Optical Communications Systems

Wavelength Division Multiplexing

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Introduction

Wavelength Division Multiplexing (WDM) is the basic technology of optical networking. It is a technique for using a fibre (or optical device) to carry many separate and independent optical channels.

WDM is the basic technology for full optical networking.
Simple (Sparse) WDM

- Wavelength selective couplers are used both to mix (multiplex) and to separate (demultiplex) the signals. The distinguishing characteristic here is the very wide separation of wavelengths used (different bands rather than different wavelengths in the same band).

- Some systems use a single fibre bidirectionally while others use separate fibres for each direction (as illustrated).

- Other systems use different wavelength bands from those illustrated in the figure (1310 and 1550 for example).

- The most common systems run at very low data rates (by today's standards).

- Common application areas are in video transport for security monitoring and in plant process control.
Each optical channel is allocated its own wavelength - or rather range of wavelengths.

A typical optical channel might be 1 nm wide. This channel is really a wavelength range within which the signal must stay. It is normally much wider than the signal itself.

The width of a channel depends on many things such as the modulated linewidth of the transmitter, its stability and the tolerances of the other components in the system.
WDM Elements

Transmitters

In practical terms the transmitter is always a laser. It must have a linewidth which (after modulation) fits easily within its allocated band. It must not go outside the allocated band so it should have chirp and drift characteristics that ensure this. Depending on the width of the allocated band, these characteristics don't need to be the most perfect obtainable. However they do have to be such that the signal stays where it is supposed to be.

Combining the signals (Channels)

The most obvious is to use a number of 3-dB splitters or Y-junctions connected in cascade. The problem with this is that you lose 3 dB at each stage.

Gratings and planar waveguide gratings have much lower loss and their loss is not dependent on the number of channels so these are most often used in systems with more than four channels.
**Transmission and amplification**

In transmission on a fibre the main issue is controlling crosstalk effects. Channel spacings, widths and power levels are system variables that can be used to minimise crosstalk.

Amplification is a major issue. When multiple amplifiers are used in a long link their non-linearities add up and cause significant difficulty.

**Separating the channels at the receiver**

There are several possible techniques we can use:

- Reflective (Littrow) gratings
- Waveguide grating routers
- Circulators with in-fibre bragg gratings
- Splitters with individual Fabry-Perot filters

**Receiving the signals**

The receiver is relatively straightforward and is generally the same as a non-WDM receiver.
Using Dense and Sparse WDM Together – an Example

There is a single channel signal in the 1300 nm band and a 4-channel WDM group in the 1550 nm region. This was produced from a real operational system.

The signals were multiplexed and demultiplexed onto the fibre using a wavelength selective coupler.

By using the wavelength selective coupler they were able to add a pair of 4-channel WDM systems without installing any new fibre.
Building Photonic Networks - Technical Challenges

- Stabilising Wavelengths
- Wavelength Conversion
- Cascading Filters
- Wavelength Tunable Lasers
- EDFA Gain Flatness and Tilt
- Equalising Signal Power
- Dispersion Compensation
- Optical Crossconnects and Switching Elements
- WDM Multiplexing and Demultiplexing
**Spectral Width and Linewidth**

In general in a dense WDM system we need a laser with only one line in its spectrum. This will mean either a DFB or a DBR laser. In general the narrower the linewidth the better but this will usually be a cost/benefit tradeoff.

**Wavelength Stability**

In most long-distance (single channel) systems we need very stable, narrow linewidth lasers to minimise the effects of dispersion and things like mode partition noise.

**Tunable Lasers**

Tunable lasers may be very important in future lightwave networks.

**Multiwavelength Lasers**

One approach that allows very fast tuning is to build a number of lasers of different wavelengths together on the same substrate. Tuning can be accomplished very quickly by selecting which laser is to transmit. Alternatively, multiple signals may be sent simultaneously.
Multiwavelength Lasers

So far devices have not yet appeared on the commercial market and in fact appear to have a number of problems:

It is very difficult to manufacture the DBR lasers to exactly the required wavelengths.

When the light is mixed (of course) a very large proportion of it is lost.

Because of the loss of light you need the SOA to amplify the combined signal. This introduces all the crosstalk and saturation problems of using an SOA with multiple wavelengths.
Multiline Lasers

A number of proposed WDM systems approaches require a “multiline” light source.

The concept here is to produce many wavelengths in the same device. This has a number of significant potential advantages:

- Lower cost
- When multiple wavelengths are generated from a single source there is a fixed relationship between the wavelengths produced. Thus if we stabilise the device with reference to one wavelength we have stabilised it for all wavelengths.

The obvious disadvantage is that we can't modulate individual channels (wavelengths) by controlling the laser's injection current. Some form of external modulation of each channel is needed.
It happens that an ordinary FP laser driven just below the lasing threshold produces a multiline spectrum very close to the spectrum we want.

This is called an “Amplified Spontaneous Emission” (ASE) source. Because it is producing below the lasing threshold the total power is low and the power is distributed among many lines. Also, as shown in the diagram, the lines produced are different in amplitude. To be useful the signal needs to both be amplified and filtered or compensated in some way such that the lines produced are of equal amplitude.
Multiplexing (Combining) the Light

- Passive couplers combine light in exactly the way we want but every time we join two fibres in a coupler we lose half the light! (If you combine eight signals on different fibres onto a single fibre using simple couplers then each individual channel in the combined output will be one eighth of the strength it started out at (a loss of 9 dB)).

- Array Waveguide Gratings (AWGs) are the devices to integrate the signal with a much lower loss.

- A typical commercial Littrow grating combining 32 channels has a loss (per channel) of around 6 dB (3/4 of each signal is lost). AWGs are quoted with total loss levels of around 5 dB for devices with up to 64 channels!

- In systems with only a few channels (say four) then we can use simple couplers. If larger numbers of channels are involved then we might typically need a grating device or an amplifier after the multiplexor.
Transmission

Control of Dispersion

With WDM we can use multiple slower streams instead of a single much faster one! So a 4-channel WDM system at 2.4 Gbps per channel will have less of a problem with dispersion than a single-channel system at 9.6 Gbps.

Interference Effects

One of the issues in WDM is the mutual interference between the optical channels both within devices and during transmission. The two most important transmission effects are called “stimulated Raman scattering” and “4-wave mixing”. Other effects occur in optical amplifiers when operating close to saturation.

Amplifier (EDFA) Issues

Inequality of response between channels can be a serious issue in long distance WDM systems.

Selecting Wavelengths

One possible way of limiting the crosstalk (noise) between channels is to space the WDM channels unevenly. That is, the spacings between the channels are calculated such that noise produced by 4-wave mixing and SRS falls between channels rather than within them.
Demultiplexing the Light

There are three generic approaches to demultiplexing:

1. Split the mixed light up into many mixed outputs (one per required output port) and then filter each port individually.

2. Split off a single channel at a time.

3. Demultiplex the whole bundle of optical channels in one operation.
In this configuration cascaded 3 dB splitters are used to divide the mixed signal up into as many equal outputs as necessary. It is then necessary to separate each individual signal from the others. In this case the separation is achieved with separate Fabry-Perot filters. It would be possible to replace the FP filters with FBGs and circulators (this would increase the precision of wavelength selection but also the cost).
Circulators with FBGs

In this configuration each wavelength is separated from the multiplexed stream individually.

1. Input consisting of many mixed wavelengths arrives.

2. It enters the first circulator and is output into the first FBG

3. The FBG reflects the selected wavelength back to the circulator but allows all other wavelengths to pass. With many types of circulators this operation can involve an attenuation of 1 dB or less.

4. The selected wavelength travels around the circulator to Port 3 where it is output.
Array Waveguide Gratings

A multiplexed stream of wavelengths arriving on one input port is demultiplexed onto particular output ports as shown in the top left-hand part of the figure. The same multiplexed stream of wavelengths arriving on a different input port is demultiplexed onto a different set of output ports.

A big advantage of the WGR is that it can be used in both directions simultaneously.
Add-Drop Multiplexors

An add-drop multiplexor adds and/or removes a single channel from a combined WDM signal without interfering with the other channels on the fibre. There are several devices which may perform this function such as:

1. Array waveguide gratings
2. Circulators with FBGs
3. A Cascade of MZIs
There are many issues to be considered:

1. Determining the width and spacing of wavebands
2. Stabilising the wavelength of wavelength-sensitive components
3. Filter alignment in cascades of filters
4. Control of non-linear effects
5. Control of dispersion
6. Control of cross-talk
7. Dynamics of optical amplifiers
8. Control of system noise (especially ASE)
Controlling Non-linear Effects

Various non-linear effects prevalent in fibre transmission need consideration and control for the system to operate successfully.

