Photonics and Optical Communication
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Multiplexing and Demultiplexing
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9.1 Introduction

Wavelength Division Multiplexing (WDM) is the state-of-the-art technology in optical communications. Each channel is transmitted at a different wavelength. In order to transmit several channels through a single fiber the channels have to be combined (multiplexed) on the transmitter side and separated (demultiplexed) on the receiver side. Each channel has typically a spectral width of 0.3nm-1nm. Therefore, the band allocated for the channel is very narrow. As a consequence only highly stabilized lasers can be used as transmitters.

Wavelength Division Multiplex System. All optical transmitters operate at a different wavelengths.

Ref.: H. J.R. Dutton, Understanding optical communications
9.1 Introduction

The operating principle of optical multiplexers and optical demultiplexers will be discussed in this following chapter.

Scheme of a Wavelength Division Multiplex System.

Ref.: H. J.R. Dutton, Understanding optical communications
9.2 Optical Couplers

In general several ways exist how to combine optical signals or optical channels. The most obvious way would be to use a coupler to combine the signals. A y-coupler can be used to combine (or separate) two signals. The coupler can be either implemented as a waveguide coupler or a fiber coupler.

Waveguide based optical couple, (left) switching of the power from one waveguide to the other, (right) a 3dB coupler.

Ref.: B.E.A. Saleh, M.C Teich, Fundamentals of Photonics
9.2 Optical Couplers

Couplers can be used to separate or merge optical channels. The amount of light that is coupled from one waveguide/fiber to another waveguide/fiber depends on the coupling length of the coupler. If the two waveguides or fiber are close to each other for the coupling length of L all the light is coupled from the incoming to the outgoing fiber. If the waveguide or the fibers are close to each other for half of the coupling length 50% of the light is couple form the incoming to the outgoing fiber. The remaining 50% of the light stays in the incoming fiber. If the waveguides are close to each other for a length which accounts for 2 times the coupling length the light stays in the incoming fiber. In this case the light is first coupled in the outgoing fiber and then coupled back in the incoming fiber.

If a lot of optical channels have to be merged, which is the case in a DWDM communication system (up to 256 channels) such a structure would be implemented as a planar waveguide structure (chip). The clear and big disadvantage of this approach is that each coupler leads to a loss of 3dB at each stage. It is clear that such an approach can not be applied if a large number of channels has to be merged. The intensity of light coupled in the fiber would be in the end simply to lower. For example in the case of $256=2^8$ channels the optical power per channel would be reduced by $8 \times 3\text{dB}= 24\text{dB}$. 
9.2 Optical Couplers

Due to their high losses optical couplers are not of particular interest for these applications as multiplexers. Optical Gratings exhibit much lower optical losses and their losses do not depend on the number of channels.
9.3 Optical filters

So far we discussed the operating behavior of optical couplers, which can be used to combine and separate optical signals. Another very classical approach to separate optical signals are optical filters. Independent of the filter characteristic (low pass, band pass etc. filter) we can distinguish between two major groups of optical filters which are absorption and interference filters. Absorption filters are used for example as part of scanners or digital camera. They are usually put in front of an optical detector.

In the case of absorption filters a certain part of the optical spectrum is transmitted, whereas the other part of the spectrum is absorbed in the filter. These kind of filters are typically low cost filters and the filter characteristic is by far not sufficient for applications in optical communication networks.

Dielectric thin film interference filter. The filter is made of an alternating stack of quarter wavelength thick layers based high and low refractive index materials.

Ref.: S.V. Kartalopoulos, Introduction to DWDM Technology
9.3 Optical filters

In optical communication systems only interference filters are of interest. In the case of interference filters a certain part of the optical spectrum is transmitted, whereas the other part of the spectrum is reflected. Only interference filters can fulfill the requirements of optical communication systems in terms of optical separation.

We have to distinguish between interference filters which operate in reflective and transmissive mode. An alternating stack of quarter wavelength layers of high and low refractive index (Bragg reflector) can only be used in reflective mode.

In order to realize a filter which operates in transmission we need a Fabry Perot filter configuration.

![Fabry Perot interference filter diagram]

Fabry Perot interference filter. The filter is made of two stacks of quarter wavelength thick layers based high and low refractive index material. A $\lambda/2$ spacer is introduced in the middle of the stack.

