1 Optical Filters in Wavelength-Division Multiplex Systems

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1.1 Network Aspects

Wavelength filters in optical transmission systems are a special subgroup of physical components defined in such a way that they select or modify parts of the spectrum of the signal. In fact, optical wavelength filters are defined with respect to the modifications which they induce on the frequency spectrum.

We will restrict our considerations to the application of optical filters in optical networks. Figure 1.1 schematically shows a global optical network combining local and regional networks via the long haul network. Most of today's network concepts are based on Wavelength Division Multiplexing (WDM), which means that WDM filters are mainly needed in order to route and select specific wavelength channels.

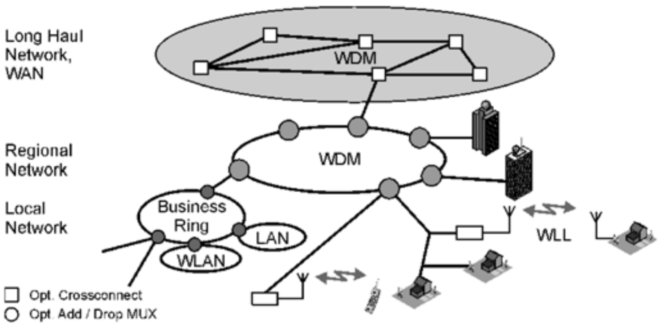

Fig. 1.1. Global optical network. WDM: wavelength division multiplexing, LAN: local area network, WLAN: Wireless LAN, WAN: wide area network, WLL: wireless local loop

The filters in optical WDM-systems are classified as bandpass filters, low pass filters, high pass filters, and notch filters.

Bandpass filters (BPFs) transmit optical power within a certain wavelength window only and reflect the rest. In the case of single channel transmission the role of an optical bandpass filter is to separate the channel information from the noise which has been added for example by optical amplifiers. This noise is in general broadband and can often be described as white noise, i.e it has a constant level in the power spectrum. By applying a bandpass filter to select the wavelength channel, the useful information is retained and most of the noise is rejected resulting in an improvement of signal-noise ratio (SNR).

In the case of many wavelength channels, in addition to rejecting the noise the bandpass filter rejects all the undesired WDM channels of the multitude of transmitted wavelength channels (see Fig. 1.2a). Furthermore, BPFs are essential components used for multiplexing and demultiplexing wavelengths in a WDM system. As shown in Fig. 1.2b, a multiplexer combines different sources with different wavelengths into a single fibre.

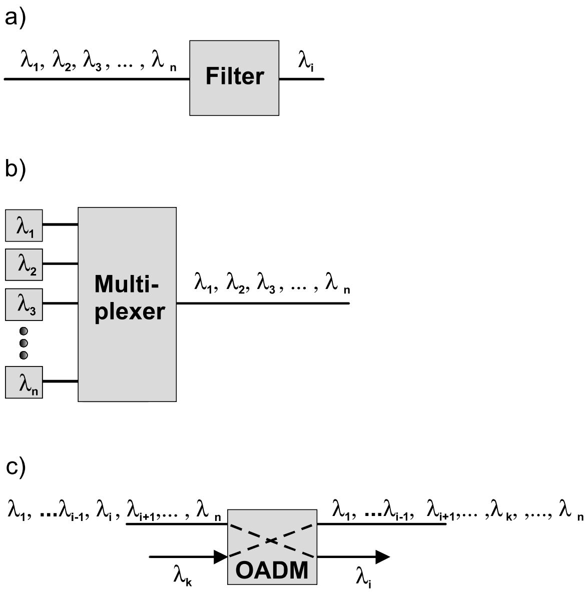

Fig. 1.2. Filter devices for WDM: (**a**) bandpass filter which selects the desired channel, (**b**) multiplexer which combines sources with different wavelengths into a single output. In reverse direction, the structure is used as demultiplexer (**c**) optical add-drop multiplexer where channel λ_k is added to and channel λ_i is dropped from the WDM spectrum [1]

In the reverse direction, the same device acts as a demultiplexer to separate different wavelengths to different outputs. Another important device for building WDM networks is the optical add-drop multiplexer (OADM) shown in Fig. 1.2c where a particular wavelength channel is added to and another wavelength channel is extracted from the WDM spectrum. Band-pass filters which are periodic in frequency can be used as so-called inter-leavers, which allow multistage multiplexing of channels. For example, with a periodic filter every second wavelength channel could be demultiplexed from a multitude of equally spaced channels (cf. Chap. 9).