*Four-Wave Mixing (FWM)*

This is a most serious issue for WDM systems. It is influenced very strongly by two factors:

1. Channel spacing
2. Fibre dispersion

*Stimulated Brillouin Scattering (SBS)*

SBS depends on a number of things:

1. Signal linewidth
2. Signal power
3. Fibre core size
4. Wavelength

*Stimulated Raman Scattering*
Nonlinear Effects in Fibre

Nonlinear effects are the result of interaction between light and matter.

Typically very small, but since the signal travels long distances on fibre, very small effects have the opportunity to build up into large ones. Non-linear effects increase exponentially as the level of optical power in the fibre is increased (above 3 mW).

These effects can be grouped into two classes. “Elastic” effects where although the optical wave interacts with and is affected by the presence of matter there is no energy exchange between the two (four-wave mixing). “Inelastic Scattering” is where there is an energy transfer between the matter involved and the optical wave (Stimulated Brillouin Scattering and Stimulated Raman Scattering).

Nonlinear effects are nearly always undesirable. After attenuation and dispersion they provide the next major limitation on optical transmission.
Stimulated Brillouin Scattering (SBS)

Scattering of light backwards towards the transmitter caused by mechanical (acoustic) vibrations in the transmission medium.

SBS can be a major problem in three situations:

1. In long distance systems where the span between amplifiers is great and the bit rate low (below about 2.5 Gbps).

2. In WDM systems (up to about 10 Gbps) where the spectral width of the signal is very narrow.

3. In remote pumping of an erbium doped fibre amplifier (EDFA) through a separate fibre. EDFA pumps typically put out about four lines of around only 80 MHz wide.

**SBS Threshold Variation with Wavelength.** The threshold value is the power level above which SBS causes a significant effect.
Stimulated Raman Scattering (SRS)

SRS is caused by a similar mechanism to the one which produces SBS. However, the interactions involved are due to molecular vibrations rather than acoustic ones. Scattered light can appear in both the forward and backward directions.

SRS is not an issue in single-channel systems but can be a significant problem in WDM systems. When multiple channels are present, power is transferred from shorter wavelengths to longer ones.

The effect of SRS becomes greater as the signals are moved further and further apart (within some limits). This is a problem as we would like to separate the signals as much as we can to avoid four-wave mixing effects and when we do we get SRS!

SRS increases exponentially with increased power. At very high power it is possible for all of the signal power to be transferred to the Stokes Wave.
Four-Wave Mixing

The four-wave mixing is an “elastic” effect where although the optical wave interacts with and affected by the presence of matter there is no energy exchange between the two.

FWM occurs when two or more waves propagate in the same direction in the same (single-mode) fibre. The signals mix to produce new signals at wavelengths, which are spaced at the same intervals as the mixing signals.

A signal at frequency $\omega_1$ mixes with a signal at frequency $\omega_2$ to produce two new signals one at frequency $2\omega_1 - \omega_2$ and the other at $2\omega_2 - \omega_1$. The effect can also happen between three or more signals.
Four-Wave Mixing (Contd)

- The effect becomes greater as the channel spacing is reduced. The closer the channels are together the greater the FWM effect.

- FWM is non-linear with signal power. As signal power increases the effect increases exponentially.

- The effect is strongly influenced by chromatic dispersion. FWM is caused when signals stay in phase with one another over a significant distance. The greater the dispersion, the smaller the effect of FWM - because chromatic dispersion ensures that different signals do not stay in phase with one another for very long. Thus to reduce the FWM effect the system architects sometimes employ a balanced structure where sections of dispersive fibre with different dispersion characteristics are joined to form the span. The idea here is that no section of fibre has zero dispersion but that different sections have dispersion of opposite sign so that the total at the end of the link (span) is zero (dispersion compensation).

- If the WDM channels are evenly spaced then the new spurious signals will appear in signal channels and cause noise. Another method of reducing the effect of FWM is to space the channels unevenly.