2.1 INTRODUCTION

We initiate our investigation regarding OADMs with a thorough look at the required characteristics and potential applications of practical OADMs. Various configurations are investigated with the emphasis on technologies using fibre Bragg gratings, optical couplers and optical circulators. We compare manufacturing methods and the performance of each type on the basis of insertion loss, channel isolation, tuning ranges, stability and cost. The most feasible methods are selected for further study.

2.2 OADM APPLICATIONS AND ATTRIBUTES

2.2.1 Functions of an OADM

The main function of an OADM is simply to add and drop wavelengths (channels) to and from a fibre. This straightforward operation possesses, however a substantial amount of potential applications. It can be used for controlling, combining, routing and monitoring wavelengths, to name but a few. (1)

Service providers rely on remote management stations to monitor and manage the optical network in real-time. Combing OADMs with computer software is one way of empowering the network manager with the means to monitor the fibre integrity of the network actively. Valuable information, such as power levels, signal distortion and congestion of channels, can be obtained. If the manager finds that certain links in the network are more active than others, he can use a dynamic channel routing OADM to route channels to different links. (1)

Figure 2.1 shows a diagram of a WDM network utilizing OADMs for various purposes to enhance functionality and performance. It can be used for the routing of channels and for testing the fibre integrity by adding a supervisory channel.