The optical crossconnect (OXC) is used for routing different WDM channels. This means that the OXC can separate wavelength channels from incoming fibre bundles and redistribute them appropriately to outgoing fibres. In general, an OXC consists of many WDM components. An example of a wavelength crossconnect is depicted in Fig. 1.3. The wavelength channels of an input port are spatially separated by demultiplexers and can then be connected via multiplexers to an output port. The OXC is called a static wavelength crossconnect if the combinations of input ports and output ports are fixed as shown in Fig. 1.3. In this crossconnect architecture a wavelength (denoted by the lower index) of an input port (denoted by the upper index) is connected to an output port. In such a way, the incoming wavelength channels can be routed according to their wavelength. OXCs with more complex functionality also have OADMs to add and drop channels. Combining optical switches with multiplexers and demultiplexers, dynamic OXCs can be built. In dynamic OXCs the connections between input ports and output ports can be changed. This enables the dynamic reconfiguration of optical networks.

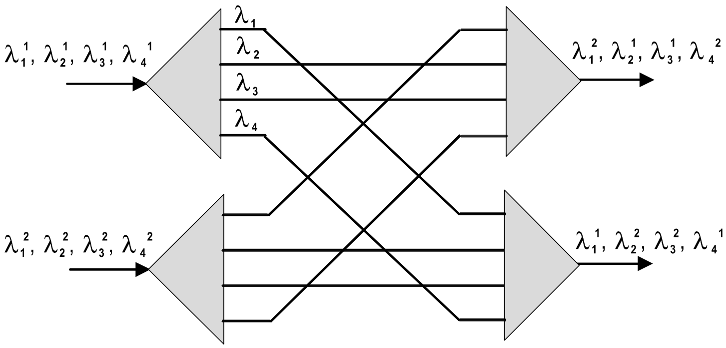

Fig. 1.3. Schematic of a static optical crossconnect. According to the wavelength a channel from an input port is routed to an output port

Notch filters reflect a specified wavelength or a narrow wavelength region with high transmission outside that region.

Low-pass filters (LPF) and **high-pass filters** (HPF) are filters which provide a sharp cut-off either above or below a particular wavelength. They are useful for isolating specific regions of the spectrum. Often referred to jointly as edge-pass filters (EPFs), low-pass filters and high-pass filters are used to pass (or transmit) a range of wavelengths and to block (or reflect) other wavelengths on one side of the passband. In the case of low-pass filters, the transmitted wavelength is long wavelength radiation, while short wavelength radiation is reflected. Conversely, high-pass filters transmit a wide spectral band of short wavelength radiation and block long wavelength radiation.

In addition, other types of optical filters exist in WDM systems. One of them are **power equalization filters**. Wavelength channels should have equal power levels. However, there are a number of reasons why different wavelength channels acquire different power levels. Adding and dropping of channels, nonuniform gain of the amplifiers, power inequalities of source lasers are some of the causes. Even if the differences in power are small in one span, they may accumulate over the transmission spans to yield large inequalities in power. Therefore, gain equalizing filters are needed in WDM systems. Furthermore, since the network configuration changes with time, this equalizing has to be done dynamically. Thus, Dynamic Gain Equalizing Filters (DGEF) are required for WDM networks.

Filters which transmit the complete frequency band but induce phase changes are called **allpass filters**. Since the group delay is the first derivative of the phase with respect to angular frequency, such filters can be designed to compensate for group velocity dispersion which accumulates during fibre transmission.

In order to illustrate generic applications of optical filters we depict an optical connection in Fig. 1.4. At the beginning and the end of the connection BPF-based multiplexers or demultiplexers are needed to combine or separate the different wavelength channels. After transmission through the fibre span dispersion compensating filters have to be applied to reduce signal degradation due to residual dispersion which has accumulated along the fibre. BPFs are needed in the OADM for adding or dropping channels. After the Erbium-doped fibre amplifier (EDFA) has amplified the WDM channels, a power equalizing filter is needed to ensure equal power on all channels. In addition, an edge filter is used to avoid perturbations of the data channels by the amplifier pump power at lower wavelengths.

Although different kinds of filters are necessary in an optical WDM transmission system, bandpass filters are by far the most important since

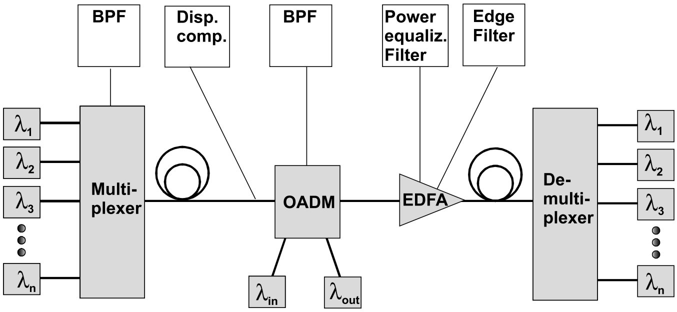

Fig. 1.4. Schematic of an optical transmission path showing examples of different filters needed in multiplexers, OADMs, or amplifiers

they are prerequisite for the add and drop, multiplex, and interleave and routing functionalities which are essentials for a WDM network.

1.2 Mathematical Description

Signals and physical components can be expressed mathematically by complex functions describing amplitude (real part) and phase (imaginary part). In the time domain the change or response of the input signal due to a component is evaluated by the convolution of the function representing the component with the complex expression for the incoming signal. According to the Fourier Transform theorem the response can equivalently be evaluated in frequency space by the product of the Fourier transform (FT) of the input signal and the FT of the function describing the physical component. Since the components we are dealing with are filters in the wavelength (or frequency) domain, we will adopt a description in the frequency domain.

For the ideal bandpass filter centred at ω_0 with filter width $\Delta\omega$ the transfer function is defined by $H(\mathrm{i}\omega)$, ($\omega = 2\pi f$ where ω is the angular frequency and f is the frequency):

$$H(\mathrm{i}\omega') = e^{-\mathrm{i}\omega'} \quad 0 \le |\omega'| \le \Delta\omega \tag{1.1}$$

with

$$\omega' = \omega - \omega_0 = 2\pi(f - f_0) \tag{1.2}$$

Here f_0 is the centre frequency of the filter. In general, f_0 is chosen to match the carrier frequency of the wavelength channel which has to be selected by the BPF. For the ideal bandpass the squared amplitude function

$|H(i\omega')|^2$, which determines the filter transmission, has rectangular shape. The ideal filter therefore perfectly separates wanted from unwanted parts of the spectrum. However, such filters are physically not realizable. Therefore filter functions have to be found which describe the properties of available physical filters.

The mathematical description of filters is useful under several aspects. Filter functions are needed as input data for numerical simulation of transmission systems, and the mathematical expressions can be used to determine the properties and requirements of filters and their physical realization. There exists a vast literature on the design of filters treating digital and analogue filters, finite and infinite impulse response filters, recursive and non-recursive filter design, which has been especially developed for the design of electronic filter circuits. Optical WDM-filters, on the other hand, are realized mainly as analogue, recursive, infinite impulse response filters (see also Chap. 2), the properties of which can be described by a complex transfer function $H(s)$ with complex variables [2]

$$H(s) = \frac{\sum_{i=0}^{m} b_i s^i}{1 + \sum_{i=1}^{n} a_i s^i} \tag{1.3}$$

m and n denote the number of zeros and poles which describe the special type of filter (see also Chap. 9, Sect. 9.3). In many cases, WDM-filters are all-pole filters, i. e. all b_i except b_0 are zero. The number of poles n is called the filter order. The distribution of the poles in the complex plane completely determines the filter properties. Tables and expressions for many filter functions can be found e.g. in [2, 3].

In order to evaluate the filter properties for the angular frequency, the transfer function is expressed as

$$H(s)\big|_{s=i\omega'} = \left|H(i\omega')\right| e^{i\Theta(\omega')} \tag{1.4}$$

The transmission properties of the filter are given by the squared amplitude function and the phase behaviour is described by $\Theta(\omega')$ which can be evaluated from (1.4)

$$\Theta(\omega') = \tan^{-1}(\mathrm{Im}(H(i\omega')/\mathrm{Re}(H(i\omega')) \tag{1.5}$$

The group delay $\tau(\omega')$ is defined as

$$\tau(\omega') = -\frac{d\Theta(\omega')}{d\omega'} \tag{1.6}$$

The filter curves given above describe bandpass filters and are easily converted into high-pass or low-pass filters by the transformations given in [3]. In the case of low-pass filters it can be shown that the transformation from the BPF to the LPF can be done by simply choosing $\omega_0 = 0$ (cf. (1.2)).

We exemplify the above formulas with a normalized Bessel filter of order 10 as a bandpass filter at centre frequency f_0. We choose a Bessel filter since it shows regions both of constant and varying group delay. With increasing order of the filter the transfer function becomes more and more Gaussian and group delay becomes constant for all frequencies. For commercially available BPFs the measured transmission and phase behaviour can often be simulated by a Bessel filter of appropriate filter order. The form of *H(s)* is found in [2]. In Fig. 1.5 we show the squared amplitude function both in linear and logarithmic scale.

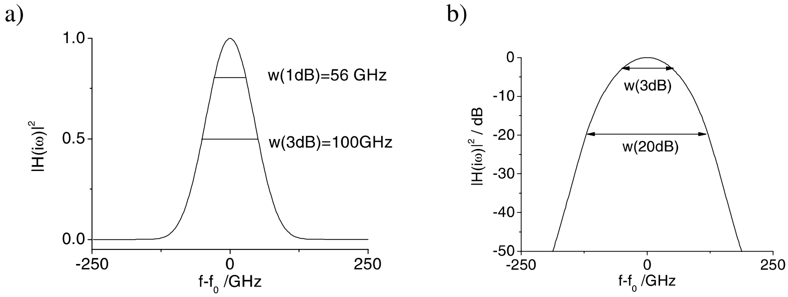

Fig. 1.5. Squared amplitude function $|H(\mathrm{i}\omega)|^2$ for a Bessel filter of order $n = 10$ and FWHM = 100 GHz: linear scale (**a**) and logarithmic scale (**b**)

For filters with non ideally steep bandpass skirts as shown in Fig. 1.5 we can define filter bandwidths *w* given for different attenuations in dB. Common choices found in data tables of physical filters are *w*(1 dB), *w*(3 dB), and *w*(20 dB), which are 56 GHz, 100 GHz, and 240 GHz for the example given in Fig. 1.5. *w*(3 dB) is also called the full-width at half-maximum (FWHM) of the filter. The flat top of the filter is called the passband. A common definition for the passband width is *w*(1 dB).

In Fig. 1.6 we depict the phase function and group delay of the 10^{th} order Bessel filter.

The phase function consists of several segments which are almost parallel. Accordingly, the group delay is constant in a frequency range of about 240 GHz which corresponds to *w*(20 dB) as shown in Fig. 1.5. Thus, such a filter will add negligible dispersion only to the signal.

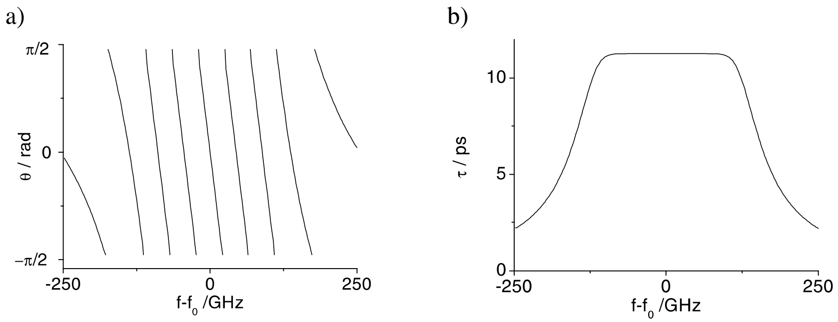

Fig. 1.6. Phase function $\Theta(\omega)$ (**a**) and group delay $\tau(\omega)$ (**b**) for a 10^{th} order Bessel filter (FWHM = 100 GHz)

The transmission curves of most physical BPFs have a similar bell shape as depicted in Fig. 1.5, but can largely differ by their phase and group delay behaviour. These special types of filter functions have been investigated widely in the literature. They differ only in the type of polynomial in the denominator of (1.3), but have specific properties. For example, **Butterworth** filters describe an optimised flat behaviour of $|H(i\omega)|^2$ near f_0 (the passband width increases with the filter order). Butterworth filters are used to describe filters with flat tops. **Bessel** filters describe filters which have optimum flat group delay as has been shown in the filter example in Fig. 1.6. For increasing filter order the amplitude transfer function of Bessel filters becomes Gaussian. **Chebychev** filters have specific ripple properties of the transmission curves in the passband and stopband. They could therefore be used to simulate ripples occuring in the transmission function of physical filters. Further filter types as well as tables for the filter polynomials are given in [2, 3]. For a good approximation of physical filters by mathematical filter functions, measurements of the transfer function as well as phase and group delay measurements have to be made. The appropriate mathematical function can then be found by fitting the filter curves to the measured data.

