power monitor
- EAM = electroabsorption modulators
- VOA = variable optical attenuator



Crosstalk in WDM systems

WDM channels should not interfere with each other during transmission

- The most important design issue is ***interchannel crosstalk***
- Loosely speaking this means power transfer between channels

Crosstalk occurs due to

- Non-ideal demultiplexing/filtering/routing components (linear crosstalk)
- Nonlinear effects in optical fibers or devices (nonlinear crosstalk)

Any crosstalk degrades the BER and causes crosstalk-induced penalty

Linear crosstalk is classified as either ***out-of-band*** or ***in-band crosstalk***

- Out-of-band crosstalk means that power ”leaks” from neighboring channels
- In-band crosstalk means that the crosstalk is at the same wavelength
  - Occurs in routing/networks
  - Adds coherently to the signal

Homowavelength linear crosstalk

Assume we use

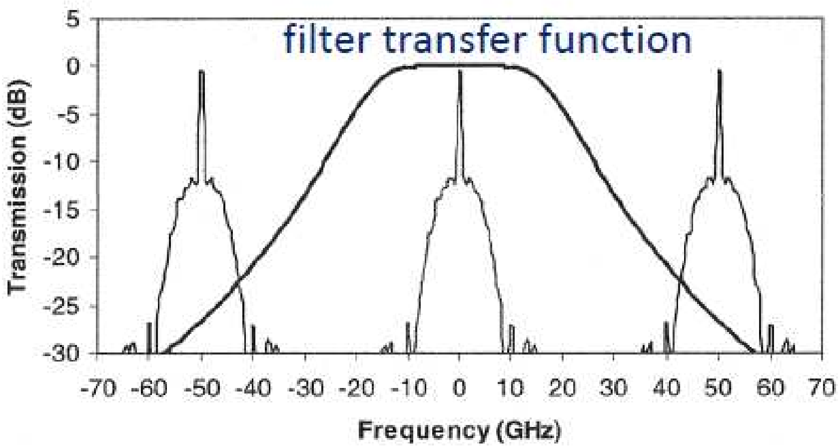
- Direct detection using a photodetector
- An optical bandpass filter for channel selection

The optical power entering channel *m* (of a total *N*) is $P = P_m + \sum_{n \neq m}^{N} T_{mn} P_n$

- T_{mn} is the filter transmission of channel *n* when channel *m* is selected

The corresponding photocurrent is $I = R_m P_m + \sum_{n \neq m}^{N} R_n T_{mn} P_n = I_{ch} + I_x$

- I_x is the crosstalk contribution
- I_x has different values depending on the data in the interfering channels
- Worst case appears when all interfering channels transmit “one” simultaneously



Homowavelength linear crosstalk

The power penalty can be estimated from the eye closure caused by I_x

- To maintain the eye opening, the signal must be increased by I_x

The power penalty is $$\delta_X = \frac{I_{\text{ch}}(I_X)}{I_{\text{ch}}(I_X = 0)} = \frac{I_{\text{ch}} + I_X}{I_{\text{ch}}} = 1 + \frac{I_X}{I_{\text{ch}}}$$

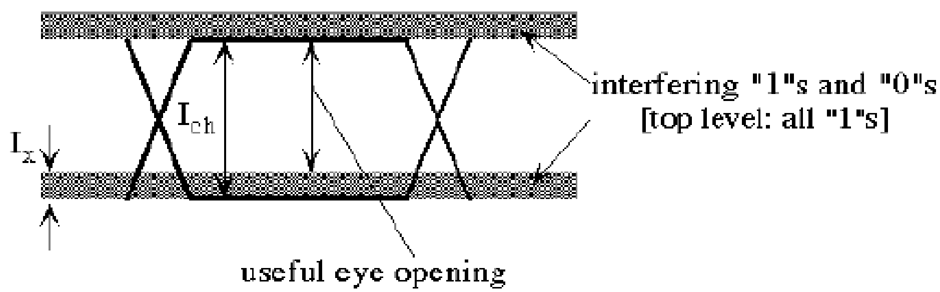
In dB units we get $$\delta_X = 10\log\left[1 + \sum_{n \neq m}^{N} \frac{R_n T_{mn} P_n}{R_m P_m}\right]$$

- P_n and P_m correspond to values for 'one' bits representing worst case

If all channels have the same power and if the responsivity is constant within the wavelength range we have

$$\delta_X = 10\log\left(1 + \sum_{n \neq m}^{N} T_{mn}\right) = 10\log(1 + X)$$

Only depends on the filter

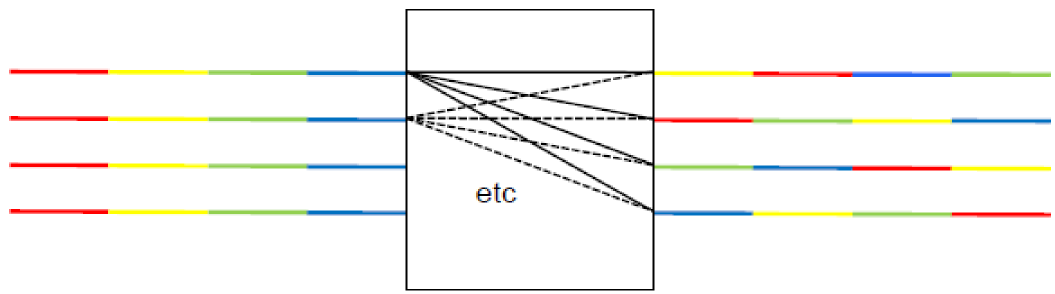


Homowavelength linear crosstalk

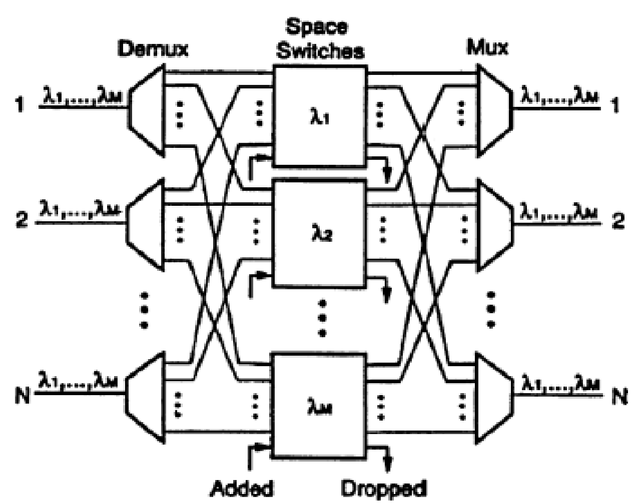
Crosstalk is within the bandwidth of the channel

Caused by non-ideal WDM components used to route/switch signals for example ***wavelength routers*** or ***optical cross connects***

– A wavelength router is static and no reconfiguration is possible



– An optical cross connect is reconfigurable



Homowavelength linear crosstalk

In an $(N+1)\times(N+1)$ router there are N interfering terms (A_n)

- The field entering the receiver is

$$E_m(t) = \left[E_m + \sum_{n \neq m}^{N} E_n \right] \exp(-i\omega_m t)$$

We have signal-crosstalk beating interference

- Compare with ASE beat noise from EDFAs

$$I(t) \approx RP_m(t) + 2R \sum_{n \neq m}^{N} \sqrt{P_m(t) P_n(t)} \cos\left[\phi_m(t) - \phi_n(t)\right]$$

All phases are random ⇒ Acts as intensity noise

The penalty is $\delta_X = -10\log_{10}(1 - r_X^2 Q^2)$ $\quad r_X^2 = \left\langle (\Delta P)^2 \right\rangle / P_0^2 = X(N-1)$

- with $X = P_n/P_m$

Nonlinear crosstalk

Stimulated Raman scattering (SRS)

- No problem in a single channel system ($P_{th} \approx 0.5$ W)
- In WDM systems SRS acts as a fiber amplifier
  - Light at a lower frequency is amplified by the light at a higher frequency
  - Depletion of power in the channel at the highest frequency increases with the number of channels
  - Max channel power is reduced with increasing number of channels

Stimulated Brillouin scattering (SBS)

- Transfers energy to a field at a lower frequency propagating in the backward direction
- SBS bandwidth is narrow (< 100 MHz)
  - Energy transfer is avoided with a channel spacing ≠ SBS frequency downshift (≈ 10 GHz)
  - SBS limitation is independent of the number of channels ($P < P_{th} \approx 10$ mW)

Nonlinear crosstalk

Cross-phase modulation (XPM)

- The phase of the signal is changed when co-propagating with other channels
  - A linear phase shift is a frequency shift ⇒ timing jitter
- The phase-shift increases linearly with the number of channels

Four-wave mixing (FWM)

- New frequency components are generated from mixing
- The number of generated new frequency components increases with number of channels
- Power in each component is reduced with increasing channel spacing
  - Process is phase sensitive

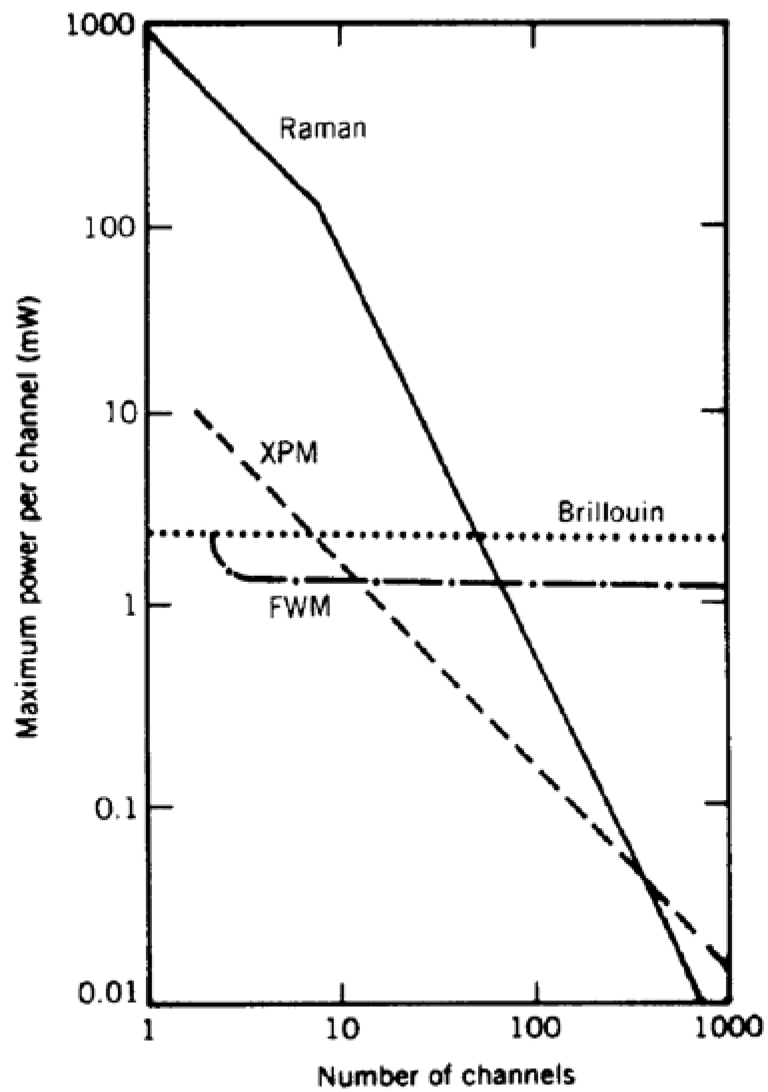
Nonlinear crosstalk

Figure shows limitation on channel power from nonlinear effects

For few channels, FWM & SBS dominate

For many channels, XPM & SRS dominate

Nonlinear crosstalk must be considered in WDM systems, when the launched power per channel is > 0.1–1 mW



Spectral efficiency and the capacity

The ***throughput*** is the number of successfully transmitted bits/second

- This is often called "capacity" in the fiber-optic world

Currently, throughput is increased by increasing the spectral efficiency

- Remember: For a WDM system, the spectral efficiency is $\eta_s = B/\Delta\nu_{ch}$
- Done using multi-level modulation formats and polarization multiplexing
- But how large can η_s be? Larger than 1 (bit/s)/Hz?

The ***channel capacity*** is given by Shannon's famous formula

- Δf is the bandwidth
- C is the ***capacity***

$$C = \Delta f \log_2(1 + \mathrm{SNR})$$

Provided that the SNR is high, η_s can be >> 1 (bit/s)/Hz

- Example: SNR = 40 dB, Δf = 10 GHz ⇒ C = 133 Gbit/s
  with $\Delta\nu_{ch}$ = 50 GHz, η_s = 2.7 (bit/s)/Hz