Ref.: S.V. Kartalopoulos, Introduction to DWDM Technology
9.3 Optical filters

Interference filters are typically realized on glass substrates by a multilayer system. The layer system usually consists of two different kind of materials (silicon oxide and titanium oxide). The difference in refractive index between the materials should be as high as possible. Furthermore, the absorption of the material should be as low as possible which is usually the case for oxide based materials (the optical bandgap of these materials is very high).

Optical filter transmission characteristic of a dielectric thin film interference filter.
9.3 Optical filters

Interference filters are usually based on quarter wavelength stacks of silicon oxide and titanium oxide based films. Depending on the required specifications several (up to 100 layers) of these films are needed. Important parameters of interference filters are the insertion loss, which should be as low as possible a flat pass band and sharp „skirt“. Furthermore, the crosstalk should be minimized.

9.4 Diffraction Grating

In the following different ways of realizing optical gratings like diffraction grating, Fiber Bragg gratings and arrayed wavguide gratings.

9.4.1 Diffraction Grating

A diffraction grating is an optical component that modulates the phase or the amplitude of an incident wave. Modulation means in this case that the light is “broken up” or diffracted in its spectral parts. The function of a diffraction grating is similar to the function of a prism. In terms of communication technology we can say that the diffraction grating carries out a Fourier Transform. The waveform in the time domain is transformed in a number of waveforms in the frequency domain.
9.4.1 Diffraction Grating

The diffraction grating can be realized by a transparent plate or a substrate with periodically modulated thickness or periodically varied refractive index, diffraction elements (e.g. apertures), or absorbing elements.

Very often diffraction gratings are made of thin metals films (lines). The thin metal films are evaporated on top of a plate or a substrate.

Light falls on a blazed grating grating. Each wavelength is diffracted differently.

Ref.: S.V. Kartalopoulos, Introduction to DWDM Technology
9.4.1 Diffraction Grating

The diffraction of light can be described by the grating equation, where $\lambda$ is the incident wavelength, $m$ is the diffraction order, $d$ is period of the grating, $\theta$ is the diffraction angle, and $\phi_m$ is the angle of the incident light.

$$m \cdot \lambda = d \cdot (\sin \theta + \sin \phi_m)$$

With increasing order of diffraction the diffraction angle will increase. As it can be seen from the diffraction equation the period of the grating does not have to be small. However, in order to get larger diffraction angles the period of the grating should be small to improve the spectral resolution.

Reflective Diffraction grating

Ref.: H. J.R. Dutton,
Understanding optical communications
9.4.1 Diffraction Grating

In general diffraction gratings can be realized as transmissive or reflective gratings. In optical communication technology only reflective gratings are applied. Therefore, we have to add the angle of the incident light $\phi_m$ to the grating equation.

Several ways are known how diffraction gratings can be used to multiplex and demultiplex wavelengths or optical channels. All setups are based on a sort of a fiber bundle, one or more diffraction gratings and additional optics to couple light out of the fiber and back in the fiber. The light can be focused by a lens or a concave mirror.

Implementation of a diffraction grating for DWDM applications.

Ref.: H. J.R. Dutton, Understanding optical communications.
9.4.2 Fiber-Bragg Gratings

The realization of dielectric interference filters is relatively expensive and time consuming. It is obviously clear that the cost increases with the required specifications and the size (area) of the optical filter.

An extremely successful alternative is based a Fiber Bragg gratings. In this case a Bragg grating was incorporated in an optical fiber. The Fiber Bragg grating is a very simple low cost, wavelength selective filter.

The grating is manufactured by the exposure of the fiber through a mask (phase mask) with UV light. The UV light (244 nm) modifies the refractive index of the fiber core.

Fiber Bragg grating made by the exposure of the fiber core with a UV pattern. Ref.: S.V. Kartalopoulos, Introduction to DWDM Technology
9.4.2 Fiber-Bragg Gratings

A fiber Bragg grating consists of a piece of ordinary single-mode fiber. The Bragg grating is incorporated by varying the refractive index along the core of the fiber. Light of particular wavelength gets reflected by the periodic structure (grating) in the fiber. The wavelengths which are not reflected pass through the fiber with little or no attenuation.