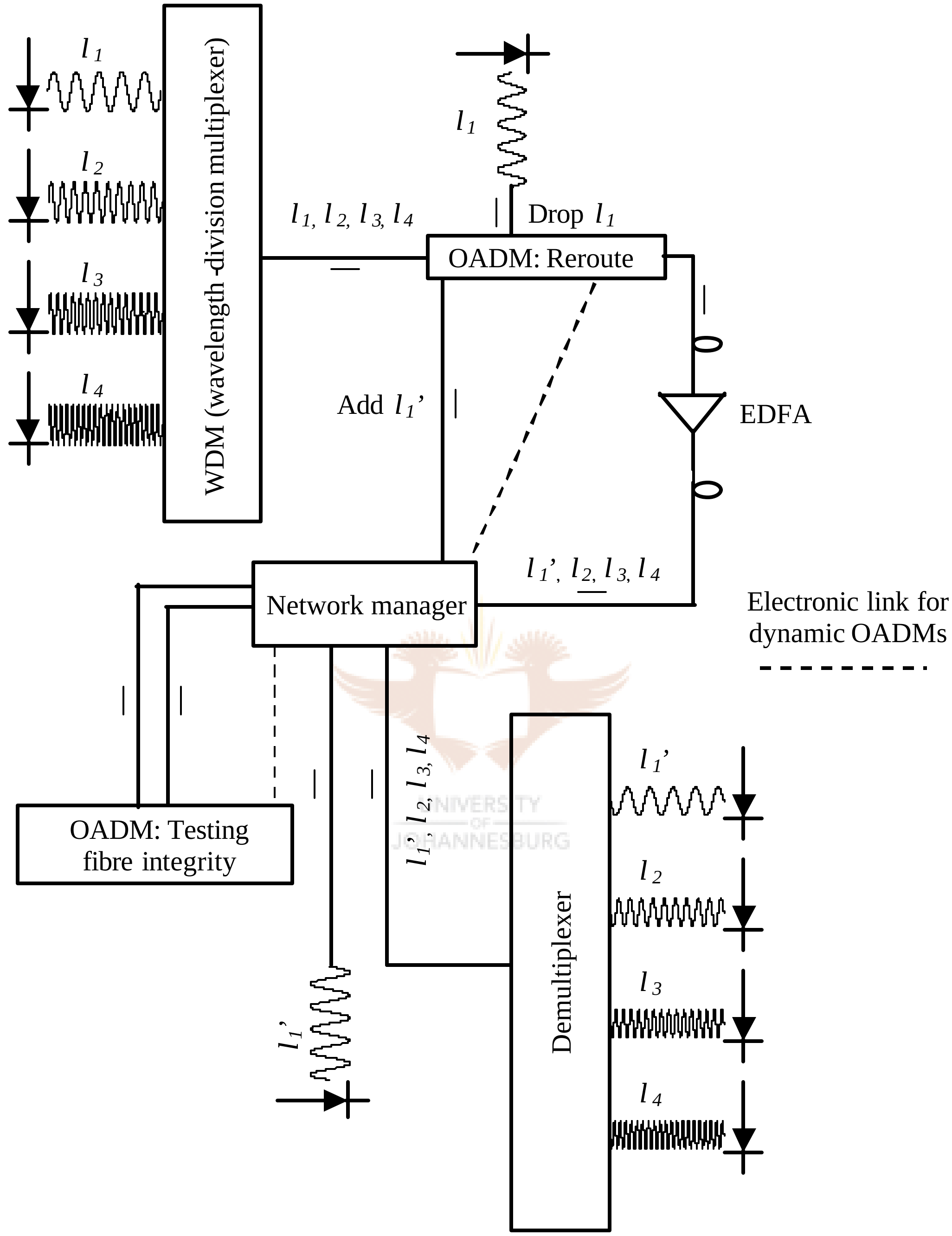

Figure 2.1 – Applications of OADMs in WDM networks

2.2.2 Required attributes for practical OADMs

For an OADM to be competitive, it has to adhere to the following characteristics:

- Low insertion loss (less than 1dB). (2)
- High channel isolation (more than 30dB). (2)
- Polarization insensitive, otherwise the output level will vary. (3), (4)
- Dispersion induced to adjacent channels must be low. (5)
- Wide wavelength tunability to extend the number of channels that can be selected. (3)
- High-speed tuning for rapid access time. (3)
- The filter must be stable to external perturbations (e.g. humidity, temperature, vibrations). (3)
- Maintenance free.
- Economically viable.

2.3 OADM CONFIGURATIONS

There is an assortment of OADMs available in the market, each using different technologies to perform in essence the same add-drop filter functions. Figure 2.2 shows a diagram of the possible options to realize optical filters using only Bragg gratings, optical couplers and optical circulators. The filters can be arranged into two types, namely reflection filters and transmission filters. The list can further be subdivided into interferometric and non-interferometric filters. (6)

Some of the filters shown in Figure 2.2 are not ideally suited to OADMs but rather to different applications (lasers etc.). In the following sections, a select few are compared on the criteria as stated in section 2.2.2 for the purpose of realizing OADMs.