Wireless systems can have spectral efficiencies as high as 10 (bit/s)/Hz

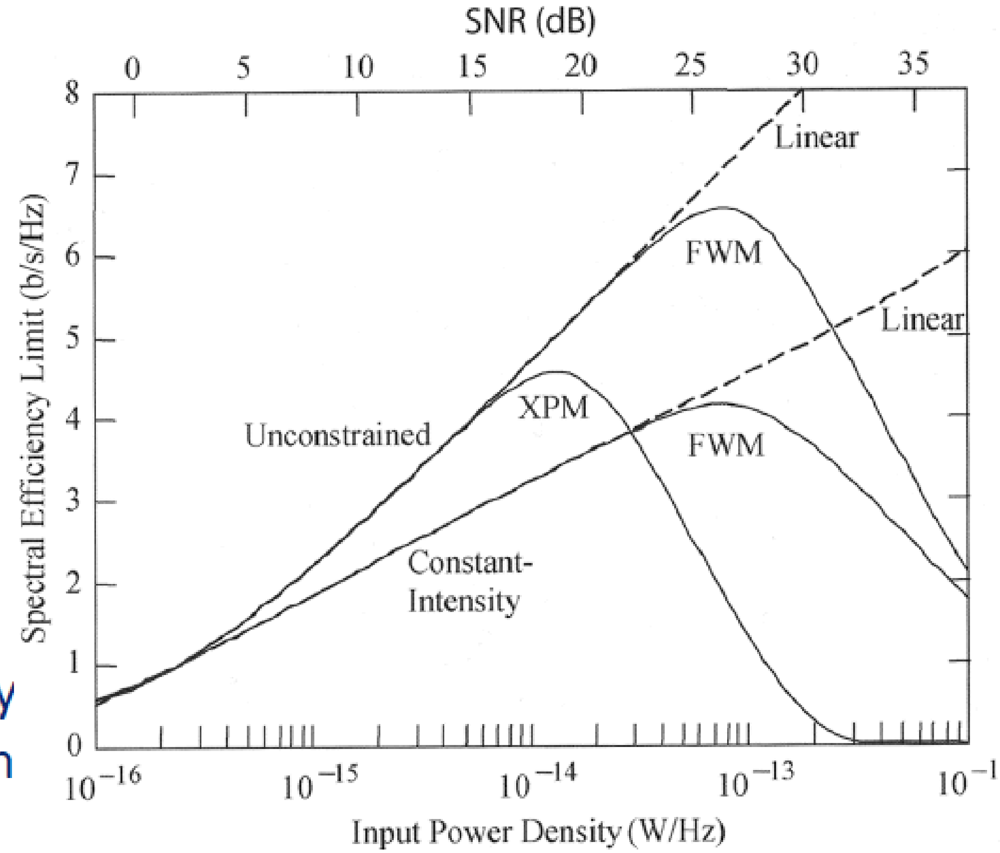
- In optical communication this is not easily achieved

Spectral efficiency and the capacity

System performance is not completely described by the SNR

Figure is from Kahn and Ho, IEEE J. Select. Topics Quantum Electron., no. 2, March/April, 2004

- Assuming a coherent receiver
- "Constant-intensity" and "Unconstrained" refer to the modulation format
  - PSK has constant intensity (without dispersion)
  - Mod. format choice determines the spectral efficiency



In general, the Shannon capacity of an optical fiber is still an open question

OTDM channel multiplexing

OTDM means ***optical time-division multiplexing***

– OTDM is a technique to eliminate the ”electronic bottleneck”
  - ”Sub-channels with lower bit rate are interleaved in time
  - Enables higher bit rates > 40 Gbit/s
  - Total bit rate per channel is $B \times N$
  - Can be combined with WDM

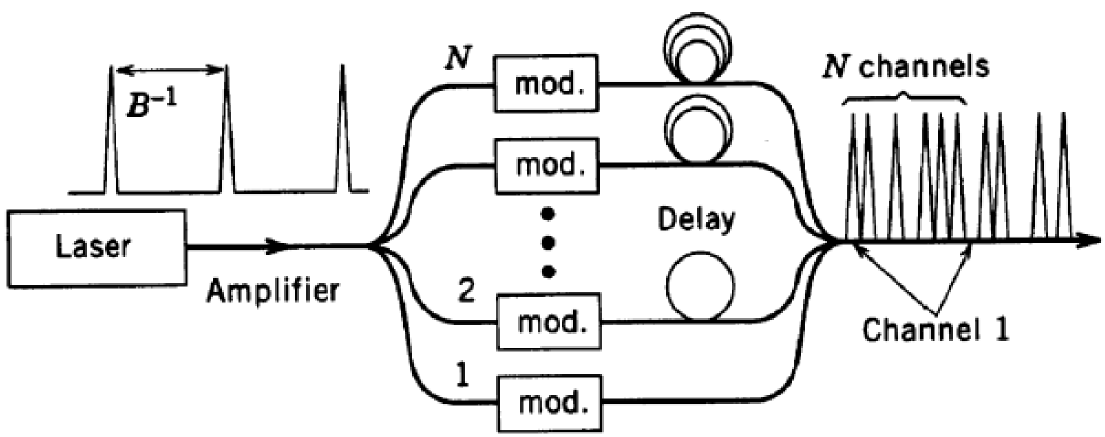
Characteristics:

– Only ”low-speed” electronics required in each “sub-channel”

– Needs RZ format

– Needs precise delay control

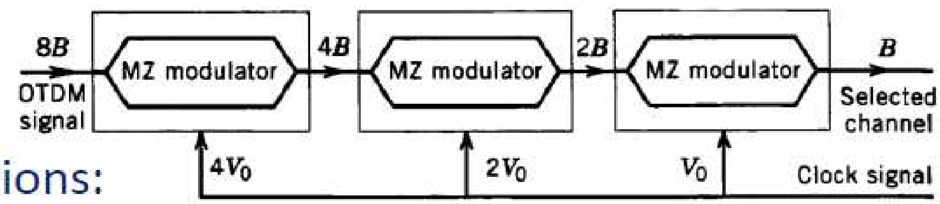
– Pulse source requirements:
  - Short pulses
  - Small timing jitter
  - High extinction ratio (> 30 dB)



OTDM channel multiplexing

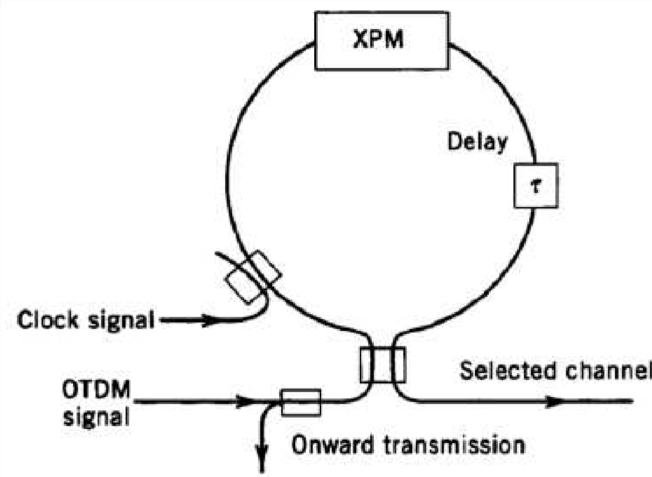
Several different approaches

- All requires a clock signal at "sub-channel" bit rate

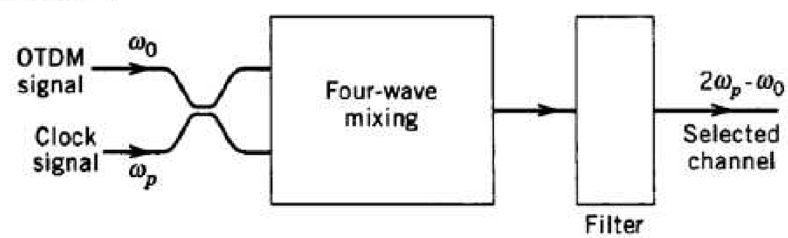


Figures show possible implementations:

- Cascaded $LiNbO_3$ modulators
  - V_0 is required for π phase shift
  - Modulators reject other "sub-channels"
- Nonlinear optical loop mirror
  - Normally reflects, based on XPM
  - Made transparent by clock signal



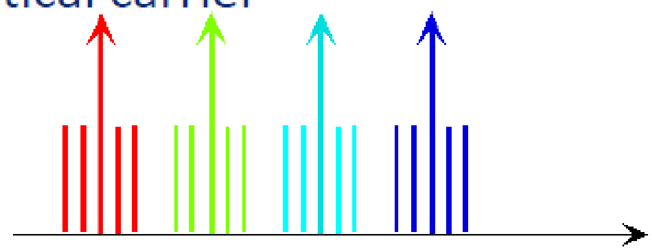
- FWM in nonlinear medium
  - Often uses highly nonlinear fiber (HNLF)
  - Signal is shifted in frequency
  - "Sub-channel" is filtered out



Subcarrier multiplexing

Subcarrier multiplexing (SCM) = electrical microwave signals encoded with data are combined to modulate a single optical carrier

- Possible to combine SCM and WDM
- Figure shows 4 WDM channels, each with 5 SCM channels



The modulation can be analog or digital (or a combination)

- Analog format is often used for video distribution