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Introduction to Add-Drop Multiplexers

In this chapter different channel routing technologies are reviewed, highlighting the advantages and drawbacks of the different devices and configurations. The parameters to characterise the performance of the add-drop multiplexers are defined.

3.1 Optical Add-Drop Technology

The evolution of single wavelength point-to-point transmission lines to wavelength division multiplexed optical networks has introduced a demand for wavelength selective optical add-drop multiplexers (OADM) to separate/route different wavelength channels. They can be used at different points along the optical link to insert/remove or route selected channels increasing the network flexibility. This feature is particularly important in metropolitan WDM lightwave services where offices or sites can be connected by different add-drop channels, for example in an interoffice ring. Additionally there is flexibility of transmitting different data rates in different WDM channels according to the capacity needs. Figure 3.1 illustrates the basic operation of an add-drop multiplexer where a stream of 16 channels with central wavelengths λ_1 through λ_{16} are launched into the input (port 1) and 8 channels are dropped at port 4, the rest go through port 2. Simultaneously, 4 channels are launched into port 3 and added to the signal stream at port 2. The channels that are added or dropped at that node depend on the network requirements.

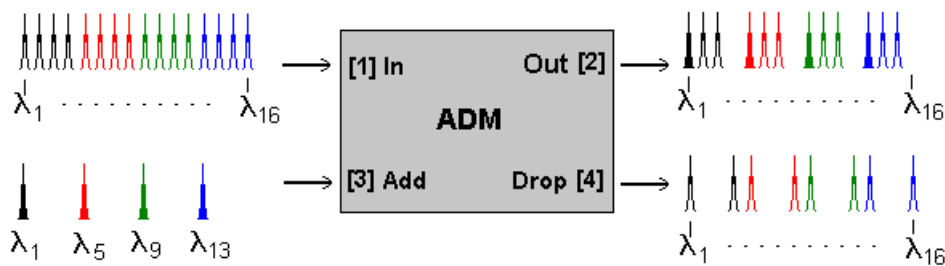


Figure 3.1 - Basic operation of an optical add-drop multiplexer.

There are two main types of OADM that can be used in WDM optical networks; fixed OADMs that are used to drop or add data signals on dedicated WDM channels, and reconfigurable OADMs that have the ability to electronically alter the selected channel routing through the optical network. The main features of the second type of OADM is to provide flexibility in rerouting optical streams,

bypassing faulty connections, allowing minimal service disruption and the ability to adapt or upgrade the optical network to different WDM technologies.

Configurations presented in the literature to perform the required add or drop functions use both planar and fibre technology. Planar devices [28-36] provide compact solutions with the possibility of adding or dropping many channels using only one integrated optical circuit using arrayed-waveguide-grating (AWG) [34] or -waveguide-grating-router (WGR) technology [35, 36]. The main drawbacks of planar devices are their high insertion loss, which can be as high as 7dB, and their polarisation dependence. Alternatively, all-fibre devices [37-47] are attractive solutions due to their low insertion losses, polarisation insensitivity (depending on the fibre and configuration) and ease of coupling between device output and inputs of the optical network using simple splices and pigtails. Typically, due to their larger dimensions these devices are sensitive to environmental variations, dependent upon the configuration. Devices based in free space optics (micro mirrors and gratings) have also been used successfully to perform add-drop operations with good performance [48]. Although, these devices are in general more expensive and have relatively high insertion losses. Finally thin film filter devices have been traditionally used for multiplexing/demultiplexers purposes. Fibre and planar add-drop configurations and their respective performance are discussed in the following section.

3.2 Add-Drop Configurations

Excellent performance and compactness offered by four-port planar-waveguide-based devices can be rivalled by the simple all-fibre add-drop configuration, as shown in Figure 3.2. It consists of a 3dB splitter and a grating in one of the output arms; light launched into port1 is split in two, λ_G is reflected by the grating then dropped at Port 4. The other coupler output port is immersed in an index matching fluid so that the light is not reflected. The selected signal emerges at both the input

and drop port. An optical isolator at port 1 protects the input network from the back-reflected signal. The dropped signal is 6dB weaker than the original input signal. In transmission, a second 3dB coupler splits the signal that was not reflected by the grating. The add function is performed by launching a signal into port 3 which is reflected by the grating and thus added to the signal at port 2, as illustrated in Figure 3.2. An isolator is also required to isolate the Add port from the signal transmitted from the input. When using the two isolators, at the input and Add ports, this non-interferometric configuration provides excellent add-drop performance. In this configuration there are no limitations on the length, position, or apodisation of the written grating. Ideal grating filters may be designed using an inverse scattering method [49, 50]. The primary drawback of this configuration is the insertion loss to all the channels that is at least 6dB. However, when comparing with planar-waveguide-based devices, it has similar insertion losses but has increased flexibility in writing and tuning ideal gratings. Notwithstanding, planar devices have the advantage of compactness and are easier to stabilise with respect to environmental changes.

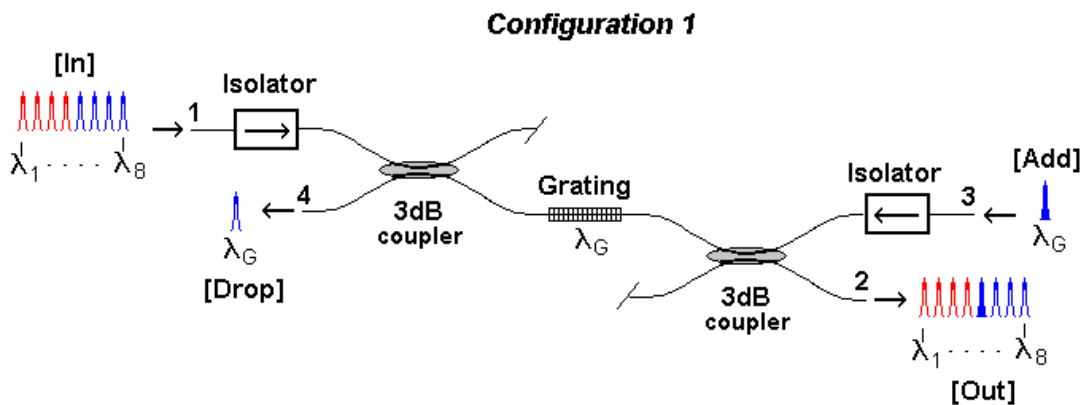


Figure 3.2 –Add-drop multiplexer configuration based on a grating and two 3dB couplers.

One method to overcome the high insertion loss of the above configuration requires an additional grating, identical to the first, written in the unused coupler ports, thus forming a Mach-Zehnder interferometer. Both planar [29-31] and fibre [40, 44, 46, 47, 51] devices using this configuration have been reported.

Theoretically this device is symmetric and can yield excellent performance in terms of insertion loss, back-reflection and cross-talk.

Figure 3.3. illustrates the principle of operation for this configuration: A 3dB coupler splits light launched into port 1 and a specific wavelength, λ_G , is reflected by the two identical gratings. These reflected signals interfere in the 3dB coupler in such a way that the signal is dropped and the back-reflected light intensity arriving at port1 is zero, providing the coupler is well matched (50% splitter). The transmitted wavelengths are made to interfere in the second 3dB coupler such that they arrive at the output port with no residual light at the Add port, again for a well-matched coupler. This configuration is based on the splitting and interference of light and is therefore quite sensitive to changes in the signals path length, the characteristics of the identical gratings, and the matching of the 3dB couplers. Therefore environmental stabilisation, UV trimming of the individual paths [47] and identical couplers and gratings are essential for good device performance. The stability and tolerances for achieving practical WDM performance using this configuration were analysed by Erdogan [31]. This configuration in planar technology has shorter path lengths and therefore is easier to stabilise. Also, identical gratings can be written with one exposure simply by using a small separation between the interferometer arms. Alternative configurations based on the dual-core fibres that present shorter interferometer arms and avoid the need for UV trimming have been demonstrated as practical devices using the MZ interferometer configuration [40, 45].

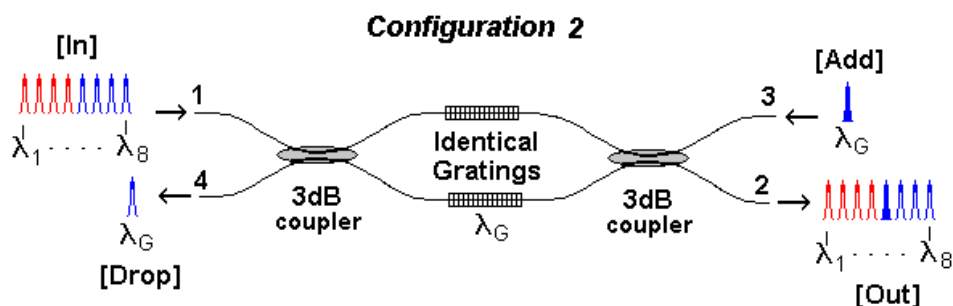


Figure 3.3 –Add-drop multiplexer configuration based on a Mach-Zehnder interferometer.

Another example of a symmetric four-port add-drop multiplexer is similar to configuration 1 shown in Figure 3.2, with the 3dB couplers replaced by optical circulators. Theoretically the operation of this non-interferometric device is ideal: The spectral properties depend principally on the performance of the grating that can be designed as an ideal square filter using inverse scattering techniques; the insertion loss and cross-talk are mainly dependent on the performance of the optical circulators. Figure 3.4 illustrates this configuration. Light launched into port 1 is directed into a fibre Bragg grating with resonant wavelength, λ_G , reflected back to the circulator and dropped to port 4 with the remaining optical channels being transmitted to arrive at port 2. Another signal of wavelength, λ_G , is launched in port 3, reflected by the grating and added to the optical stream at port 2.

The main drawback of this configuration is that circulators are expensive and bulky devices. However, with the advent of cheaper circulators and with low insertion losses, it will be a very attractive add-drop multiplexer solution, due to its inherent stability and performance [51].

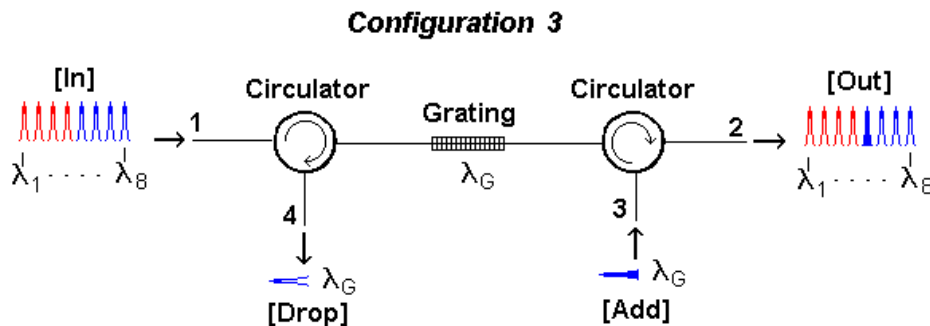


Figure 3.4 – Add-drop multiplexer configuration based on a grating and two circulators.

The stability of the interferometric add-drop multiplexer shown in Figure 3.3, configuration 2, can also be improved by using the interference between the eigenmodes of a fibre coupler. Writing a grating in the waist of a half-cycle (100%) coupler has been demonstrated in both fibre [41, 42] and planar configurations as a means of achieving add-drop performance. The device is compact, but in principle only has an ideal symmetric performance when the grating is a point-like reflector.

This is only possible by using very short and strong gratings or very long couplers. Figure 3.5 shows schematically this configuration. Light launched into port 1 is transferred to the even and odd eigenmodes of the coupler. A grating is placed at the centre of the coupler where the phase difference between the eigenmodes is $\pi/4$ i.e., where light is equally split between the two coupled waveguides (see chapter 4 for the eigenmode description of a fused coupler). The channel at the grating resonance wavelength λ_G is reflected and the remaining signals propagate through the coupler arriving at the output port. In reflection, the eigenmodes reach the beginning of the coupler with a $\pi/2$ total phase difference and therefore, the channel is dropped to port 4. In principle, the stabilisation of this interferometric device is improved with respect to the Mach-Zehnder (*configuration 2*) due to the point-like reflection point and the interference achieved through the beating between the propagating coupler eigenmodes. However, limitations in the grating strength and the length of fabricated couplers compromise the expected performance. Optimisation and discussion of different schemes using *configuration 4* are addressed in Chapter 8.

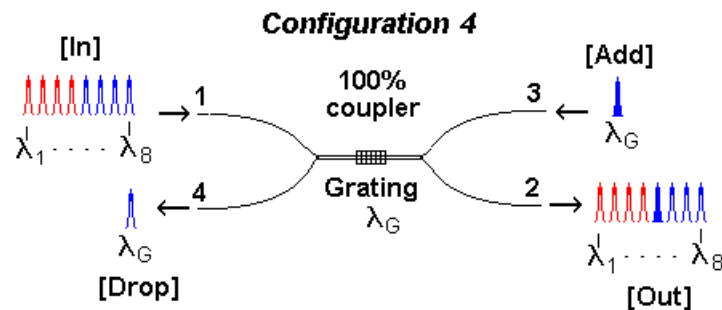


Figure 3.5 – Add-drop multiplexer configuration based on grating inscribed in the waist of a coupler.

3.2.1 Reconfigurable Add-Drops

The ability to reconfigure an add-drop multiplexer by changing the filter resonance wavelength or to switch the device on or off provides extra flexibility in an optical network. Compact multi-channel devices using arrayed waveguide grating technology have been reported with individual routing of each channel, by switching

it on or off [32, 34]. Even though low cross-talk is achievable with multiple passes through the multiplexer, these devices have unavoidably high insertion losses.

On the other hand, all-fibre add-drop configurations have potentially no cross talk (depending on the filter design) with very low insertion loss. When using the non-interferometric add-drop configurations 1 or 3, wavelength selection is achievable by straining [52] or heating [53] the Bragg grating. Whilst using the interferometric configuration 2, both fibre gratings should be affected equally and therefore wavelength tuning is not practicable. However, switching is possible by unbalancing the interferometer by straining or heating only one of the arms.

3.3 Add-Drop Performance

The analogue performance of add-drop multiplexers is characterised by using scattering parameters S_{ij} for each pair of ports [54]. The first subscript, i , refers to the destination port and the second subscript, j , the input port. Several properties may be characterised using the scattering parameter namely; the insertion loss, polarisation dependent loss (PDL), dropped channel isolation, channel uniformity, frequency accuracy and bandwidth considerations. In appendix A system application characteristics for the isolation of the optical ports achievable with current 50, 100, 200 and 400 GHz channel-spacing technologies as well as, cross-talk, back-reflection and insertion loss requirements are given. The remaining parameters are defined to in [54].

3.3.1 Isolation and Crosstalk

The two main parameters related to the isolation of channels in an add-drop multiplexer are the through-port isolation of a dropped channel (S_{21} parameter) and the drop-port isolation of through channels (S_{43} parameter). Note that in a symmetric device $S_{43}=S_{21}$. These two parameters represent the sources of the interchannel crosstalk for the device illustrated in Figure 3.6, where the S_{21} isolation parameter is

highlighted. If the amount of power launched into port 1, P_1 , and the dropped power to port 4, P_4 , the remaining transmitted power, P_2 , emerges at port 2 as interchannel crosstalk. The measure of isolation is given by $-10\log(P_1/P_2)$.

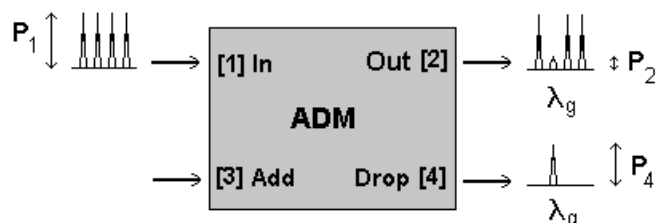


Figure 3.6 – Example of the S_{21} isolation of the through port of a dropped channel.

