WAVELENGTH DIVISION
MULTIPLEXED OPTICAL FIBRE SYSTEM

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MULTIPLEXED OPTICAL FIBRE SYSTEM

By

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Abstract

The design, construction techniques and results of evaluation of two types of optical fibre multiplexing and demultiplexing devices are given.

The first type of device is a three channel optical multiplexer/demultiplexer operating in the 750 to 900 nm band. This device allows the simultaneous transmission of 3 different wavelengths through the same optical fibre. It employs a diffraction grating, in the Littrow configuration, as the wavelength selective element. The device is compact and rugged due to the use of a gradient index lens to which the other assemblies are cemented. The wavelength channels have centre wavelengths of 790, 830 and 870 nm and are nominally 30 nm wide at the -1 dB points. The loss is 2.2 to 2.5 dB when used as a demultiplexer and 7 to 8 dB when used as a multiplexer. Crosstalk is less than -30 dB at the channel centres.

The other device is a two channel multiplexer-demultiplexer which allows a bidirectional system to be constructed. This device has a short wavelength channel from 770 to 890 nm and a long wavelength channel from 1100 to 1400 nm. It employs an interference filter as the wavelength selective element. The filter is cemented between two gradient index lenses to form a compact rugged device. The loss is 1.5 dB for the 770 to 890 nm wavelength channel and 3.5 dB for the 1100 to 1400 nm wavelength channel.

Combining the two and three channel devices results in a four channel bidirectional system for use in integrated distribution services.

Suggestions for improvements in the design and construction of the devices are also given.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

There is a great deal of interest in the use of fibre optical communications systems. This is shown by the number of completed installations currently being field tested. Since installation of cables, optical or electrical, requires a large investment communications systems are normally designed to fully utilize the available bandwidth of the installed medium. At present fibreoptic systems are limited by the combined frequency responses of the source, detector and fibre (limited by dispersion) and do not approach the information carrying capacity of the optical carrier. One method of utilizing more of the information capacity is to multiplex several optical wavelengths over a single fibre. This technique is known as Wavelength Division Multiplexing (WDM).

WDM is not necessarily restricted to use in new systems. It could also be used to upgrade an installed system by increasing its bandwidth and versatility by assigning different data streams to different wavelengths. This allows the system bandwidth to grow as demand grows. WDM is also an obvious method for implementing bidirectional transmission since different optical wavelengths could carry data in different directions simultaneously with no mutual interference.

A WDM system requires the development of new devices to multiplex and demultiplex the optical signals. While these devices are not yet commercially available, the potential benefits of WDM systems have created much interest in such devices (see references 1 through 5). The devices proposed and demonstrated by various authors will be discussed in more detail in the next chapter.

The purpose of this project was to construct and test the devices required for a four channel WDM system (discussed in Chapter 2). This system has three short wavelength channels situated between 790 and 870 nm and a long wavelength channel situated between 1100 and 1400 nm. The multiplexers and demultiplexers for the short wavelength channel can be used without the long wavelength devices to implement a three channel WDM system.

The short wavelength multiplexer and demultiplexer have losses of approximately 10.5 and 2.5 dB respectively. The long wavelength device has a loss of 3.5 dB for the long wavelength channel and 1.5 dB for each of the short wavelength channels. The devices required by a four channel system would have an insertion loss of 13 dB for the short wavelength channels and 7 dB for the long wavelength channel, excluding connection losses. The crosstalk into adjacent channels is less than -30 dB from the channel centre and less than -10 dB from the channel edge.

The short wavelength multiplexer and demultiplexer were later used with laser diode source and pin diode receivers to demonstrate analog video transmission over 1 km of fibre.

The remainder of this report is divided into four chapters. WDM system design is discussed in Chapter 2. The design and construction of the short wavelength devices is given in Chapter 3 and the design and construction of the long wavelength device is given in Chapter 4. The results and possible improvements are discussed in Chapter 5.

CHAPTER 2

WDM SYSTEM DESIGN

A potential four channel WDM system is shown in Figure 2.1. Three of the channels, called the short wavelength channels, carry information from the central office to the subscriber and the fourth, called the long wavelength channel, carries information from the subscriber to the central office. All of the information is carried over a single "trunk" fibre.

System Constraints

The wavelength bands allocated to the channels are shown in Figure 2.2. The short wavelength channels are intended for use with laser diode sources. The channel centre wavelengths were chosen in the wavelength region (790 to 870 nm) where optical fibres having low (on the order of 3 dB/km) attenuation are available. The 30 nm channel widths were chosen to accommodate laser diode characteristics. The breakdown of the 30 nm is:

1)	laser centre wavelength temperature shift (0 to 50°C)	16 nm
2)	laser centre wavelength manufacturing tolerance	10 nm
3)	laser spectral width	4 nm