Important characteristics of fiber Bragg gratings:

The selected wavelength is reflected towards the source and the non-resonant wavelengths are transmitted. This has to be considered while designing an optical network. Obviously the fact that devices operate in reflection rather than transmission is not ideal.

The grating is realized by periodic variations in the refractive index of the core along the fiber. Already a very small variation of the refractive index in the order of 0.0001 is sufficient to realize high efficient filters.
9.4.2 Fiber-Bragg Gratings

The center wavelength of the reflected band is given by:

\[ \lambda = 2 \cdot n_{\text{eff}} \cdot d \]

where \( \lambda \) is the center wavelength of the reflection band, \( n_{\text{eff}} \) is the average refractive index of the material, and \( d \) is the period of the fiber grating.

We already discussed that the refractive index of the fiber can be tuned to a certain extend by adding germanium throughout the manufacturing process. The germanium usually forms chemical bonds with the silicon or the oxygen atoms. However, some germanium atoms form bonds with other germanium atoms. These bonds can be broken by the UV light. As a consequence the refractive index of the exposed areas of the fiber core slightly changes by 0.001.

The change in the refractive index is very small. However, if a large number of periods is use the grating can be very efficient. The fiber grating is typically 1cm long, so that around 10,000 wavelength periods are used to form the grating.
9.4.2 Fiber-Bragg Gratings

The fiber Bragg grating technology cannot only be used to select specific wavelength (or channels) out of an optical spectrum. An alternative application are gratings which compensate for chromatic dispersion of ordinary optical fibers.

Fiber Bragg (chirped) grating which compensates for chromatic disperion
Ref.: S.V. Kartalopoulos, Introduction to DWDM Technology
9.4.3 Arrayed waveguide grating

Arrayed waveguide gratings (AWG) are also called Waveguide Grating Routers (WGRs). Like fiber Bragg gratings these devices are the most important “new” optical communication devices. The function of a arrayed waveguide grating is similar to the function of a diffraction grating. However, the arrayed waveguide grating has the advantage that it can be manufactured as a waveguide structure (integrated optics) rather than a discrete component. This leads to more reliable, more compact devices at lower manufacturing cost.

How does this device work? The operating principle of an arrayed waveguide grating is based on the effect of interference. Let's say light is couple through a single input F into the first coupler S₁, which is coupled to a number of waveguides indicated by w₁ to wₙ.

Arrayed waveguide grating.

Ref.: S.V. Kartalopoulos, Introduction to DWDM Technology
9.4.3 Arrayed waveguide grating

The coupler $S_1$ is called a „star coupler“ or a free space coupler because the inside of the coupler is just „free space“. Now the input signal will couple to a large number of modes in free space. These modes then couple in the outgoing waveguides.

The central part of the arrayed waveguide is a grating (even though it is not a „real grating“). The „grating“ introduces a phase difference for each signal due to the fact that all waveguides have a different length. Now the signals are again coupled in a „star“ or free space coupler. The different wavelengths of the light in combination with the particular output (port) forces the signal to couple in a particular output of the coupler $S_2$.

Distribution of signals (modes) in a „star coupler“ or free space coupler.

Ref.: H. J.R. Dutton, Understanding optical communications
9.4.3 Arrayed waveguide grating

Remark: In the case of a single input channel, the second free space coupler would not be necessary to separate the different channels.

Feeding only a single channel in an arrayed waveguide grating is a special case. Usually a large number of input signals is fed into the arrayed waveguide grating. Under such conditions, it becomes evident why we need two free space couplers in combination with a waveguide grating.

The coupling behavior of coupler $S_2$ depends on both the wavelength and the location of the port (which has a specific phase delay).

Arrayed Waveguide Grating or so called waveguide grating router.

Ref.: H. J.R. Dutton, Understanding optical communications
9.4.3 Arrayed waveguide grating

Advantages of arrayed gratings:

- Multi-channels (multi-wavelength) appearing as a single input can be separated so that each channel is fed into different output ports.
- Combine many inputs from different input ports onto the same output port.
- A arrayed waveguide can operate bi-directionally
- The device can be used as a multiplexer and demultiplexer.

Basic function of a waveguiding router.

Ref.: H. J.R. Dutton, Understanding optical communications
References:


