## Arrayed Waveguide Grating (AWG)

An arrayed waveguide grating (AWG) is a passive optical device that is constructed of an array of waveguides, each of slightly different length. With a AWG, you can take a multi-wavelength input and separate the component wavelengths on to different output ports. The reverse operation can also be performed, combining several input ports on to a single output port of multiple wavelengths. An advantage of AWGs is their ability to operate bidirectionally.

AWGs are used to perform wavelength multiplexing and demultiplexing, as well as wavelength add/drop operations.

## Bit Error Rate/Q-Factor (BER)

Bit error rate (BER) is the measure of the transmission quality of a digital signal. It is an expression of errored bits vs. total transmitted bits, presented in a ratio. Whereas a BER performance of 10-9 (one bit in one billion is an error) is acceptable in DS1 or DS3 transmission, the expected performance for high speed optical signals is on the order of 10-15.

Bit error rate is a measurement integrated over a period of time, with the time interval required being longer for lower BERs. One way of making a prediction of the BER of a signal is with a Q-factor measurement.

## C Band

The C-band is the “center” DWDM transmission band, occupying the 1530 to 1562nm wavelength range. All DWDM systems deployed prior to 2000 operated in the C-band. The ITU has defined channel plans for 50GHz, 100GHz, and 200GHz channel spacing. Advertised channel counts for the C-band vary from 16 channels to 96 channels. The C-Band advantages are:

- Lowest loss characteristics on SSMF fiber.
- Low susceptibility to attenuation from fiber micro-bending. EDFA amplifiers operate in the C-band window.

## Chromatic Dispersion (CD)

The distortion of a signal pulse during transport due to the spreading out of the wavelengths making up the spectrum of the pulse.

The refractive index of the fiber material varies with the wavelength, causing wavelengths to travel at different velocities. Since signal pulses consist of a range of wavelengths, they will spread out during transport.

## Circulator

A passive multiport device, typically 3 or 4 ports, where the signal entering at one port travels around the circulator and exits at the next port. In asymmetrical configurations, there is no routing of traffic between the port 3 and port 1.

Due to their low loss characteristics, circulators are useful in wavelength demux and add/drop applications.

## Coupler

A coupler is a passive device that combines and/or splits optical signals. The power loss in the output signals depends on the number of ports. In a two port device with equal outputs, each output signal has a 3 dB loss (50% power of the input signal). Most couplers used in single mode optics operate on the principle of resonant coupling. Common technologies used in passive couplers are fused-fiber and planar waveguides.

**WAVELENGTH SELECTIVE COUPLERS**

Couplers can be "tuned" to operate only on specific wavelengths (or wavelength ranges). These wavelength selective couplers are useful in coupling amplifier pump lasers with the DWDM signal.

## Cross-Phase Modulation (XPM)

The refractive index of the fiber varies with respect to the optical signal intensity. This is known as the "Kerr Effect". When multiple channels are transmitted on the same fiber, refractive index variations induced by one channel can produce time variable phase shifts in co-propagating channels. Time varying phase shifts are the same as frequency shifts, thus the "color" changes in the pulses of the affected channels.

## DCU

A dispersion compensation unit removes the effects of dispersion accumulated during transmission, thus repairing a signal pulse distorted by chromatic dispersion. If a signal suffers from the effects of positive dispersion during transmission, then the DCU will repair the signal using negative dispersion.

**TRANSMISSION FIBER**

- Positive dispersion (shorter "blue" ls travel faster than longer "red" ls) for SSMF
- Dispersion value at 1550nm on SSMF = 17 ps/km*nm

**DISPERSION COMPENSATION UNIT (DCU)**

- Commonly utilizes Dispersion Compensating Fiber
- Negative dispersion (shorter "blue" ls travel slower than longer "red" ls) counteracts the positive dispersion of the transmission fiber… allows "catch up" of the spectral components with one another
- Large negative dispersion value … length of the DCF is much less than the transmission fiber length

## Dispersion Shifted Fiber (DSF)

In an attempt to optimize long haul transport on optical fiber, DSF was developed. DSF has its zero dispersion wavelength shifted from the 1310nm wavelength to a minimal attenuation region near the 1550nm wavelength. This fiber, designated ITU-T G.653, was recognized for its ability to transport a single optical signal a great distance before regeneration. However, in DWDM transmission, signal impairments from four-wave mixing are greatest around the fiber's zero-dispersion point. Therefore, with DSF's zero-dispersion point falling within the C-Band, DSF fiber is not suitable for C-band DWDM transmission.

DSF makes up a small percentage of the US deployed fiber plant, and is no longer being deployed. DSF has been deployed in significant amounts in Japan, Mexico, and Italy.

## Erbium Doped Fiber Amplifier (EDFA)

**PUMP LASER**

The power source for amplifying the signal, typically a 980nm or 1480nm laser.