MULTIPLEXED TRUNK SYSTEM

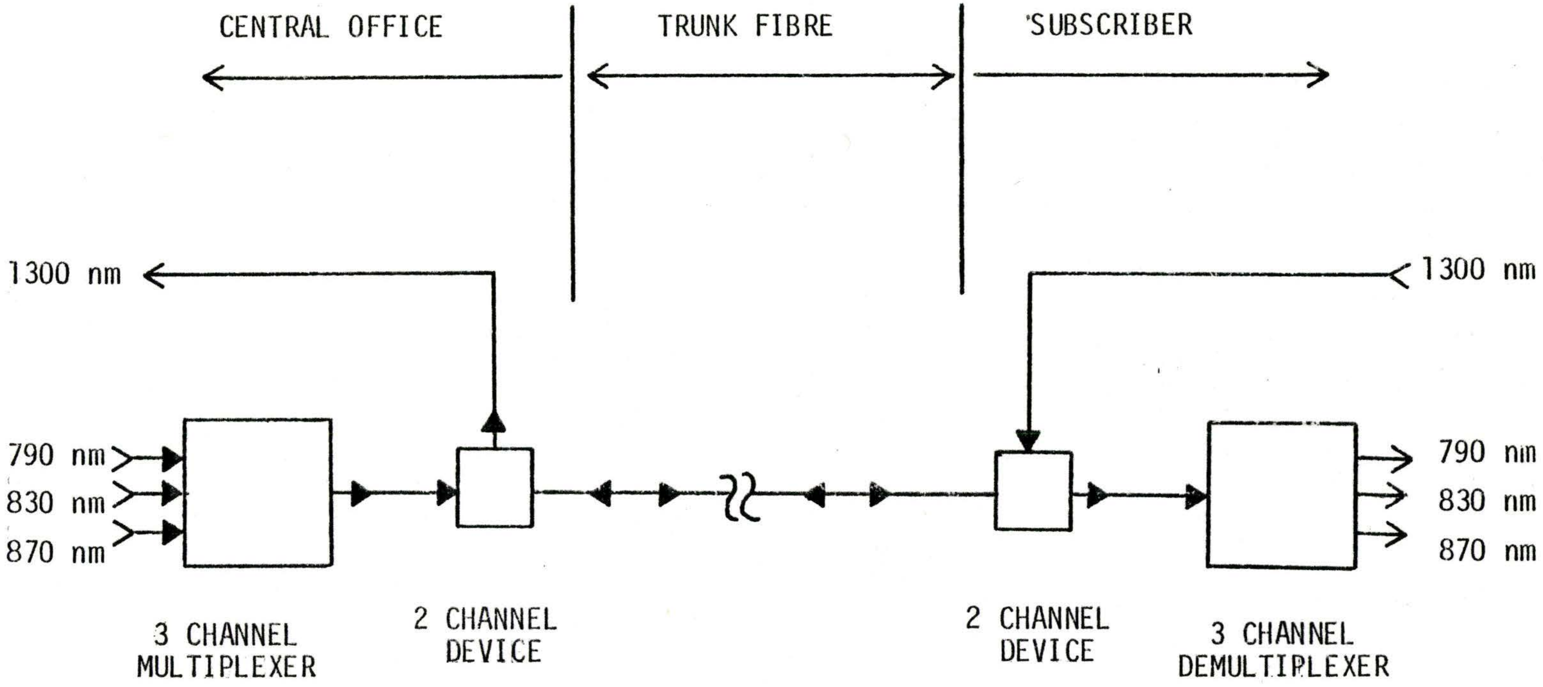


FIGURE 2-1

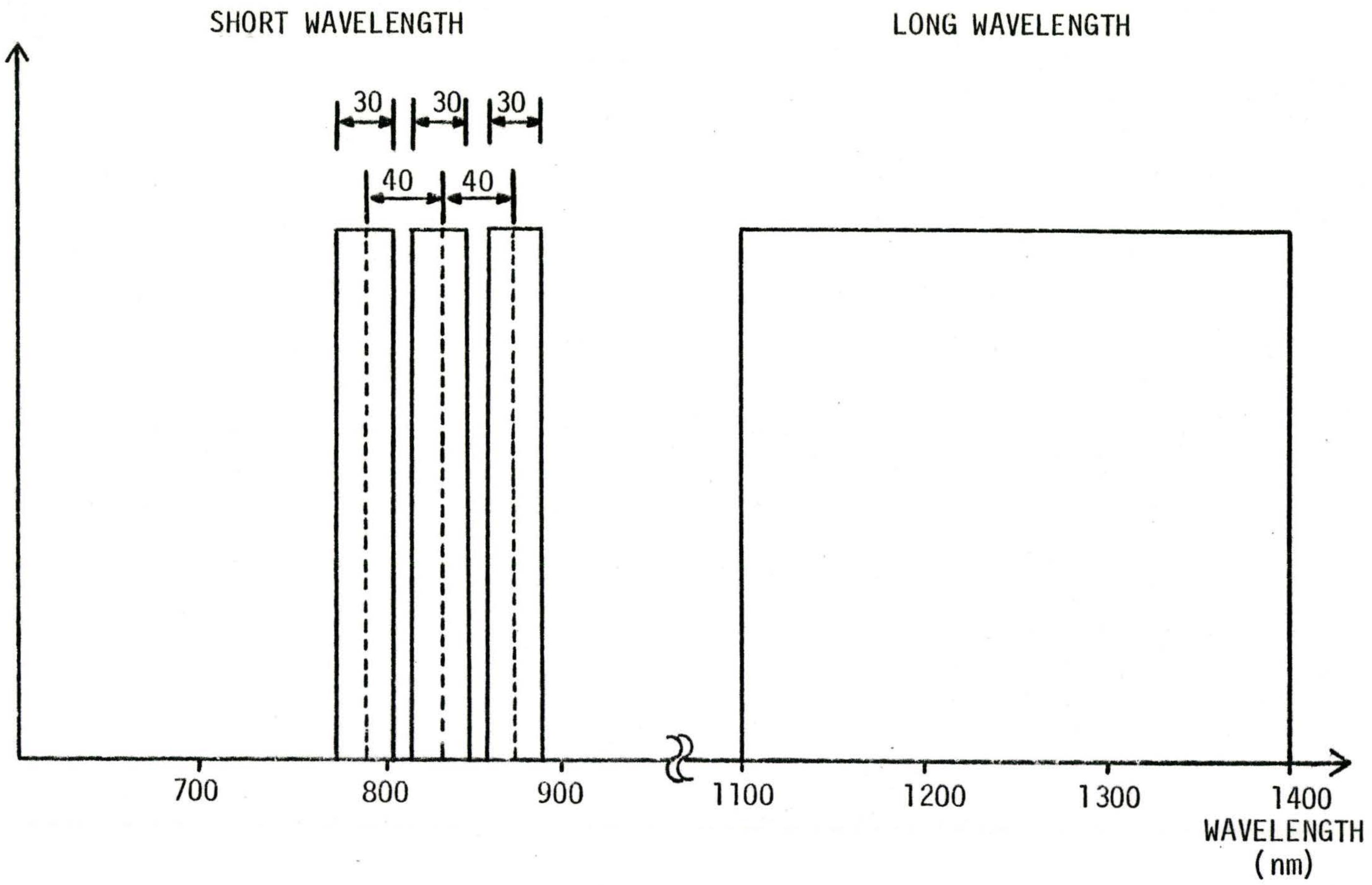


FIGURE 2-2
WDM SYSTEM TRANSMISSION BANDS

There is a 10 nm guard band between the channels to reduce the crosstalk.

The long wavelength channel is intended to be used with LED sources in the 1100 to 1300 nm region. It is very wide (300 nm) compared to the spectral width of an LED (typically 40 nm) to allow use of a variety of LED wavelengths. Since optical fibres have very low attenuation (1 dB/km or less) in the region of the long wavelength channel (ie. near 1300 nm) this channel can be used with lower power leds over similar distances to those possible with higher power lasers emitting in the short wavelength region. If required the long wavelength channel could also be broken up in a similar fashion to the short wavelength channel.

As shown in Figure 2-1 the multiplexing and demultiplexing at each end of the trunk fibre is performed by two devices. The device closest to the trunk fibre, called a two channel device, separates the long wavelength band (1100 to 1300 nm) from the short wavelength band (790 to 870 nm). The other element, called a