1.3 Physical Realization of Filters

The physical realisation of WDM filters based on different principles of operation and fabrication on different materials will be discussed in the following chapters of the book. Here, we will therefore only define the main specifications of WDM filters. Further filter parameter definitions are given in the glossary.

In addition to the filter transfer function we have to consider optical loss, polarisation, temperature behaviour, and crosstalk.

1. *Insertion loss*. Insertion loss is the input to output loss of the filter for the passband and is, of course, required to be low.
2. *Polarisation-dependent loss (PDL).* Loss should be independent of the state of polarisation of the incoming signals.
3. *Temperature shift*. The temperature shift is the amount of wavelength shift per unit degree change in temperature. Temperature shift is required to be low.
4. *Passband width*. The passband width is defined by the 1 dB width $w(1\,\text{dB})$. It is a measure for the flatness of the filter top. Flat passbands are required to allow for small shifts in laser wavelength over time. As more and more filters are cascaded the overall passband becomes narrower. Thus the individual filter passband width does also determine the number of filters which can be cascaded.
5. *Crosstalk*. Crosstalk energy is defined as the relative amount of energy passed through from adjacent channels. Different kinds of crosstalk are defined in the glossary.
6. *Group delay*. Group delay is defined in (1.6). For bandpass filters it should be constant to avoid the build-up of chirp in the signals when passing through the filter. For filters used for dispersion compensation, a suitable change in group delay over the wavelength is required.
7. *Free spectral range (FSR).* The FSR describes the spectral periodicity of the filter transmission function, i. e. the frequency difference between two filter maxima.
8. *Finesse.* The finesse of a filter is defined by the FSR divided by the 3 dB width of the filter.
9. *Tuneability.* Tuneability is defined as the ability to change properties of the filter, mainly its centre wavelength.

In addition we summarize the main physical principles of operation for WDM filters:

1. *Coupler* type filters make use of the change of coupling length with wavelength to separate different wavelengths. Normal couplers operate as broadband devices, and consequently they can separate only wavelengths which are far apart. A typical example is combining and separating the pump wavelength of a fibre amplifier at 0.98 µm wavelength from the data channel at 1.55 µm by couplers. Standard dielectric waveguide couplers will not be treated in detail in the present book, but the reader is referred for example to the classical paper by Kogelnik [4].

2. As discussed before, signals passing optical filters are in general affected with respect to amplitude and phase. In many cases the amplitude-wavelength dependence is of higher interest, but phase effects become particularly relevant for high bit rates and narrow channel widths. As a consequence, a discussion of phase characteristics is included in most of the individual chapters, but a separate chapter (Chap. 2) provides a more coherent treatment of phase-related phenomena.
3. *(Bulk) Diffraction Gratings* are based on the interference of multiple optical signals originating from the same source but with different phase shifts. Gratings can be operated in reflection/transmission or as diffraction gratings. In the case of diffraction gratings, signals of different wavelength can be resolved spatially. They can therefore be used for routing. Bulk diffraction gratings for WDM applications are described in Chap. 3.
4. *Fibre Bragg gratings* are gratings which consist of one dimensional periodic perturbations along the fibre. They can be used for add-drop functions and for dispersion compensation and are treated in detail in Chap. 5.
5. *Fabry–Perot* type filters are based on resonance in a cavity formed by two highly reflective mirrors placed parallel to each other, also called etalon (Chap. 6). Cascading of many cavities leads to very flat passbands and to sharp skirts. Examples of filters based on this principle are the thin-film resonant multicavity filters, discussed in Chap. 7. Related filter types are the ring filters where the resonator is a waveguide ring. Ring filters are treated in Chap. 8. Fabry–Perot type filters are also suited for constructing allpass filters which only induce a desired phase change without attenuation in the amplitude transfer function.
6. *Mach–Zehnder Interferometer (MZI)* type filters make use of two interfering paths of different lengths to separate different wavelengths. (Cascaded) MZIs constitute the fundamental building block of wavelength interleavers (Chap. 9), and the *Arrayed Waveguide Grating* filter can be considered as a generalisation of the MZI filter (Chap. 4), while its characteristics look like the 2-dimensional equivalent of a diffraction grating.

References

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