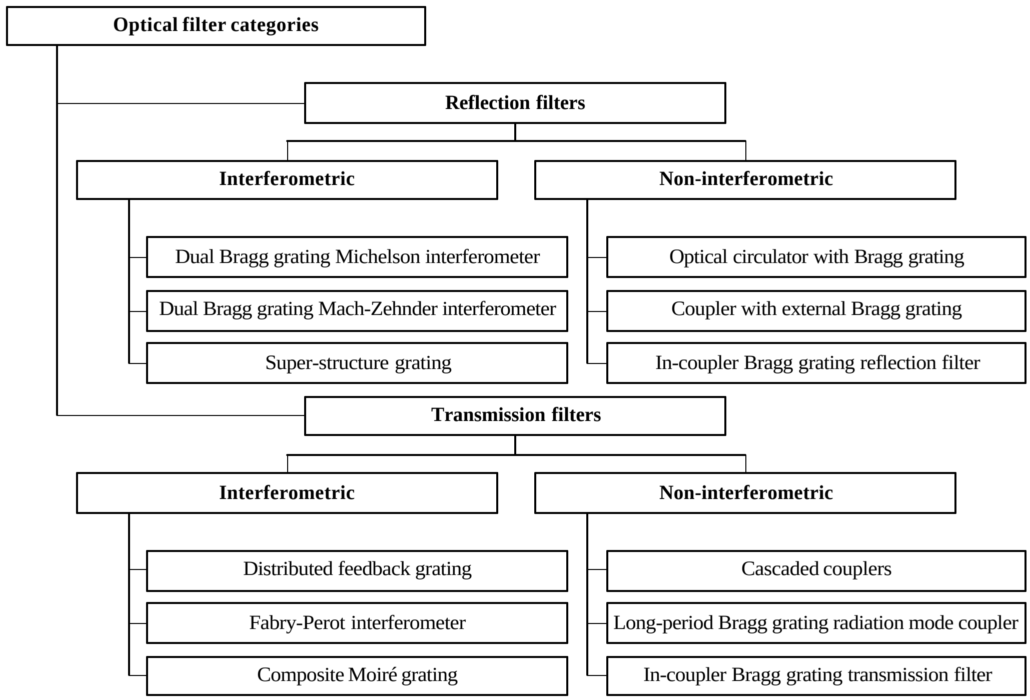

Figure 2.2 – Optical filter categories

2.3.1 Dual Bragg grating Mach-Zehnder interferometer OADM

OADMs based on interference filters, such as the Fabry-Perot, Michelson and Mach-Zehnder interferometers, are some of the more established methods used to realize optical filters. Extensive research has shown that these filters exhibit a relatively high extinction and low insertion loss. They are polarization sensitive, relatively difficult to manufacture and extremely sensitive to external perturbations (e.g. temperature and strain). [(6)]

Figure 2.3 shows an all-fibre dual Bragg grating Mach-Zehnder OADM. The method was first proposed by D.C. Johnson *et al.* and later optimized by F. Bilodeau *et al.* [(7), (8)] The Mach-Zehnder interferometer comprises two fused *3 dB* couplers with the two arms of the Mach-Zehnder ideally equal. Two identical Bragg gratings are then written symmetrically in the arms of the Mach-Zehnder. The component is therefore perfectly balanced.

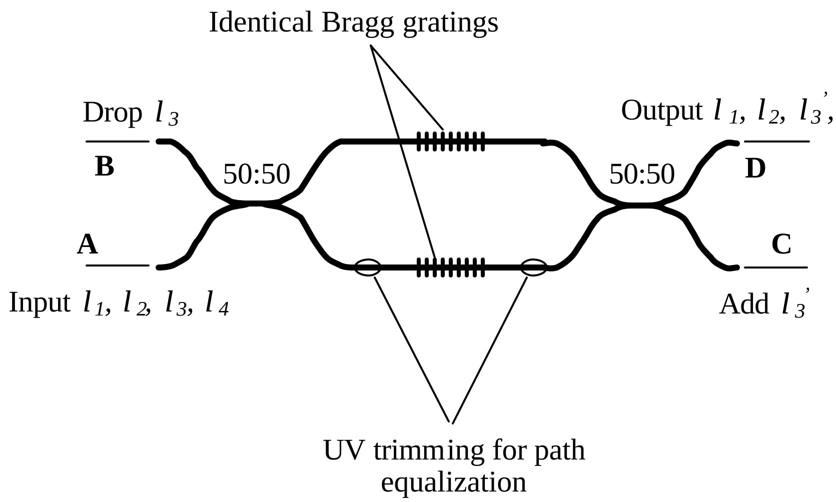

Figure 2.3 – Dual Bragg grating Mach-Zehnder interferometer OADM [8]

The Bragg gratings are written with a resonant wavelength equal to l_3. The unaffected wavelengths (l_1, l_2 and l_4) therefore ideally see a normal Mach-Zehnder interferometer, which splits the light at the first coupler equally and recombines the light in the second 3 dB coupler. If the Mach-Zehnder is perfectly balanced, no light will emerge at port C. l_3 on the other hand is also split by the first 3dB coupler but is reflected by the two identical Bragg gratings. On reaching the first coupler, coherent recombination occurs and l_3 exits the dropped port. [7] The symmetry of the component lends itself to add l_3' to the remaining wavelengths. By adding more matched gratings with different resonant wavelengths, several different wavelengths can be added or dropped. [8]

F. Bilodeau *et al.* optimized the device by manufacturing the Mach-Zehnder interferometer with two continuous fibres (without splicing). [8] The fibres are placed in a fused-taper-coupler manufacturing jig. Two very short couplers (stopping the elongation process at the first 3 dB point) are then manufactured. The short couplers vary slowly with wavelength and are extremely insensitive to polarization. UV trimming is used to balance the interferometer after the gratings are written. UV trimming relies on photoinduced changes in the refractive index to adjust the optical path-length difference. [6] The compact design makes the balance of the interferometer insensitive to ambient temperature fluctuations. The drift in the dropped wavelength is mainly due to the temperature sensitive Bragg gratings. [8]

A unique method for manufacturing a Mach-Zehnder OADM was developed by S. Bethuys *et al.*[9] Theirs is a dual Bragg grating Mach-Zehnder OADM written in a twincore fibre. The special twincore fibre is used to improve the balance of the interferometer.