three channel device, multiplexes or demultiplexes the three short wavelength channels (790, 830 and 870 nm). The required spectral characteristics of these devices are given in Figure 2-3.

The most important parameters of the two and three channel devices are the loss and crosstalk. The loss added by a set of WDM devices (ie. two each of the two channel and 3 channel

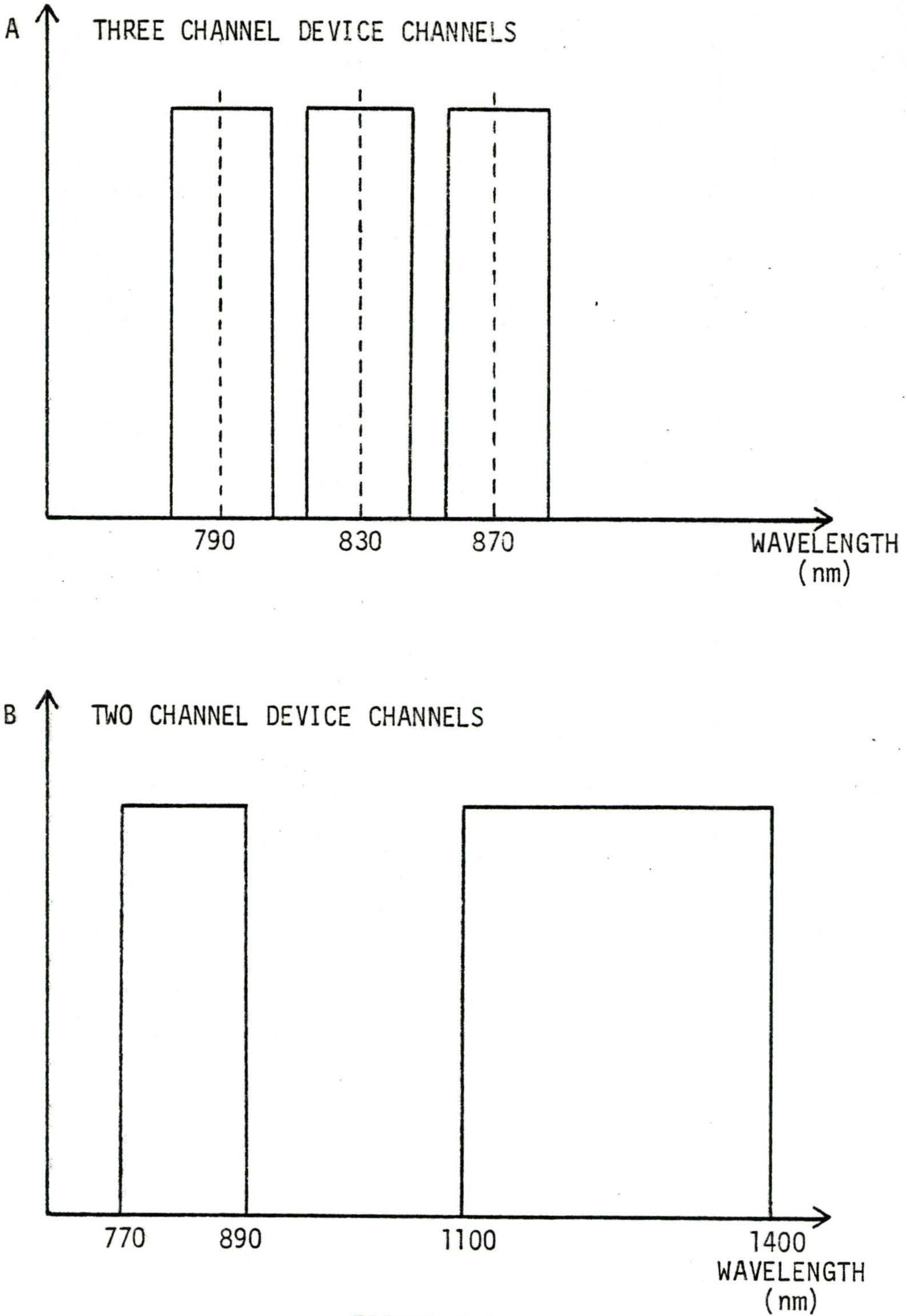

A
THREE CHANNEL DEVICE CHANNELS
790
830
870
WAVELENGTH
(nm)
B
TWO CHANNEL DEVICE CHANNELS
770
890
1100
1400
WAVELENGTH
(nm)

FIGURE 2-3

devices) should be kept as low as possible and should be uniform for the three short wavelength channels. Since the short wavelength light must pass through all four devices, as opposed to two devices for the long wavelength light, the short wavelength channel of the two channel device should have the lower loss. The crosstalk between channels should be held to a maximum of -30 dB optical (60 dB electrical) except for crosstalk from the long wavelength channel to the short wavelength channel which is unimportant since the silicon detectors used for the short wavelength light are insensitive to wavelengths longer than 1100 nm.

The other parameters and constraints which were placed on the two and three channel devices are:

1) they must be passive (ie. no electronics)
2) they must be constructed of readily available components (less than three months was available to purchase components and assemble the first devices)
3) the devices must operate from 0 to +50°C
4) the trunk fibre and the fibre connecting the two channel device to the three channel device must have a 50 μm core, 125 μm outside diameter (OD) and a numerical aperature (NA) of 0.16.
5) they should be useable for multiplexing or demultiplexing by changing only the fibres.
6) the components used should be manufacturable in large quantities at reasonable cost.

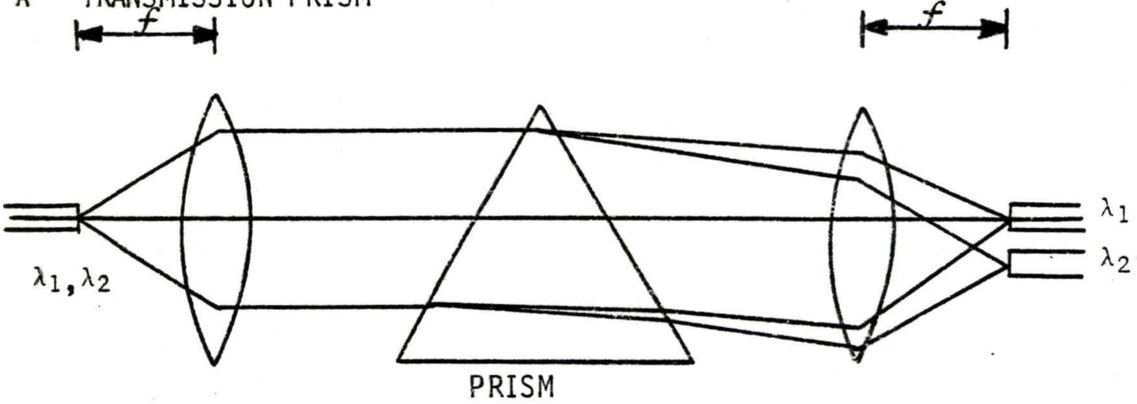
Before presenting the design of the devices reported the various approaches to making WDM devices will be discussed.

Types of WDM Devices

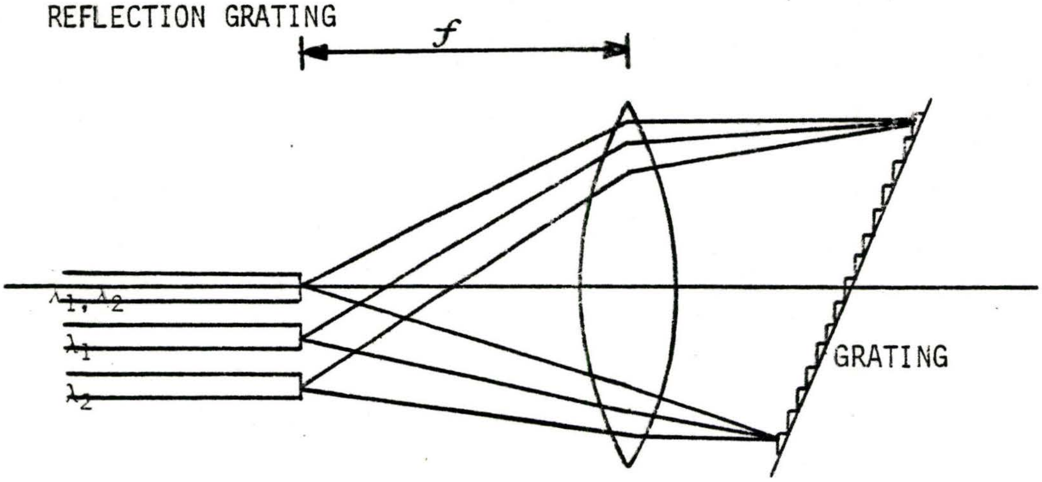
The multiplexing and demultiplexing devices reported in the literature, which seem suitable considering the parameters listed above, can be divided into two groups(1) by the component used to give the wavelength selective property. One group employs angularly dispersive elements whereas the other group employs optical filters (which have wavelength-dependent reflectivity and transmission). Non wavelength selective devices violate requirement 5 above since they cannot be used as demultiplexers. Many configurations are possible for the devices in either group and no attempt will be made here to review the possible configurations. Only the major features of each group will be given with references to more extensive articles.

The angularly dispersive devices reported employ either gratings[1,2,3] or prisms[1,4] as the dispersive element. The operation of the grating and prism devices is very similar. The light from the input fibre, of wavelengths say $\lambda 1$ and $\lambda 2$, is collimated by a lens and is incident on the grating or prism which diffracts or refracts $\lambda 1$ and $\lambda 2$ at different angles. If a transmission grating or transmission prism is employed a second lens is required to convert the angular dispersion into a spatial dispersion (in the focal plane). This is shown in Figure 2-4A. If a reflection grating or Littrow (reflection) prism is employed

A TRANSMISSION PRISM



B REFLECTION GRATING



C FILTER

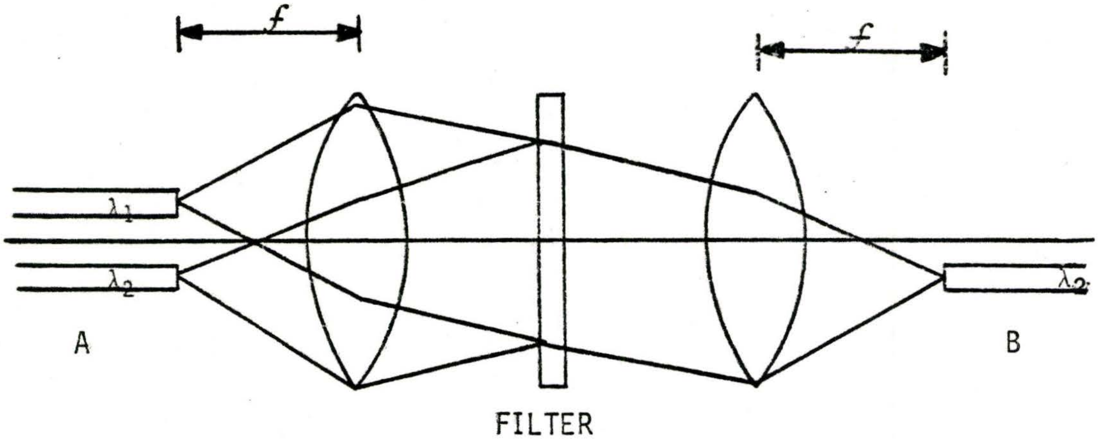


FIGURE 2-4
POSSIBLE WDM DEVICES

the input collimating lens also serves to convert the angular dispersion to a spatial dispersion. A reflection grating device is shown in Figure 2-4B. Optical fibres are arranged in the focal plane to collect the required wavelengths. Detectors could also be placed in the focal plane for use in a repeater, but only fibres will be considered in this report.

Filter devices[1,5] employ multilayer dielectric filters, which absorb very little in the spectral region of interest, to provide wavelength selectivity as shown in Figure 2-4C. The light from the input fibre consisting of wavelengths $\lambda 1$ and $\lambda 2$ is collimated by the first lens and is incident on the filter. One wavelength, say $\lambda 1$, is reflected by the filter and is focussed by the same lens onto output fibre A. $\lambda 2$ which is transmitted by the filter is focussed by the second lens onto output fibre B.

The major difference between the angularly dispersive devices and the filter devices is the method of determining the wavelengths which are passed to the output(s). The spectral content of the output(s) of a filter device are determined by the filter characteristics whereas the size and location of the output fibre(s) determine the spectral content of the output(s) of the dispersive device. The filter device is therefore limited to two channels per filter (one reflected and one transmitted) whereas the dispersive device can have many channels. Filter devices can be cascaded to add extra channels with a corresponding increase in loss. Which device has the best performance depends on the characteristics of the input or output wavelength channels, ie. how wide the channel is and how close it is to the next channel. In general the filter type devices are preferred for applications where two wide bands are required (using long wavelength or short wavelength pass filters) or where one very narrow channel is required (using a bandpass filter) and dispersive devices are indicated when many relatively narrow channels are required.

Design of the WDM Devices

A grating design was chosen for the three channel device which multiplexes or demultiplexes the three short wavelength channels. The grating design satisfied all of the requirements listed above and can be designed to give channels with the nominal widths and spacings shown in Figure 2-3. A prism design was not used because prisms, even when fabricated from materials such as arsenic trisulphide which have absorption edges near 900 nm, have lower angular dispersion than gratings and would require very long focal length lenses. For example a 1200 l/mm grating has angular dispersion of approximately 70 x 10^{-3} deg/nm whereas an arsenic trisulphide prism has an angular dispersion on the order of .2 x 10^{-3} deg/nm. A long focal length would increase the size of the device and is not available in the most suitable lens type (gradient index). A filter design could not be used since filters with the channel widths required as well as low crosstalk and low loss were not available and apparently cannot be fabricated using current technology.

A filter design was chosen for the two channel device which separates the long and short wavelength channels. A grating device would tend to have high loss over such a large spectral range and a prism device while it would have reasonable loss would be more expensive and more difficult to fabricate. The filters for the two channel device can be easily and inexpensively constructed using current filter technology. A long wavelength pass filter was chosen over a short wavelength pass filter for the reasons given in Chapter 4. A bandpass filter was not used as the channels are too wide.

The design, construction and testing of a three channel device and a two channel device are described in Chapters 3 and 4 respectively.

CHAPTER 3

THE THREE CHANNEL MULTIPLEXER/DEMULTIPLEXER

The three channel device is required to multiplex and demultiplex the three short wavelength channels. It is shown schematically in Figure 3-1. This configuration, suggested by Tomlinson[1], is compact and rugged as the entire unit is cemented together with no air spaces. A "Selfoc" lens, produced by the Nippon Sheet Glass Company is important to the design. A "quarter period" Selfoc lens, the type used, has its focal point on the end of the lens (Appendix A gives more information about Selfoc lenses). Since the end of the lens is flat and coincident with the focal plane, the lens will collimate light from a fibre which is cemented to the end of the lens. All four of the fibres in the three channel device are mounted in a fibreholder, positioned and cemented to the lens. This contributes to the compactness and ruggedness of the device. A prism, which is glued to the other end of the lens to hold the grating in the correct orientation, also contributes to the compactness and ruggedness of the device. The grating, a gold coated replica, is replicated on a microscope slide and cemented to the prism.

Principle of Operation

The operation of the device is explained below for the case where it is used as a demultiplexer, i.e. light is incident from the trunk fibre. The other three fibres are thus the outputs.

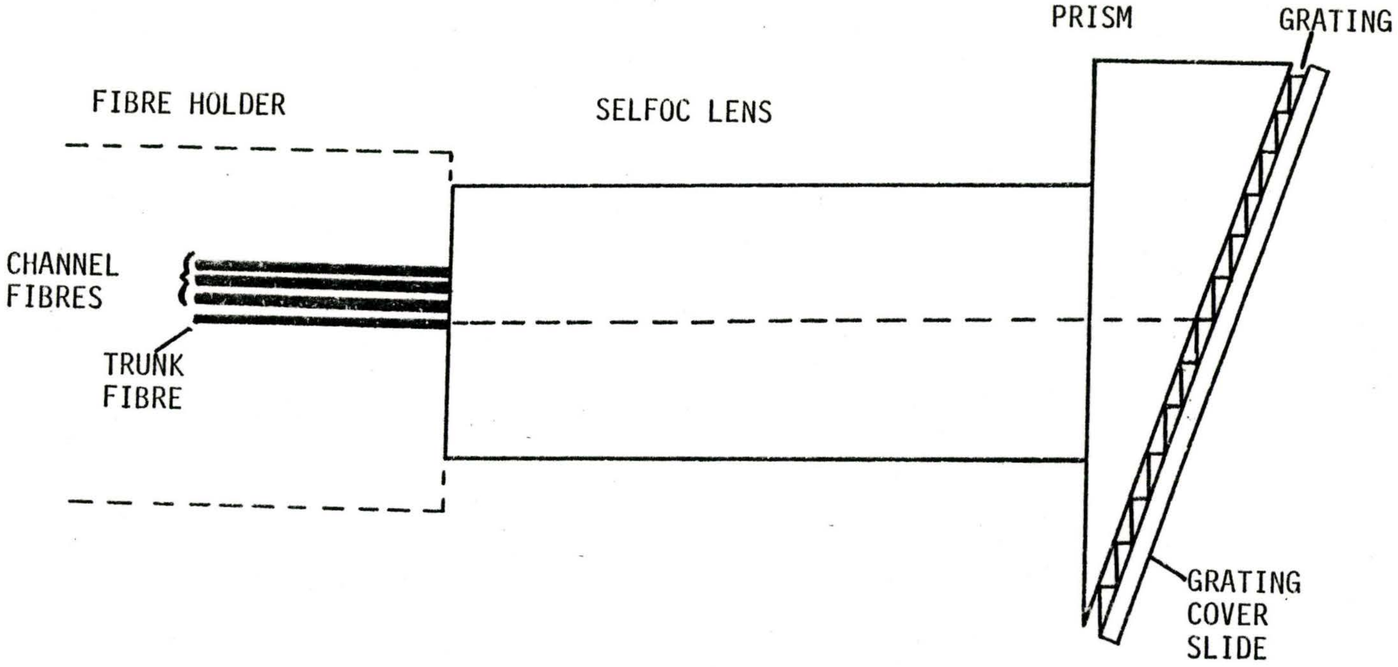


FIGURE 3-1

THREE CHANNEL MULTIPLEXER/DEMULTIPLEXER

Spectrally the outputs are 30 nm wide and centered at 790, 830 and 870 nm (see Figure 2-2). Operation as a multiplexer is exactly the reverse process.

Let monochromatic light be incident from a point on the trunk fibre. Then, neglecting diffraction effects and aberration in the lens, the light is collimated by the lens, passes through the prism with negligible dispersion and is incident on the reflection grating. The diffraction of the grating causes the light to travel back towards the lens at an angle, Δ, with respect to the input. This is shown in Figure 3-2. "Δ" is given by:

$$\Delta = \theta - \phi \qquad (1)$$

where: θ - is the angle between the grating normal and the input light

ϕ - is the angle between the grating normal and the diffracted light

"θ" and "ϕ" are related by the first order grating equation since the grating used is blazed for the first order, i.e.:

$$\lambda = n\,(\sin(\theta) + \sin(\phi))/c \qquad (2)$$

where: λ - vacuum wavelength of the light

n - index of refraction of the epoxy filling the grooves of the grating

c - number of grooves in the grating per unit length.

