Wavelength multiplexing: WDM and DWDM systems

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Abstract

The demand for bandwidth has increased in an extremely fast pace over the past few years and is likely to continue to do so for the near future. To be able to meet the customers needs, telecommunication companies have to find solutions for increasing their channel capacity at the lowest cost possible.

Several possibilities were investigated in this text. For most cases, *wavelength division multiplexing* (WDM) seems to be a promising solution. In WDM, several different wavelengths are transmitted over one single mode fibre at the same time. If the channel spacing is below 200 GHz, one speaks of *dense WDM* (DWDM). The main advantages of WDM systems are their capability of being compatible to existing hardware, being modular and having the ability of saving a lot of costly equipment if designed properly.

A short overview of the different components used for the assembly of a WDM system is presented. The key components of WDM systems are the multiplexers and demultiplexers. Several approaches for (de)multiplexer concepts were investigated in this text – ranging from commercially available technology to newest research concepts.

Contents

1. Increased demand for bandwidth

The demand for bandwidth has been increasing significantly during the last few years and will most probably continue to increase in the near future. The network capacity increased by 72% in 2007 and an even higher rise is expected for 2008 and 2009 (84%, 99%). The main drivers for the increased demand are: Video applications (video download, video telephony), IP telephony, multimedia applications and employees working from home instead of in the office [1].

An example: In 1997, a single fibre pair had a capacity of 1.2 Gbps. This is fast enough to transmit one thousand books per second over the channel [2]. In contrast, a single compressed high definition video (HD-DVCPRO) will use a datarate of 100 Mbps [3]. That means that only 12 videos can be simultaneously transmitted over the standard connection from 1997. But that also means, that the download of a single two hour video will block the whole connection for ten minutes!

Many networks were built using standard formulas to forecast the amount of data a single customer would want to send over the connection. These formulas were not able to predict the future accurately: "Consequently, forecasts of the amount of bandwidth capacity needed for networks were calculated on the presumption that a given individual would only use network bandwidth six minutes of each hour. [...] In fact, today many people use the bandwidth equivalent of 180 minutes or more each hour." [2]

Those two facts – the fast increasing demand for network bandwidth and the lack to predict the network usage accurately – forced the telecommunication providers to look for new solutions. These solutions should be compatible with existing infrastructure and should be able to deal with an expected future increase in demand.

2. How to increase the Bandwidth

2.1. Laying new fibre

The most obvious approach to increase the bandwidth of a connection is to add additional channels by laying more fibres. This can be the cheapest solution if it is easy to add new fibres beneath the existing ones [2]. In most cases, this approach is impractical, as the estimated price for adding a mile of cable is around 70'000 US$ (around 40'000 Australian dollars per kilometre) [4].

2.2. Increasing the Bit Rate and using TDM

Increasing the bit rate seems a good idea at first sight. The problem is, that the needed faster electronic circuitry is more complex and usually more expensive [4]. There is also a limit for the speed achievable at the moment. This limit is somewhere around 100GHz [5]. Besides the cost, there are other technical issues with increasing the bit rate: Chromatic dispersion that increases more than linearly with the bit rate, nonlinear effects due to increased transmitting power and various other effects [4]. A further disadvantage is that when upgrading, the jump to the higher bitrate has to be made in one step. This leads to unused capacity at the beginning of a new setup and is therefore uneconomical [2].

If it is decided to increase the bitrate, one can use *Time Division Multiplexing* (TDM) to increase the throughput. The basic idea is that existing low speed channels get divided into smaller bits and then transmitted piece after piece over the fast channel [4].

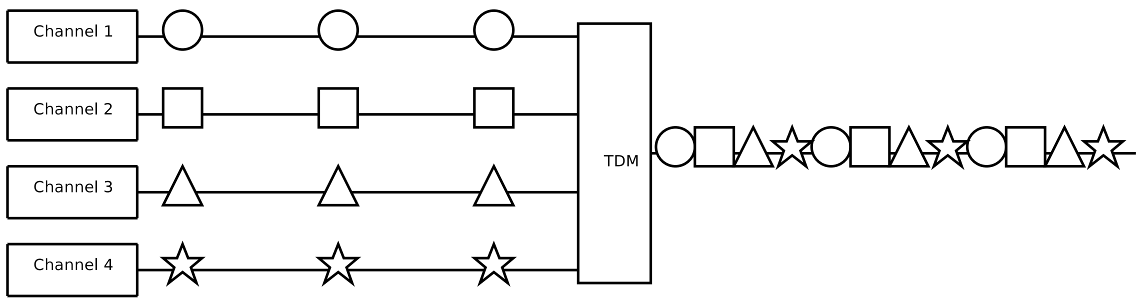

Figure 1: Schematic of a TDM system. On the left side, there are 4 channels that work with normal speed (e.g. older technology). These four channels can be transmitted over one fast channel by splitting the single channels up into tiny bits and then transmitting a piece of each channel in a round robin manner.

2.3. Available bandwidth

Today's record for transmitting data over a single channel in a real life system is around 100 Gbps. This is equal to sending the amount of data that fits on two DVD's over the fibre in one second [6]. The limiting factor is not the fibre, but the bandwidth of the used lasers, modulators, switches, ... [5]. A single mode fibre could be bandwidth modulated around 1550 nm at a data rate of 25'000 Gbps, before optical losses limit the transmission [5].

The wavelength of 1550nm for single mode fibres corresponds to a frequency of (using formula 6)

$$f_c \approx 3 \cdot 10^8 \; ms^{-1} \; / \; 1550 \; nm \approx 1.935 \cdot 10^{14} \; Hz \approx 193.5 \; THz \tag{1}$$

Using Nyquist's theorem, one finds that the signal must be bandlimited to 25 THz around f_c. The frequency range the signal operates is therefore:

$$S(f) = 0 \; for \; |f| < 193.5 - \frac{25}{2} \; THz \; or \; |f| > 193.5 + \frac{25}{2} \; THz \tag{2}$$

Using formula 6 again, the wavelengths one can operate in are:

$$\lambda_{low} = 3 \cdot 10^8 \; ms^{-1} \; / \; 206 \; THz = 1456 \; nm \tag{3}$$

$$\lambda_{high} = 3 \cdot 10^8 \; ms^{-1} \; / \; 181 \; THz = 1657 \; nm \tag{4}$$

$$\lambda_{low} < \lambda_{operate} < \lambda_{high} \tag{5}$$

These results correspond to figure 11. It is therefore clearly visible that using a single wavelength is a waste of capacity.

2.4. Using several wavelengths

The logical consequence is using several wavelengths. If N different wavelengths are used, the capacity of the channel can be increased by a factor of N, without changing the modulation speed of the single laser [5]. There are systems working today that are operating at $N = 160$ channels. It is not yet determined, what the maximum amount of different channels is, but 160 doesn't seem to be near the limit yet [4].

3. Wavelength division multiplexing (WDM)

3.1. Basic Operation

A single mode fibre can support many different wavelengths at the same time (see section A.3). If two different colored lasers (different wavelength, fibre chosen in a way that both are single mode) excite a mode in a fibre each and then both of them are *multiplexed* onto the same singlemode fibre, the fibre has now two first order modes with different wavelengths travelling in it [5]. This is not to be confused with a multimode fibre, where every color has several different modes! The different channels are independent of each other [4]. The wavelength also serves another purpose: As it is unique for every channel, it can be seen as a kind of an address to route the signal. At the end of the fibre, the different wavelengths have to be separated from each other (*demultiplexed*) and then detected separately [5].

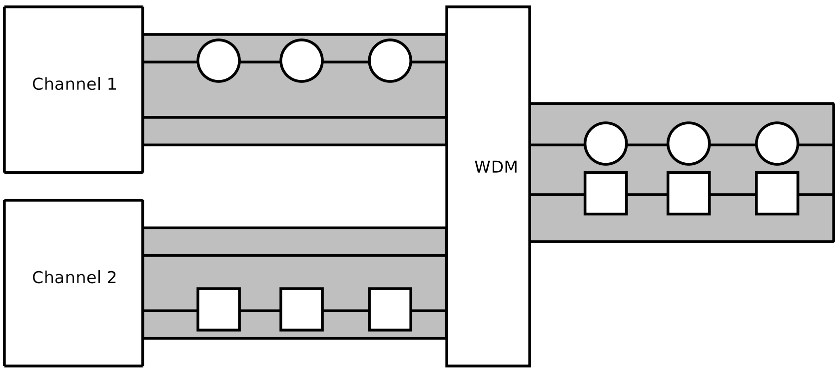

Figure 2: Simple schematic of a WDM system for $N = 2$: In each of the two different fibres, one channel at a different wavelength gets excited. All the other channels are still unused (in this example, there is only one other channel). Both signals then get multiplexed onto a single fibre (in this example, both available channels are now occupied). As a result, the capacity of the fibre can be doubled without having to increase the bitrate of a single channel.

3.2. Advantages of WDM

Wavelength division multiplexing has several advantages over the other presented approaches to increase the capacity of a link:

- Works with existing single mode communication fibre [4, 5].

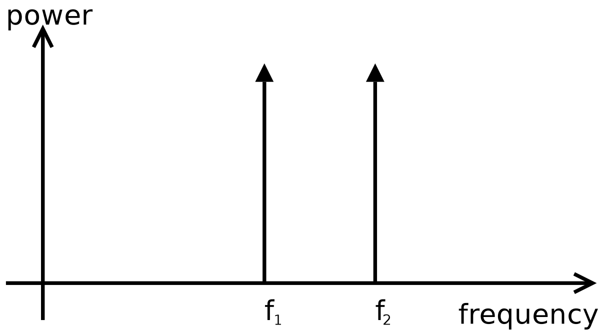

Figure 3: The frequency spectrum of a fibre using two WDM channels. There are in an ideal case (continuous light, ideal lasers) just two peaks at the wavelengths λ_1 and λ_2

- Works with low speed equipment [4, 5]
- Is transparent: Doesn't depend on the protocol that has to be transmitted [4, 2].
- Is scalable: Instead of switching to a new technology, a new channel can easily be added to existing channels. Companies only have to pay for the bandwidth they actually need [4, 2].
- It is easy for network providers to add additional capacity in a few days if customers need it. This gives companies using WDM an economical advantage. Parts of a fibre can be leased to a customer who then gets fast network access without having to share the connection with others. The telecommunication company on the other hand still has an independent part of the fibre available for other customers [4, 2].

3.3. Special Case of WDM: Dense WDM

Instead of just using different wavelengths (e.g. the three main communication windows at 850nm, 1300nm and 1550nm [7]), the different wavelengths can be chosen nearer together. The minimal spacing achieved in the late 1990's was 25GHz, which is equivalent to a difference in channel wavelength of approximately 0.6 nm (using the same formulas as before). Generally, if the spacing between the channels is below 200 GHz, one speaks of *dense WDM* (DWDM) [8]. DWDM has again advantages over general WDM:

- Channels are nearer together which leads to a higher possible capacity [4]

- If the different DWDM channels are chosen in a way that they lie all around the 1550 nm communication window, all channels can be amplified simultaneously using optical amplifiers as *EDFA*'s (*erbium doped fibre amplifier*). This saves additional equipment and therefore money [4].

4. Tasks in a DWDM / WDM Network

- **Generating** signals: Stable lightsource, with a narrow specific wavelength and the possibility of fast modulation [9].
- **Combining** signals: Merging all the different lightsources into one fibre [9].
- **Transmission** of signals: Controlling parameters as crosstalk and loss. Control over variables as channel spacing or input power. For long links: Amplification needed (flat gain amplifiers to amplify all used wavelengths together). It may further be necessary to remove or add certain wavelengths from the link, before they reach the end [9].
- **Separating** the received signals at the receiver end (demultiplexing) [9].
- **Detecting** the separated signals [9].

4.1. Generating Light Pulses

Usually, the lightsource is a semiconductor laser. Out of all different semiconductor laser types, the *distributed feedback laser* (DFB) seems to fit the needs of a DWDM system best. DFB lasers have nearly monochromatic light, are capable of high modulation speeds and have good signal to noise and linearity characteristics. And finally they are available in a large range of precisely defined wavelengths around 1550 nm (for example *ITU draft standard G.692*) [9].

4.2. Transmission

For the transmission, single mode fibres and EDFA's are used. EDFA's allow fully optical long distance links. The link length is basically limited by nonlinear effects, as linear effects can be compensated. Most nonlinear effects become important, when the power used in a fibre becomes large. This is the case in DWDM as many channels are used. Important nonlinear effects are: *Nonlinear gain* of the EDFA, *stimulated Brillouin scattering* (see section A.6.1), *stimulated Raman scattering* (see section A.6.2), *self phase modulation* (see section A.6.3) and *four wave mixing* (see section A.6.4) [9]. For bit rates above 40 Gbps, it becomes very important, that the fibre and the sourrounding hardware are designed together and not as independent systems [9].

4.3. Detection

Light detectors are generally broad band devices. Therefore the channels need to be demultiplexed first, before they can be detected [9]. Similar to their electronical counterpart, optical detectors can use preamplifiers and filters. There are two major technologies for detecting light coming out of a fibre: *PIN diodes* and *avalanche photodiodes* (*APD*) [10].

PIN photodiodes are built like normal diodes, but with an intrinsic layer in the middle. Detectors based on PIN diodes usually have waveguides built in to get a maximum amount of light from the fibre to the detector. PIN diodes can operate up to around 50 GHz [10].

Avalanche photodiodes are usually used in long haul networks, because they have a superior sensitivity compared to PIN diodes (up to a factor of 10 better). APD's are generally strongly reverse biased PN-diodes. Impact ionization by photons creates an avalanche of free carriers (junction breakdown) which then can be measured. APD's are generally slower than PIN diodes. They are usually used up to 2.5 GHz. APD's up to 10 GHz are possible, but usually too expensive [10].

4.4. Combining / Separating: Multiplexer and Demultiplexer

Multiplexers and demultiplexers can either be active or passive devices. Passive devices use prisms, gratings or fixed filters, whereas active designs work with tunable filters. The main challenge in designing a (de)multiplexer is to get a high channel separation and low cross talk [9]. The isolation between the channels should be at least

20 dB. This means, that each neighbouring channel gets damped by at least a factor of 100 when detecting the wanted channel [8].

4.4.1. (De)Multiplexers based on a Prism

As a Prism can be used to split up light into its different components (rainbow at the "output" of a prism), it can basically be used to demultiplex different wavelengths. A sample system is shown in figure 4. Systems based on prisms seem to be highly complicated for standard telecommunication applications. Using prisms to (de)multiplex WDM channels of *Polymer Optical Fibres* (*POF*) based systems on the other hand seems to be promising. Those fibres have a large core (around 1 mm) and are used for example in the aerospace sector, in the medical sector or in the automotive industry [11].

Prism based demultiplexers can usually not be used for DWDM systems.

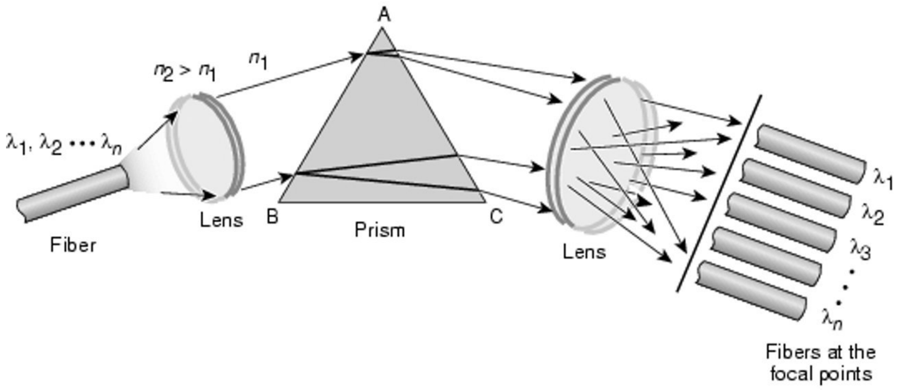

Figure 4: Demultiplexer based on a prism: The first lens is used to produce a parallel beam of all available wavelengths. As every channel gets diffracted in a different angle by the prism (see section A.5), they leave the prism in different locations. Using another lens, the channels can be collected on a focal point, where either another fibre or a detector can be placed. If the system is run in the opposite direction, it can be used as a multiplexer (exchanging detector with lightsources) [9]. Image source: [9]

4.4.2. (De)Multiplexers based on Interference Filters

Interference filters (also called *dielectric filters*, *multilayer interference filters* or *thin film filters*) are usually built out of two different materials with a different refractive index each [9, 8]. They take advantage of the effect, that each change in the refractive index results in some part of the light being reflected and some part being transmitted (see section A.2 formulas 9 to 12). Using several alternating layers of the two materials, a kind of a cavity can be built. Some wavelengths interfere with their reflected parts constructively, whereas others interfere destructively. Those wavelengths that interfere constructively can pass the filter, whereas the others get reflected. Besides the material parameters, the incident angle plays a major role, as each layer gets relatively thicker when tilting the filter. A sample system based on interference filters is depicted in figure 5 [8].

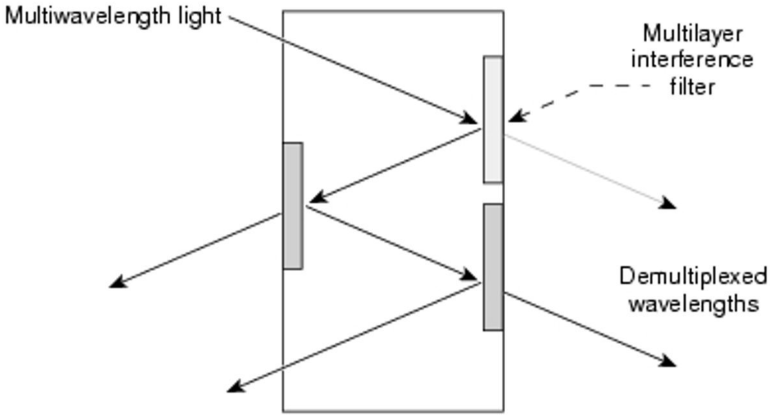

Figure 5: Demultiplexing using *interference filters*: Each of those filters lets pass exactly one wavelength and reflects all the others. By using several of those filters, the different wavelengths can be sorted out [9]. Image source: [9]

Interference filters are manufactured for a long time and therefore high quality filters are readily available. They usually have sizes of several square millimetres. Interference filters therefore are a valid choice to build (de)multiplexers [8].

Designing a (de)multiplexer out of interference filters causes several problems: To be able to use the filters, the light has first to be extracted from the fibre, focused using a lens, passed through the filter, collected by another lens and finally fed back into the fibre [8]. It is obvious that a process including so many different elements is generally expensive to produce and difficult to align.

Another problem is that the filters don't reflect 100% of the incident light at the "wrong" wavelengths. This is no problem for 8 channels, but leads to significant losses for 16 channels. To reduce such losses, other setups can be used to reduce the amount of reflections. A possibility is to use a filter with a broader band first and sort half of the wavelengths out [8].

A large advantage of (de)multiplexers based on interference filters is their ability to be built in a modular way. The telecommunication company therefore has to buy only the amount of channels that they actually need and can buy further equipment later (at hopefully lower prices) [8].

There are interference filters available that are narrow enough for the use in DWDM systems [8].

4.4.3. (De)Multiplexers based on Bragg Gratings

Bragg Gratings are the exact opposite of filters: Instead of allowing a single wavelength to pass, they reflect one single wavelength. As they are usually built of fibre, they are easy to couple to existing systems (splicing). The main problem is the reflected light. This problem can be solved using *Optical Circulators*. A sample system can be seen in figure 6. Several such (de)multiplexers could be put together in an array. In most cases, this is not done because of the high cost and complexity of the used Optical Circulators [8]. Bragg Grating based (de)multiplexers can be used for WDM and DWDM systems [8].

4.4.4. (De)Multiplexers based on Fused-Fibre Couplers

The operation of *Fused-Fibre Couplers* is dependent on the used wavelength. Shorter input wavelengths couple in a shorter distance than longer ones. Once coupled to the other fibre, the wavelengths couple back again to the initial fibre. If two wavelengths λ_1 and λ_2 are known, a coupler can therefore be designed to separate the wavelengths into the two outputs of the coupler. If run in the opposite direction, the same device can be used to multiplex two known wavelengths together. Coupler based (de)multiplexers work well if the spacing between the channels is sufficiently large - for example the third communication window (1550 nm) and the pump laser of an EDFA (980nm) [8].

4.4.5. (De)Multiplexers based on Mach-Zehnder Interferometers

Mach-Zehnder interferometers (also called *interleavers*) basically use two Fused-Fibre Couplers in series. A first coupler (*coupler 1*) splits the light into two equally strong parts. The path difference introduced by different lengths of fibre between the two

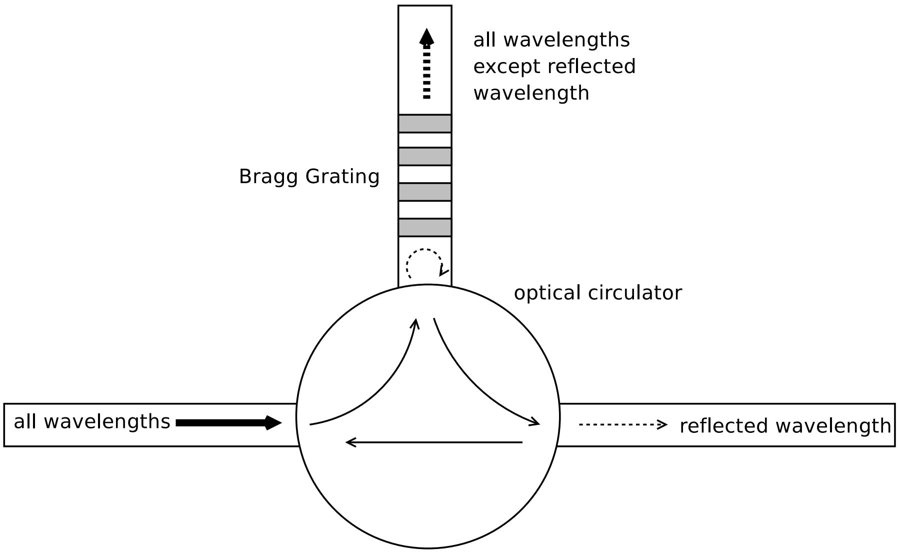

Figure 6: Demultiplexer based on an Optical Circulator and a Bragg Grating. All wavelengths are coming from the fibre from the left. They get redirected to the fibre at the top by the optical circulator. Facing the Bragg Grating, one wavelength gets reflected. All other wavelengths are able to pass the Bragg Grating and leave the multiplexer in the top fibre. The reflected wavelength passes the Optical Circulator again and leaves it in the fibre to the right. The same arrangement can be used as a multiplexerwhen run in the opposite direction [8].

couplers causes interference between the two inputs of *coupler 2* [8]. A schematic can be seen in figure 7. The Mach-Zehnder interferometer can also be used as a multiplexer when run the other way [8].

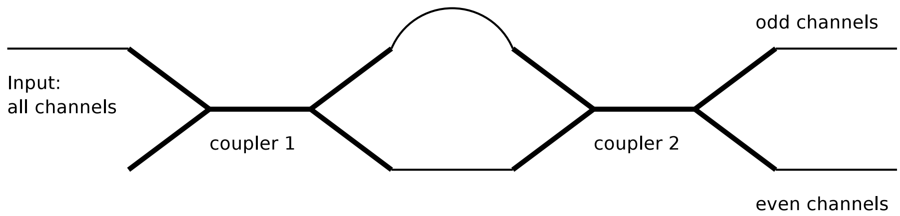

Figure 7: A simple Mach-Zehnder interferometer: A first coupler splits the light into two equal parts. These then take a different time to reach the second coupler, as one of the fibres is chosen to be slightly longer. This causes interference and redirects some channels to the first output, whereas other channels get redirected to the second output [8].

If properly designed, the Mach-Zehnder interferometer is able to route a well defined subset of channels to its first output, whereas the rest gets routed to the second output. If adding several Mach-Zehnder interferometers in a tree-like configuration, one can (de)multiplex all channels available in a fibre. For (de)multiplexing N channels, $N - 1$ interferometers are needed. The tree-like configuration allows large channel numbers to be (de)multiplexed, as the average number of devices that have to be passed is smaller than for example in the approach with the interference filters and losses are reasonably low [8].

4.4.6. (De)Multiplexers based on Diffraction Gratings

A parallel series of lines or grooves is able to diffract light into its spectrum. A simple example is a CD that splits incoming light into its components (a "rainbow" is visible). (De)Multiplexers based on diffraction gratings usually need a lens to focus the incoming and the outgoing light. This can either be normal optical lens or a rod with a *GRIN lens* structure (GRaded INdex). A simple setup can be seen in figure 8 [8].

(De)Multiplexers based on diffraction gratings usually only work for WDM systems, as the channel separation of closely spaced channels is bad. This disadvantage can be turned into an advantage when used for measurement instruments: The bad separation (or the continuous splitting) allow for measurements over a whole frequency band [8].

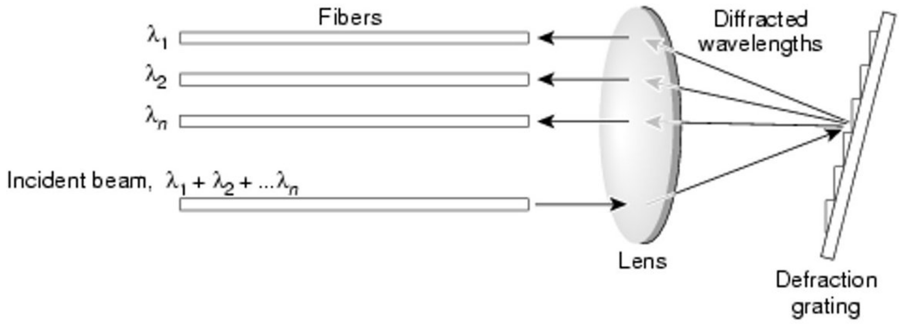

Figure 8: Demultiplexer based on diffraction and interference: The incident light beam with all channels is directed on a diffraction grating. Each wavelength gets diffracted at a different angle and can therefore be collected at a different location. This setup can be used as a multiplexer when run in the opposite direction [9]. Image source: [9]

Special gratings called *echelle gratings* seem to be able to meet the needs of DWDM systems [8] - but they still seem to be in development phase for commercial use DWDM systems [12].

4.4.7. (De)Multiplexers based on Waveguide Arrays

Arrayed Waveguide structures (sometimes also called *Arrayed Waveguide Gratings*) again use interference to split up or combine different channels. It is basically a large scale version of a Mach-Zehnder interferometer. The large difference is: Arrayed Waveguides structures are able to easily split up 40 channels with low channel spacing. They are usually built monolithically on planar waveguide technology. As a drawback, insertion losses are relatively high [8] and the overall device size is sometimes larger than a complete eight inch wafer [13]. A schematic of a demultiplexer using arrayed waveguides is visible in figure 9. To circumvent size problems, three dimensional structures are developed using the same principle. They are still in development stage [13]. A schematic of such a three dimensional device can be seen in figure 10.

4.4.8. Tunable (de)multiplexers

Tunable (de)multiplexers are widely used for measurement equipment [8]. They could also be used in next generation networks to allow for a dynamic channel allocation. There are several approaches to build tunable (de)multiplexers. The simplest approach

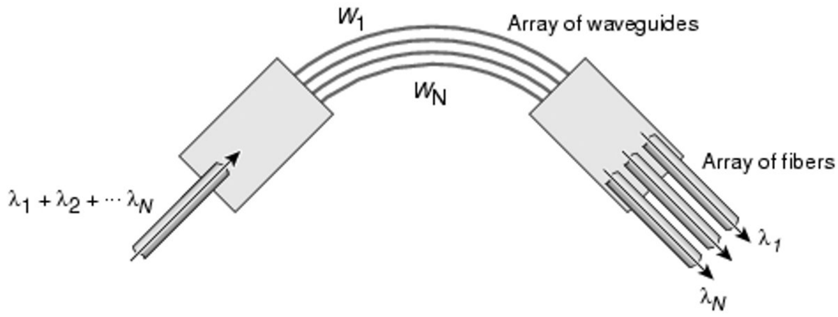

Figure 9: Demultiplexers using *arrayed waveguides*: The light enters the first cavity and gets split up into the different waveguides. As the different waveguides have different lengths, the light at the output has a well defined relative phase difference to all other waveguides. Interference is then used in the second cavity to separate the channels [9]. Arrayed waveguides have the advantage of being able to handle large numbers of channels [9] with good performance [13] and – if designed correctly – being able to multiplex and demultiplex at the same time [9]. Image source: [9]

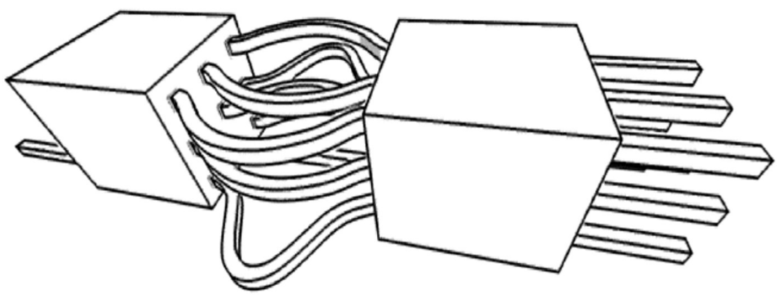

Figure 10: Simplified schematic view of a 3D-MMI-PHASAR. The proposed device is able to demultiplex 65 channels with a spacing of 0.2 nm. The device has similar properties to the arrayed waveguide gratings, but is smaller and therefore easier to package [13]. Image source: [13]

is to use interference filters and tilt them. Another approach is to use a *Fabry-Perot interferometer*, which basically consists of two partially transparent mirrors and a cavity in between. The problem with Fabry-Perot interferometers is, that they are generally not narrow banded enough [8].

A totally different approach is to use *acousto-optic filters*. By adjusting a sound wave, a clear material can get denser and less dense regions. The denser regions have a higher refractive index and the whole structure creates a grating in the material. The resonant light wavelength can be chosen by adjusting the acoustic frequency [8].

4.5. Other components

There is a range of other components that are used in today's WDM and DWDM networks. These include optical boosters after the (de)multiplexer, dispersion compensation measures, preamplifiers in front of the demultiplexer and add/drop multiplexers (to add or remove certain channels) [14].

5. Possible future improvements

As shown in calculations, today's networks – even using DWDM – still only reach a small part of their possible capacity. If in future *coherent detection* (interference of signal with a reference signal) was used instead of simple intensity detection, part of the capacity could be increased. This is due to today's widely used "on-off-keying" for optical networks [15]. If instead multilevel intensity keying or phase modulation was used [15] - as used in other fields of telecommunication [16] - the capacity could further be increased [15, 16]. This of course results in more complex circuits.

6. Conclusion

The customers demand for bandwidth has increased fast during the last few years. Grow rates of over 70% were measured in 2007. The most important driver for this increased demand on bandwidth are video applications. Due to insufficient estimates, today's networks are not built for the extremely high demand in network capacity. Telecommunication providers therefore have to develop new solutions solve the problem.

There are three totally different approaches: Laying new fibres, increasing the datarate and using several wavelengths simultaneously in one fibre. Laying new fibre is most often not a valid solution, as the costs are too high. Increasing the datarate is basically possible, but there are limits to the speed one can achieve and hardware gets highly expensive for fast datarates. Using several wavelengths at once – wavelength division multiplexing – circumvents these problems, as the data rate stays the same as before and no new fibres are needed. WDM also has other benefits: It is highly scalable and can be built in a modular way. This allows telecommunication providers to install just the amount of hardware they actually need an upgrade their networks slowly, when needed.

WDM networks need several components. Most of them are similar to standard telecommunication systems. The key components for WDM systems are the multiplexers and the demultiplexers. They allow the combining of several wavelengths into one fibre and the separation of those wavelengths at the end of the fibre.

Different types of multiplexers were investigated. Each of the approaches has it's advantages and disadvantages – there is no solution that would be obviously better than all the other ones. The choice of the multiplexer design also heavily depends on the system specifications: Not all concepts are available for dense WDM (DWDM), where the channel spacing is below 200 GHz. Wavelength division multiplexing seems to be a major step forward in increasing the bandwidth of existing telecommunication systems, as an increase of at least a factor of 160 seems to be possible. As there is an upper limit to the amount of channels that can be used due to optical losses (Rayleigh Scattering and Intrinsic Absorption), also WDM systems will reach a limit sometimes in the future. In that case, more sophisticated modulation and demodulation techniques could be used, as today's on-off-keying is inefficient in terms of bandwidth use.

A. Appendix

A.1. Nyquists Theorem

A continuous signal $s(t)$ sampled at a frequency f_s can be rebuilt without error if the following two conditions are satisfied [17]:

1. The signal $s(t)$ is bandlimited to W Hz which means: $S(f) = 0 \; for \; |f| > W$
2. $f_s > 2W$

The same is true for passband signals [18]:

1. The passband signal $s_p(t)$ is bandlimited to W Hz around f_c which means: $S_p(f) = 0 \; for \; |f| < f_c - \frac{W}{2} \; and \; |f| > f_c + \frac{W}{2}$
2. $f_s > W$

The easiest way to proof the second part is by shifting the signal to the baseband and realizing, that the new base band signal is now bandlimited to $W/2$ Hz. Now the first part can be used.

A.2. Collection of Optical Formulas

Dependence between speed of light (c), wavelength (λ) and the frequency (f) [7]:

$$c = \lambda \cdot f \tag{6}$$

The modal phase velocity is the speed at which the planar phase front of a mode propagates [19]:

$$v_{ph} = \frac{c_0}{n_e} \tag{7}$$

The modal group velocity is the speed at which the power of a mode propagates [19]:

$$v_g = \frac{c_0}{n_e - \lambda \frac{dn_e}{d\lambda}} \tag{8}$$

IMPORTANT: Light in two different mediums has different wavelengths, whereas the frequency stays the same (speed of light changes according to formula 7). In this text, the term *wavelength* is always meant to be the *freespace wavelength*.

The *Fresnel formulas* for reflection (R) and transmission (T) of a light wave on a material interface [20]:

$$R_{\parallel} = \frac{\tan(\Theta_i - \Theta_t)}{\tan(\Theta_i + \Theta_t)} \tag{9}$$

$$R_{\perp} = -\frac{\sin(\Theta_i - \Theta_t)}{\sin(\Theta_i + \Theta_t)} \tag{10}$$

$$T_{\parallel} = \frac{2 \cdot \sin(\Theta_t) \cdot \cos(\Theta_i)}{\sin(\Theta_i + \Theta_t) \cdot \cos(\Theta_i - \Theta_t)} \tag{11}$$

$$T_{\perp} = \frac{2 \cdot \sin(\Theta_t) \cdot \cos(\Theta_i)}{\sin(\Theta_i + \Theta_t)} \tag{12}$$

The incident angle Θ_i and the transmitted angle Θ_t are defined by *Snell's law* [20]:

$$n_i \cdot \sin(\Theta_i) = n_t \cdot \sin(\Theta_t) \tag{13}$$

A.3. Single Mode Fibre

A fibre usually has the following parameters [21]:

- refractive index of the core: n_{co}
- refractive index of the cladding: n_{cl}
- core radius: ρ
- source wavelength: λ
- fibre parameter: V

The fibre parameter is defined as [21]:

$$V = \frac{2 \cdot \pi \cdot \rho}{\lambda} \cdot \sqrt{n_{co}^2 - n_{cl}^2} \tag{14}$$

The fibre is single mode (only supports fundamental mode), when the following equation is satisfied [21]:

$$V < 2.405 \tag{15}$$

This on the other hand doesn't mean, that it is not possible to have two different wavelengths travelling in the fibre. For example: If the fibre is single mode for a wavelength of 1300 nm, the fibre is also single mode for 1550 nm (proof using formula 14, where everything is constant with exception of the wavelength). Formula 8 predicts, that the two different wavelengths will travel at differend speeds and therefore have different wavevectors.

To avoid crosstalk and therefore signal degradation between the two (ore more) frequencies, the channels have to be properly separated [5].

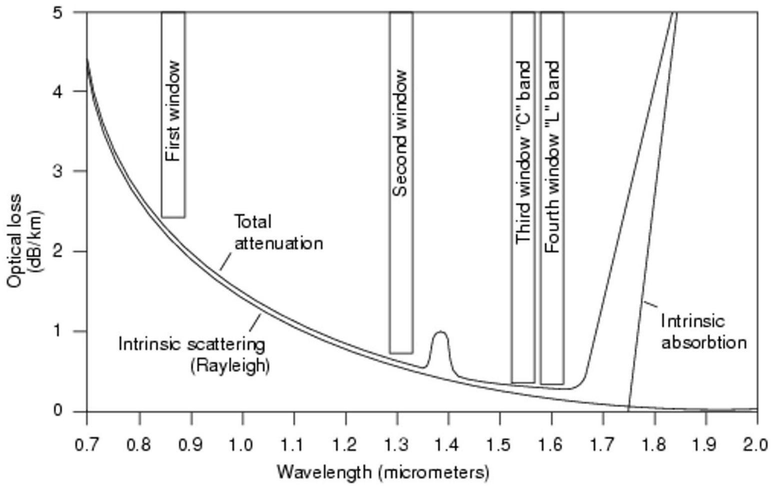

Figure 11: Single mode fibre attenuation due to Rayleigh scattering and intrinsic absorption [9]. Image source: [9]

A.4. Optical Transmission Protocols: SONET, SDH

There are two major protocols for long distance optical telecommunication systems: SONET (Synchronous Optical NETwork) and SDH (Synchronous Digital Hierarchy). SONET is mostly used in Northern America and Japan, whereas SDH is mostly used in Europe. The difference between the protocols is minimal [22].

The main idea behind these protocols is, that all the devices in the network work with the same clock-signal – synchronous. They were developed to get rid of incompatible proprietary system approaches. Both protocols have an extensive part of the bandwidth reserved for management purposes (nearly 5%), have the possibility to deal with input signals with slightly wrong timing and are flexible enough, to transport all todays available protocols reliably [22].

A.5. Prism

When light enters the prism, it bends because of the change in refractive index. The material is chosen in a way, that different wavelengths have different speeds in the prism and therefore different bending angles. A prism therefore can be used to separate light into its spectral components [23].

A.6. Nonlinear Effects

A.6.1. Stimulated Brillouin Scattering

A photon can be converted into a lower energy photon and a phonon. This effect is called Brillouin scattering. If the power density reaches a certain level, Brillouin scattering not just happens spontaneously but in a stimulated way that decreases the signal to noise ratio dramatically [24].

A.6.2. Stimulated Raman Scattering

Optical material doesn't reply instantaneous to incident light - lattice vibrations experience a small delay. When two waves of different wavelength travel in the same waveguide, it can happen that the one with the larger wavelength gets amplified on the cost of the one with the smaller wavelength [25].

A.6.3. Self Phase Modulation

Temporary high optical density (high power) in an optical medium can lead to a temporary change in the refractive index and therefore a temporary phaseshift. This distorts the signal and therefore increases the signal to noise ratio [26].

A.6.4. Four Wave Mixing

Four wave mixing exists because of the nonlinear properties of the refractive index in a fibre. Several channels can interact with each other and transfer power to another channel which therefore decreases the signal to noise ratio. This kind of noise cannot be filtered out [9].

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