By optimizing the dual Bragg grating Mach-Zehnder OADF, a stable device with a channel isolation of more than *20 dB*, an insertion loss of less than *0.5 dB* and a channel spacing of less than *100 GHz* (*0.8 nm*) is achievable. [8]

2.3.2 Cascaded fused coupler OADM

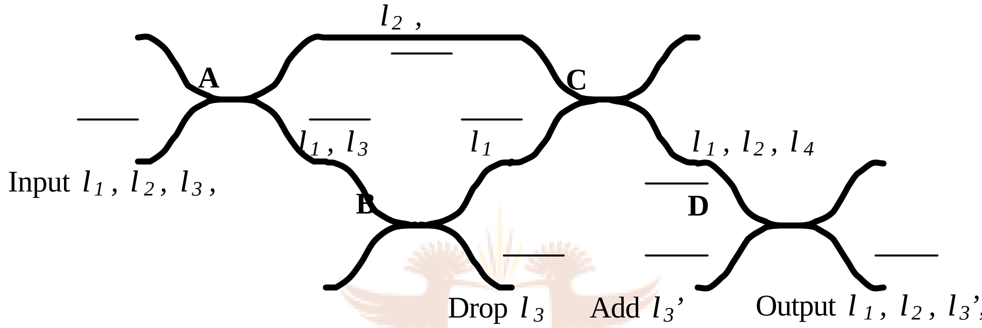

Figure 2.4 – Cascaded fused coupler OADM [4], [10]

An all-fibre OADM can be manufactured by cascading different fused WDM couplers with matching wavelengths. [4],[10]

WDM couplers can be manufactured by the process as presented by M.N. McLandrich *et al.* [11] Two single mode fibres are laid parallel, fused together, and tapered. Light with an arbitrary state of polarization is launched into one fibre, and the sinusoidal coupling as a function of tapered length is monitored at the two output ends.

The unequal coupling coefficients of the two polarizations cause the sinusoidal coupling to be modulated by an envelope. The fibre pulling is stopped at either a minimum or a maximum of the sinusoidal variation. By ensuring that the device is simultaneously at a maximum in the polarization envelope, one attains polarization independent couplers. To achieve small wavelength spacings, the fibre elongation is stopped after many cycles, and hence one or more peaks in the polarization envelope have occurred. [4]

Smaller channel spacings therefore call for longer couplers with smaller diameters, which will in turn decrease the performance of the OADM to such an extent that sufficient channel isolation for most WDM applications will not be possible. [4]

Four-channel OADMs using cascaded fused WDM couplers with high channel isolation (> 25 dB) and low insertion loss (< *0.5 dB*) is routinely achievable at a channel spacing of approximately 5 to 7 nm. An eight-channel add-drop filter with a channel isolation of more than *20 dB* and an insertion loss for any channel of less than *0.8 dB* is also reported by T.T. Vu *et al.* [4]

A great advantage of this device is the fact that it is all-fibre and therefore potentially inexpensive. The device is however a bulk, wide channel-spaced and non-tunable OADM.

2.3.3 Optical circulators with Bragg gratings OADMs

2.3.3.1 Two-circulators and a tunable Bragg grating OADM

A more expensive OADM is shown in Figure 2.5. The filter is made up of two three-port circulators and a tunable Bragg grating. The circulator is in essence a bulk optical component with input and output ports. The device comprises a multiple of lenses, prisms, polarization beam splitters and rotators (Faraday rotator or nonreciprocal rotator and optical active rotator or reciprocal rotator) in order to channel the light to specific ports. [12] Circulator 1 routes the input wavelengths from port A to B. The tunable Bragg grating is designed only to reflect l_1 to be dropped at port C, and to leave the remaining wavelengths to propagate unhindered to port E. l_1' launched at port D will be routed to port E to be reflected back by the Bragg grating and multiplexed with the remaining wavelengths. The output is retrieved at port F.

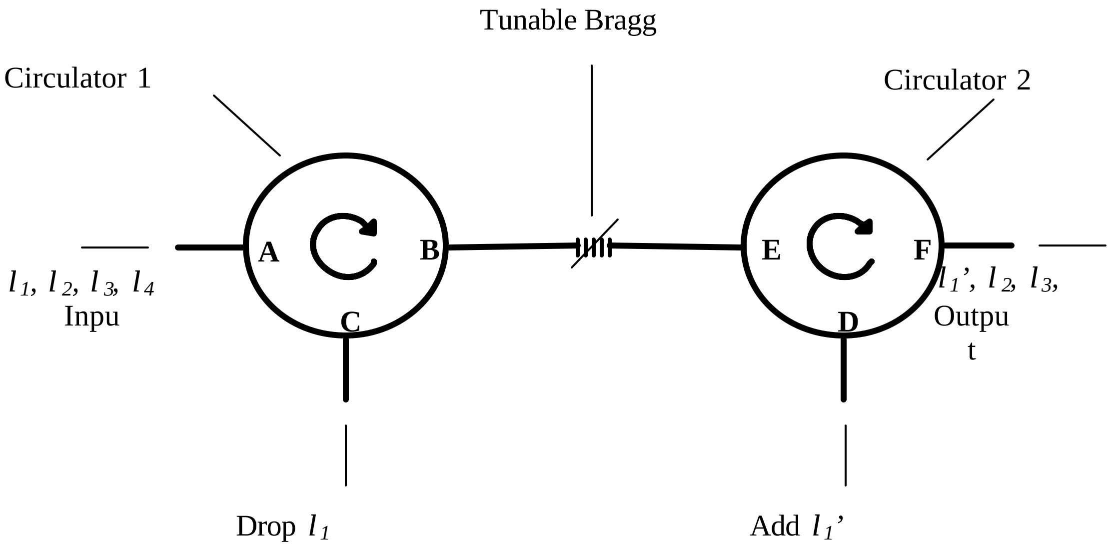

Figure 2.5 - Two-circulators and a tunable Bragg grating OADM

The Bragg grating can be tuned by mechanical strain (e.g. piezoelectric-stack actuator) to drop l_2 instead of l_1. [13] The same add-drop principles will apply. Adding and dropping of any of the four wavelengths are thus achievable. A fully reconfigurable system is a little more complex using optical switches to select different Bragg gratings. [14] By controlling the switch pair and Bragg gratings properly, one can achieve an excellent dynamic channel routing device for fairly complex networks.

OADMs using the above configurations with channel spacings of less than *0.8 nm*, an insertion loss for any channel of less than *0.3 dB* and a channel isolation of more than *30 dB* are easily achievable. [14]

2.3.3.2 One-circulator and a tunable Bragg grating OADM

A compact OADM using a 6-port circulator and a Bragg grating is shown in Figure 2.6. The add-drop functions are performed at ports C and D. The device can also be made tunable by replacing the Bragg grating with a tunable Bragg grating.

A high quality grating with a channel isolation of more than 30 dB must be used to prevent crosstalk. [15]

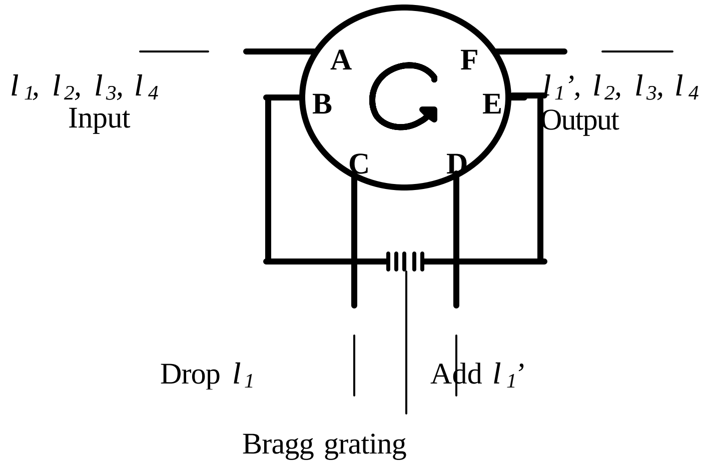

Figure 2.6 - One 6-port circulator and a tunable Bragg grating (15)