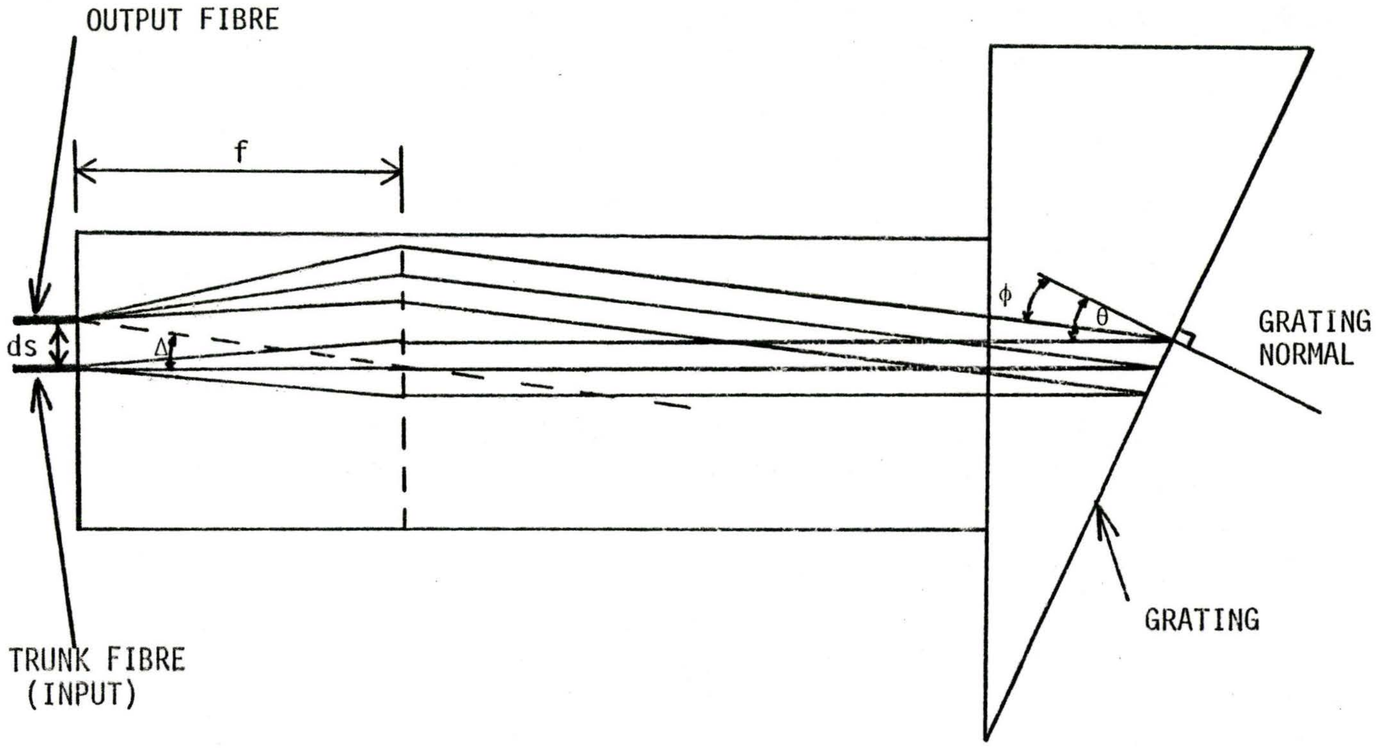


FIGURE 3-2

RAY TRACE OF A THREE CHANNEL DEMULTIPLEXER

The angular relationship of the light rays and the grating grooves is shown in Figure 3-3.

The diffracted light travels back through the prism and lens and is focussed to a point on the end of the lens. This point is centered a distance, dS, from the input point source given approximately by:

$$dS \simeq f.\Delta \qquad (3)$$

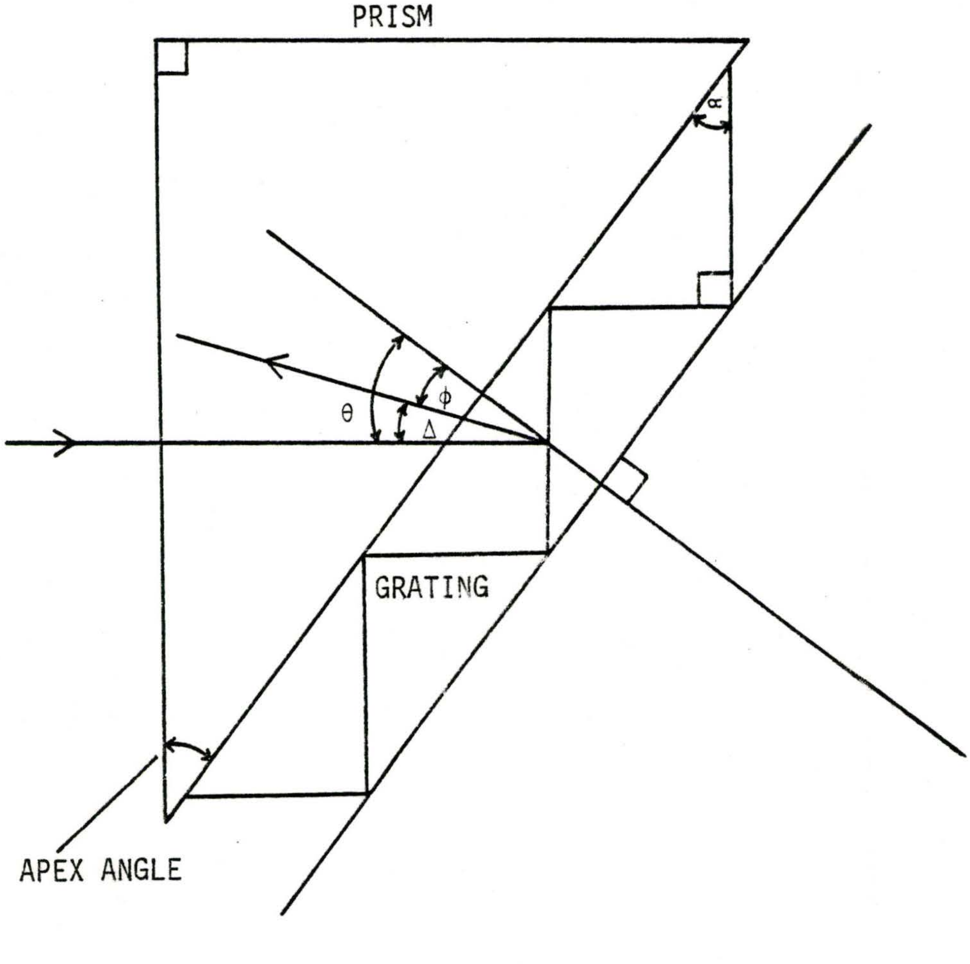
where: f - focal length of the lens.

Using a 1200 l/mm grating with $\theta = 16.5°$, $f = 2.15$ nm and $\lambda = 790$ nm results in $dS \simeq 110$ µm.