**ERBIUM DOPED FIBER**

Single mode fiber, doped with erbium ions, acts as the gain fiber, transferring the power from the pump laser to the target wavelengths.

**WAVELENGTH SELECTIVE COUPLER**

Couples the pump laser wavelength to the gain fiber while filtering out any extraneous wavelengths from the laser output.

**ISOLATOR**

Prevents any back-reflected light from entering the amplifier.

EDFA Advantages are:

- Efficient pumping
- Minimal polarization sensitivity
  High output power
- Low noise
- Low distortion and minimal crosstalk

EDFA Disadvantages are:

- Limited to C and L bands

## Fiber Bragg Grating (FBG)

A fiber Bragg grating (FBG) is a piece of optical fiber that has its internal refractive index varied in such a way that it acts as a grating. In its basic operation, a FBG is constructed to reflect a single wavelength, and pass the remaining wavelengths. The reflected wavelength is determined by the period of the fiber grating.

If the pattern of the grating is periodic, a FBG can be used in wavelength mux / demux applications, as well as wavelength add / drop applications. If the grating is chirped (non-periodic), then a FBG can be used as a chromatic dispersion compensator.

## Four Wave Mixing (FWM)

The interaction of adjacent channels in WDM systems produces sidebands (like harmonics), thus creating coherent crosstalk in neighboring channels. Channels mix to produce sidebands at intervals dependent on the frequencies of the interacting channels. The effect becomes greater as channel spacing is decreased. Also, as signal power increases, the effects of FWM increase. The presence of chromatic dispersion in a signal reduces the effects of FWM. Thus the effects of FWM are greatest near the zero dispersion point of the fiber.

## Gain Flattening

The gain from an amplifier is not distributed evenly among all of the amplified channels. A gain flattening filter is used to achieve constant gain levels on all channels in the amplified region. The idea is to have the loss curve of the filter be a “mirror” of the gain curve of the amplifier. Therefore, the product of the amplifier gain and the gain flattening filter loss equals an amplified region with flat gain.

The effects of uneven gain are compounded for each amplified span. For example, if one wavelength has a gain imbalance of +4 dB over another channel, this imbalance will become +20 dB after five amplified spans.

This compounding effect means that the weaker signals may become indistinguishable from the noise floor. Also, over-amplified channels are vulnerable to increase non-linear effects.

### Isolator

An isolator is a passive device that allows light to pass through unimpeded in one direction, while blocking light in the opposite direction. An isolator is constructed with two polarizers (45o difference in orientation), separated by a Faraday rotator (rotates light polarization by 45o).

One important use for isolators is to prevent back-reflected light from reaching lasers. Another important use for isolators is to prevent light from counter propagating pump lasers from exiting the amplifier system on to the transmission fiber.

### L Band

The L-band is the "long" DWDM transmission band, occupying the 1570 to 1610nm wavelength range. The L-band has comparable bandwidth to the C-band, thus comparable total capacity. The L-Band advantages are:

- EDFA technology can operate in the L-band window.

### Lasers

A LASER (Light Amplification by the Stimulated Emission of Radiation) produces high power, single wavelength, coherent light via stimulated emission of light.

Semiconductor Laser (General View)

Semiconductor laser diodes are constructed of p and n semiconductor layers, with the junction of these layers being the active layer where the light is produced. Also, the lasing effect is induced by placing partially reflective surfaces on the active layer. The most common laser type used in DWDM transmission is the distributed feedback (DFB) laser. A DFB laser has a grating layer next to the active layer. This grating layer enables DFB lasers to emit precision wavelengths across a narrow band.

### Mach-Zehnder Interferometer (MZI)

A Mach-Zehnder interferometer is a device that splits an optical signal into two components, directs each component through its own waveguide, then recombines the two components. Based on any phase delay between the two waveguides, the two re-combined signal components will interfere with each other, creating a signal with an intensity determined by the interference. The interference of the two signal components can be either constructive or destructive, based on the delay between the waveguides as related to the wavelength of the signal. The delay can be induced either by a difference in waveguide length, or by manipulating the refractive index of one or both waveguides (usually by applying a bias voltage). A common use for Mach-Zehnder interferometer in DWDM systems is in external modulation of optical signals.

### Multiplexer (MUX)

**DWDM Mux**

- Combines multiple optical signals onto a single optical fiber
- Typically supports channel spacing of 100GHz and 50GHz

**DWDM Demux**

Separates individual channels from the aggregate DWDM signal

**Mux/Demux Technology**

- Thin film filters
- Fiber Bragg gratings
- Diffraction gratings
- Arrayed waveguide gratings
- Fused biconic tapered devices
- Inter-leaver devices

## Non-Zero Dispersion Shifted Fiber (NZ-DSF)

After DSF, it became evident that some chromatic dispersion was needed to minimize non-linear effects, such as four wave mixing. Through new designs, $\lambda 0$ was now shifted to outside the C-Band region with a decreased dispersion slope. This served to provide for dispersion values within the C-Band that were non-zero in value yet still far below those of standard single mode fiber. The NZ-DSF designation includes a group of fibers that all meet the ITU-T G.655 standard, but can vary greatly with regard to their dispersion characteristics.