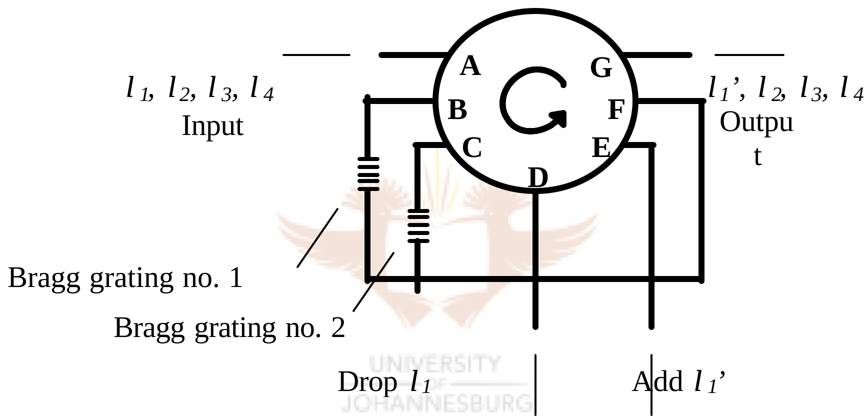

Figure 2.7 - One 7-port circulator and two Bragg gratings (15)

If the Bragg gratings that are used have a high reflection outside the Bragg wavelength a 7-port circulator with a second Bragg grating is needed. The second Bragg grating works as a bandpass filter to remove out-of-band wavelengths in order to reduce crosstalk. (15)

OADMs using only one circulator and two Bragg gratings can also be made tunable if both the gratings are tuned at the same time with perfect synchronization. By combining the one-circulator devices with a single optical switch, it is again possible to construct a reconfigurable OADM for dynamic channel routing.

The one-circulator device is much more economical than the two-circulator device with the possibility of higher channel isolation when using one circulator combined with two gratings.

2.3.4 In-coupler Bragg grating reflection OADMs

2.3.4.1 Bragg grating assisted mismatched coupler OADM

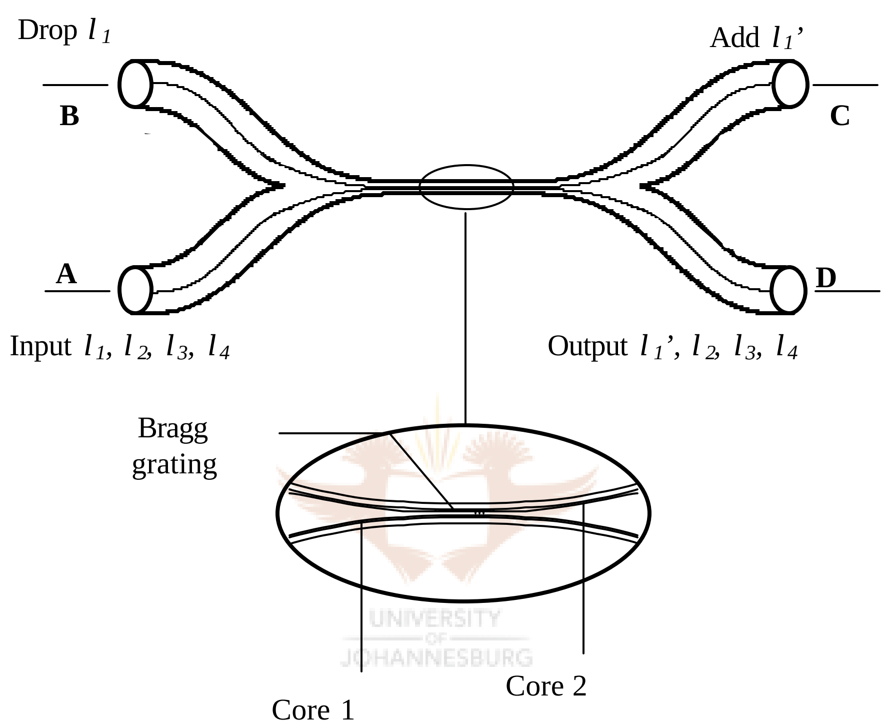

Figure 2.8 - Bragg grating assisted mismatched coupler OADM [16]

Figure 2.8 illustrates a compact OADM utilizing a polished coupler and a single Bragg grating, first demonstrated by L. Dong *et al.* [16]

A Bragg grating with a resonant wavelength equal to l_1 is written into core 2 over the coupling region. The two single mode fibres with different core radii and numerical apertures are then placed in polished blocks and polished very close to the cores. [16] The method of manufacturing the polished coupler is similar to that of M.J.F. Digonnet *et al.* [17] Micrometer positioners are used to align the coupler and to adjust the coupling ratio.