The second kind of crosstalk is due to unwanted signals transferred from neighbouring channels to the filtered one, and is named intrachannel crosstalk [55]. It can appear in the interferometric configurations as a result of an incorrect splitting ratio in the 3dB (50%-50%) couplers. This kind of crosstalk however, has a low power penalty in the performance of the WDM system.

3.3.2 Insertion losses

Insertion losses are the attenuation in the optical power of the channels due to the insertion of the device. The effect of the device insertion loss is schematically illustrated in Figure 3.7 where both the dropped channel and the output channels are attenuated.

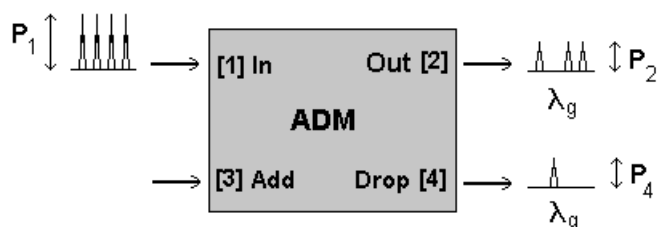


Figure 3.7 – Schematic representation of the insertion loss of an add-drop multiplexer.

The insertion loss, l_{ins} corresponding to the transfer efficiency of light from port i to port j affects all the channels equally and is described by

$$l_{ins} = 10 \log \left(\frac{P_i}{P_j} \right)$$

P_i and P_j are the powers of a given signal channel at the respective ports assuming there is no cross-talk or polarisation-dependent loss (PDL).

3.3.3 Back-reflections

Back-reflections are defined by the scattering parameters S_{ii} . The subscript i is 1 or 3 corresponding to the input or add ports respectively. Figure 3.8 shows schematically the effect described by these parameters. If the channel selection is based on a Bragg grating with a resonance wavelength λ_G (as in configurations 1 to 4), then when that channel is launched into either port 1 or port 3 it will be reflected to either the drop or out port respectively. However, there is also a percentage of light, which is reflected back to the original ports P'_1 or P'_3 , thus the S_{ii} back-reflection parameter is defined as $10 \log(P_i/P'_i)$. The effect of the back-reflections can be avoided by introducing isolators into both of these ports (as shown in Figure 3.2). However, the problem can be avoided by adequate add-drop multiplexer balancing.

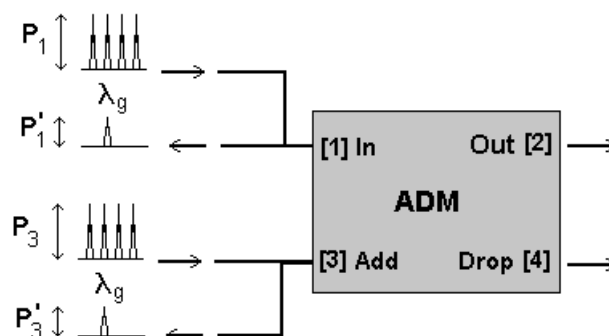


Figure 3.8 – Schematic representation of the S_{11} and S_{33} back-reflection parameters of an add-drop multiplexer.

3.4 Summary

Add-drop multiplexers are devices in high demand compatible with both LAN and long haul networks. Due to the number of nodes used in LANs, and thus the number add-drop multiplexers required, demand for cheap devices is the primary motivation. All-fibre add-drop multiplexer configurations are potential candidates for providing such cheap devices. The different schemes will be further addressed in chapter 8. In summary, this chapter was a review of the existing technologies for routing wavelength channels, with discussion regarding the advantages and drawbacks for each. Parameters, which are used to characterise the performance of add-drop multiplexers, were also introduced. This chapter provides OADM fundamentals relevant to section III, where the optimisation of three different all-fibre add-drop multiplexer schemes is discussed.