First available around 1996, NZ-DSF now makes up about 60% of the US long-haul fiber plant. It is growing in popularity, and now accounts for approximately 80% of new fiber deployments in the long-haul market. (Source: derived from KMI data)

## Optical Add Drop Multiplexing (OADM)

An optical add/drop multiplexer (OADM) adds or drops individual wavelengths to/from the DWDM aggregate at an in-line site, performing the add/drop function at the optical level. Before OADMs, back to back DWDM terminals were required to access individual wavelengths at an in-line site. Initial OADMs added and dropped fixed wavelengths (via filters), whereas emerging OADMs will allow selective wavelength add/drop (via software).

## Optical Amplifier (OA)

**POSTAMPLIFIER**

Placed immediately after a transmitter to increase the strength on the signal.

**IN-LINE AMPLIFIER (ILA)**

Placed in-line, approximately every 80 to 100km, to amplify an attenuated signal sufficiently to reach the next ILA or terminal site. An ILA functions solely in the optical domain, performing the 1R function.

**PREAMPLIFIER**

Placed immediately before a receiver to increase the strength of a signal. The preamplifier boosts the signal to a power level within the receiver’s sensitivity range.

## Optical Bandwidth

Optical bandwidth is the total data carrying capacity of an optical fiber. It is equal to the sum of the bit rates of each of the channels. Optical bandwidth can be increased by improving DWDM systems in three areas: channel spacing, channel bit rate, and fiber bandwidth. The current benchmark for channel spacing is 50GHz. A 2X bandwidth improvement can be achieved with 25GHz spacing.

### CHANNEL SPACING

Current benchmark is 50GHz spacing. A 2X bandwidth improvement can be achieved with 25GHz spacing.

Challenges:

- Laser stabilization
- Mux/Demux tolerances
- Non-linear effects
- Filter technology

### CHANNEL BIT RATE

Current benchmark is 10Gb/s. A 4X bandwidth improvement can be achieved with 40Gb/s channels. However, 40Gb/s will initially require 100GHz spacing, thus reducing the benefit to 2X.

Challenges:

- PMD mitigation
- Dispersion compensation
- High Speed SONET mux/demux

### FIBER BANDWIDTH

Current benchmark is C-Band Transmission. A 3X bandwidth improvement can be achieved by utilizing the “S” & “L” bands.

Challenges:

- Optical amplifier
- Band splitters & combiners
- Gain tilt from stimulated Raman scattering

## Optical Fiber

Optical fiber used in DWDM transmission is single mode fiber composed of a silica glass core, cladding, and a plastic coating or jacket. In single mode fiber, the core is small enough to limit the transmission of the light to a single propagation mode. The core has a slightly higher refractive index than the cladding, thus the core/cladding boundary acts as a mirror. The core of single mode fiber is typically 8 or 9 microns, and the cladding extends the diameter to 125 microns. The effective core of the fiber, or mode field diameter (MFD), is actually larger than the core itself since transmission extends into the cladding. The MFD can be 10 to 15% larger than the actual fiber core. The fiber is coated with a protective layer of plastic that extends the diameter of standard fiber to 250 microns.

## Optical Signal to Noise Ratio (OSNR)

Optical signal to noise ratio (OSNR) is a measurement relating the peak power of an optical signal to the noise floor. In DWDM transmission, each amplifier in a link adds noise to the signal via amplified spontaneous emission (ASE), thus degrading the OSNR. A minimum OSNR is required to maintain good transmission performance. Therefore, a high OSNR at the beginning of an optical link is critical to achieving good transmission performance over multiple spans.

OSNR is measured with an optical signal analyzer (OSA). OSNR is a good indicator of overall transmission quality and system health. Therefore OSNR is an important measurement during installation, routine maintenance, and troubleshooting activities.

### Optical Supervisory Channel

The optical supervisory channel (OSC) is a dedicated communications channel used for the remote management of optical network elements. Similar in principal to the DCC channel in SONET networks, the OSC inhabits its own dedicated wavelength. The industry typically uses the 1510nm or 1625nm wavelengths for the OSC.

### Polarization Mode Dispersion (PMD)

Single mode fiber is actually bimodal, with the two modes having orthogonal polarization. The principal states of polarization (PSPs, referred to as the fast and slow axis) are determined by the symmetry of the fiber section. Dispersion caused by this property of fiber is referred to as polarization mode dispersion (PMD).

### Raman

Raman fiber amplifiers use the Raman effect to transfer power from the pump lasers to the amplified wavelengths. Raman Advantages are:

- Wide bandwidth, enabling operation in C, L, and S bands.
- Raman amplification can occur in ordinary silica fibers

Raman Disadvantages are:

- Lower efficiency than EDFAs

### Regenerator (Regen)

An optical amplifier performs a 1R function (re-amplification), where the signal noise is amplified along with the signal. For each amplified span, signal noise accumulates, thus impacting the signal's optical signal to noise ratio (OSNR) and overall signal quality. After traversing a number of amplified spans (this number is dependent on the engineering of the specific link), a regenerator is required to rebaseline the signal. A regenerator performs the 3R function on a signal. The three R's are: re-shaping, re-timing, and re-amplification. The 3R function, with current technology, is an optical to electrical to optical operation (O-E-O). In the future, this may be done all optically.

### S Band

The S-band is the "short" DWDM transmission band, occupying the 1485 to 1520nm wavelength range. With the "S+" region, the window is extended below 1485nm. The S-band has comparable bandwidth to the C-band, thus comparable total capacity. The S-Band advantages are:

- Low susceptibility to attenuation from fiber micro-bending.
- Lowest dispersion characteristics on SSMF fiber.

### Self Phase Modulation (SPM)

The refractive index of the fiber varies with respect to the optical signal intensity. This is known as the “Kerr Effect”. Due to this effect, the instantaneous intensity of the signal itself can modulate its own phase. This effect can cause optical frequency shifts at the rising edge and trailing edge of the signal pulse.

### SemiConductor Optical Amplifier (SOA)

What is it?

Similar to a laser, a SOA uses current injection through the junction layer in a semiconductor to stimulate photon emission. In a SOA (as opposed to a laser), anti-reflective coating is used to prevent lasing. SOA Advantages are:

Solid state design lends itself to integration with other devices, as well as mass production.

- Amplification over a wide bandwidth
- SOA Disadvantages are:

High noise compared to EDFAs and Raman amplifiers

- Low power
- Crosstalk between channels
- Sensitivity to the polarization of the input light
- High insertion loss
- Coupling difficulties between the SOA and the transmission fiber

### Span Engineering

Engineering a DWDM link to achieve the performance and distance requirements of the application. The factors of Span Engineering are:

Amplifier Power – Higher power allows greater in-line amplifier (ILA) spacing, but at the risk of increased non-linear effects, thus fewer spans before generation.

Amplifier Spacing – Closer spacing of ILAs reduces the required amplifier power, thus lowering the susceptibility to non-linear effects.

Fiber Type – Newer generation fiber has less attenuation than older generation fiber, thus longer spans can be achieved on the newer fiber without additional amplifier power.

Channel Count – Since power per channel must be balanced, a higher channel count increases the total required amplifier power.

Channel Bit Rate – DWDM impairments such as PMD have greater impacts at higher channel bit rates.

### SSMF

Standard single-mode fiber, or ITU-T G.652, has its zero dispersion point at approximately the 1310nm wavelength, thus creating a significant dispersion value in the DWDM window. To effectively transport today’s wavelength counts (40 – 80 channels and beyond) and bit rates (2.5Gbps and beyond) within the DWDM window, management of the chromatic dispersion effects has to be undertaken through extensive use of dispersion compensating units, or DCUs.

SSMF makes up about one-third of the deployed US terrestrial long-haul fiber plant. Approximately 20% of the new fiber deployment in the US long-haul market is SSMF. (Source: derived from KMI data)

### Stimulated Raman Scattering (SRS)

The transfer of power from a signal at a lower wavelength to a signal at a higher wavelength. SRS is the interaction of lightwaves with vibrating molecules within the silica fiber has the effect of scattering light, thus transferring power between the two wavelengths. The effects of SRS become greater as the signals are moved further apart, and as power increases. The maximum SRS effect is experienced at two signals separated by 13.2 THz.

### Thin Film Filter

A thin film filter is a passive device that reflects some wavelengths while transmitting others. This device is composed of alternating layers of different substances, each with a different refractive index. These different layers create interference patterns that perform the filtering function. Which wavelengths are reflected and which wavelengths are transmitted is a function of the following parameters:

- Refractive index of each of the layers
- Thickness of the layers
- Angle of the light hitting the filter

Thin film filters are used for performing wavelength mux and demux. Thin film filters are best suited for low to moderate channel count muxing / demuxing (less than 40 channels).

### WLA

Optical networking often requires that wavelengths from one network element (NE) be adapted in order to interface a second NE. This function is typically performed in one of three ways:

- Wavelength Adapter (or transponder)
- Wavelength Converter
- Precision Wavelength Transmitters (ITU l)