The coupler would normally not transfer power from one core to another due to the strong mismatch of the two cores. Due to the Bragg grating, l_1 is ideally the only wavelength that couples from core 1 to core 2 to be reflected back and dropped at port B. The same Bragg grating can be used to reflect l_1' that is added at port C. l_1' is therefore multiplexed with the remaining wavelengths and the output is retrieved at port D.

The main problems with the design that contribute to power loss are: [16]

- The Bragg grating raises the average refractive index in core 2 to such an extent that the fibre changes locally from single mode to two moded. The second mode is however lost beyond the grating.

- The two cores are curved (induced by the fabrication process) causing the grating to be blazed (at an angle). In general, blazed gratings couple the guided mode to the cladding mode. [6] The LP_{01} mode in core 1 can therefore be coupled to the LP_{11} mode in core 2. This phenomenon can be restricted if the two cores are made parallel in the coupling region so that the Bragg grating is nonblazed.

- The coupling length can be made longer (coupling length > grating length) to reduce loss due to reflections to ports A and C.

The device shows a channel isolation of more than *20 dB* with an insertion loss of *1.9 dB* for the dropped channel and less than *0.4 dB* for the output channels, at a channel separation of about *0.4 nm*. [16]

The device is non-interferometric but still mechanically unstable because it uses a polished coupler, not a fused coupler.

2.3.4.2 Fused 0 dB Bragg grating coupler OADM

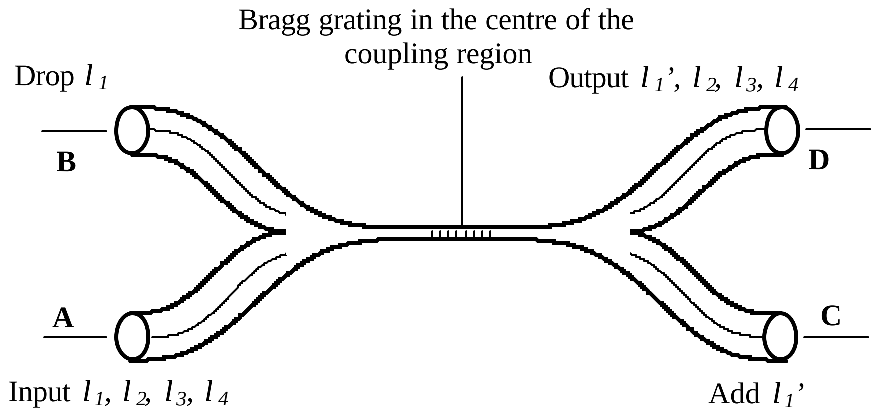

Figure 2.9 - Fused 0 dB Bragg grating coupler OADM [18]

A compact method demonstrated by F. Bakhti *et al.* combines a *0 dB* fused coupler and a Bragg grating written in the centre of the coupling region. [18] Figure 2.9 shows the configuration of such a filter. Without the grating, the device will act as a normal *0 dB* coupler, directing the light from the input port to the output port, with ideally no back reflection. Inscribing a Bragg grating in the centre-coupling region transforms this simple device into an OADM. Only light at the resonant Bragg wavelength will ideally be reflected to the input port. The remaining wavelengths will once again be directed to the output port. Couplers are bi-directional and can therefore carry light in either direction. The device described above could easily be used for the dropping and adding of wavelengths at port B and port C respectively.

A special fibre with an index profile close to that of standard single mode fibre but with a portion of the cladding made highly photosensitive is needed in order to write a Bragg grating in the coupling region. [18]

The device is compact, stable and non-interferometric, and shows a channel isolation of more than *20 dB* and an insertion loss of less than *1 dB*. The filter can be applied at a channel spacing of less than *1 nm*. [18]

2.3.5 In-coupler LPG transmission OADM

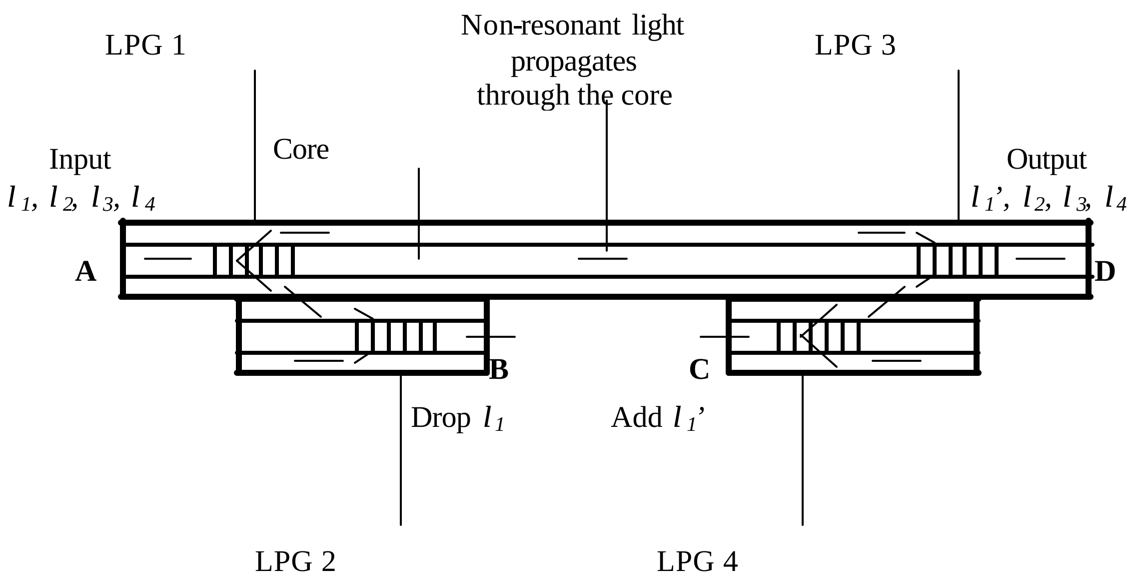

Figure 2.10 - In-coupler LPG transmission OADM [19]

Figure 2.10 shows a different approach using long-period fibre gratings. The fibres are stripped of their coatings and placed parallel to each other to form a coupling region with approximately *5 mm* between the claddings (no fusion is needed). [19]

A long-period grating (LPG 1) converts light from the core mode to the cladding mode of the same fibre at l_1. The rest of the wavelengths (non-resonant light) propagate unchanged to the output. The cladding mode (l_1) however couples to the cladding of the second fibre to be transformed to the core mode by LPG 2 in the second fibre. LPG1 and LPG 2 are identical. Only light at the resonant wavelength l_1 is therefore dropped at port B. The same principle applies to the adding of l_1’. The main advantages of the device are: [19]

- Long-period gratings cause no back reflection.
- Non-resonant light shows no loss.
- High channel isolation (> *40 dB*).

The device shows however a high insertion loss for the dropped channel (> *3 dB*). The polished couplers are once again not as practical as fused couplers, making this device unsuitable for practical WDM networks.

2.4 CONCLUSION

Various methods to realize OADMs using fibre Bragg gratings, fibre optic couplers and optical circulators for WDM networks were reviewed.

The eventual choice of one technology over the other depends on the characteristics of the system that the customer wishes to deploy. Cost and performance are the two main variables to bear in mind.

The ability of Bragg gratings to provide a calibrated means to pre-select wavelengths for routers and channel filters makes it an obvious choice for component selection in the design of OADMs. Bragg gratings offer a stable, reliable, versatile and cost-effective means to facilitate the realizing of WDM networks.

Combining an optical coupler and a Bragg grating results in an inexpensive, all-fibre, compact OADM, with basically the only disadvantage being that the filter is not tunable.

Circulators and Bragg gratings seem to be the perfect choice for an OADM. The filter is tunable, has high channel isolation and shows a low insertion loss. Systems incorporating optical switches to select different channels are excellent for dynamic channel routing devices for complex networks. A downside is, however, that optical circulators are bulk optical components that are very expensive. The cost may decrease as the demand for more and more WDM networks with optical components increases.

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