When diffraction and aberrations are considered, the light is seen to focus not to a point but to a finite spot called the "blur spot". Every point on the input (trunk) fibre will then focus to a blur spot a distance dS away on the end of the lens. Thus an image is formed which is the convolution of the trunk fibre output and the blur spot of the lens/prism/grating assembly. This image is circular but has a larger diameter than the core of the trunk fibre (by approximately 10%). If the wavelength of the input light was the centre wavelength of one of the channels then the image of this light would fall on the centre of one of the "output" fibres. Only the light which falls on the core of an output fibre is collected by the output fibre. The remainder, which falls on the output fibre cladding or which

FIGURE 3-3

GEOMETRY OF LIGHT RAYS AND GRATING GROOVES



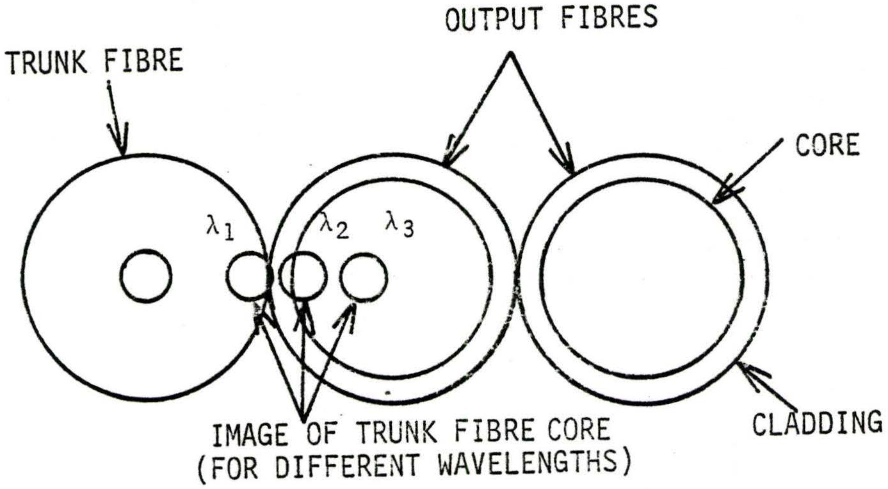
is in the epoxy between fibres, is lost. As the wavelength varies, the image would move across the face of the output fibre as shown in Figure 3-4A. The resulting spectral output is shown in Figure 3-4B.

The spectral width of the demultiplexer outputs are therefore determined by the ratio of the diameter of the image of the trunk fibre to the diameter of the "output" fibre. The centre wavelength of each output channel depends on the spacing between the centre of the trunk fibre and the centre of the output fibre.

The "shape" of the output channels would ideally be the square shape shown in Fig. 2-3 however, the response of a channel may in practise extend into the space between two channels without causing crosstalk. Thus, the sloped sides on the spectral responses shown in Figure 3-4B are not a problem unless the slope overlaps an adjacent channel. It is however desireable that the top of the spectral response be flat (within 3 dB) over a 30 nm region. The output fibres for a demultiplexer are always larger than the trunk fibre since this determines the output spectral width. It also ensures that the device is relatively efficient.

The same device is also used as a multiplexer. It can be seen that when the three channel device is used as a multiplexer the (3) input fibres are larger than the trunk fibre. The channel spectral shape will not change but there will be a large loss since the image of the input fibre will be much larger than the trunk fibre. While using a smaller fibre for the input would

A



B

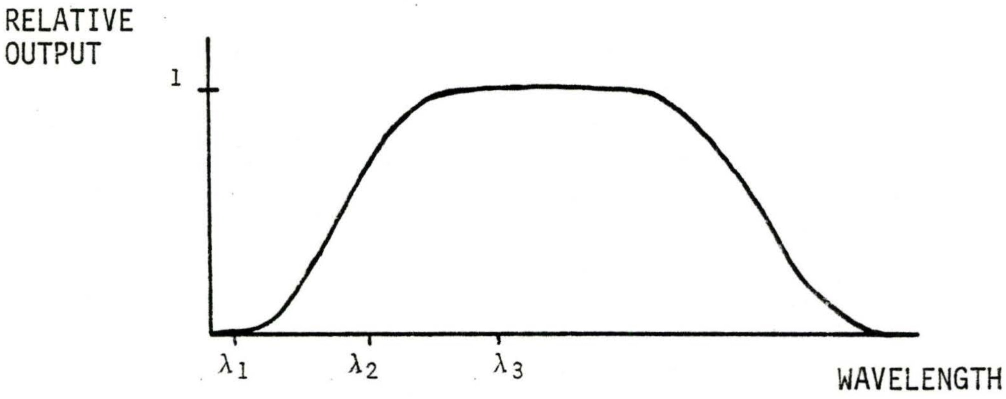


FIGURE 3-4

OPERATION OF THE THREE CHANNEL DEMULTIPLEXER reduce the loss, experiments indicate that a compensating loss would be suffered when coupling the input fibre to the laser diode. This type of multiplexer is an inherently lossy device however it has the advantage of filtering the inputs of unwanted wavelengths present in the source which would otherwise appear as crosstalk. Other multiplexers are discussed in more detail in Chapter 5.

Detailed Design

The design of the 3 channel device follows from equations 1, 2 and 3 if dS in equation 3 is the centre to centre spacing of the fibres since all of the fibres have the same outside diameter and are placed side by side to form a "ribbon". The device is designed to have the trunk fibre on the optical axis. This is done because the first devices, which did not have the trunk fibre on axis, had crosstalk problems.

The spacing of the channel wavelengths is 40 nm and the first channel has a centre wavelength of 790 nm thus light of wavelength 750 nm should return to the trunk fibre. Referring to Figure 3-3 it is clear that $\theta = \phi$ for light at 750 nm and therefore the grating is being operated in the Littrow configuration at this wavelength. The Littrow configuration minimizes the aberrations caused by the grating but to achieve maximum efficiency the grating must be operated at the "blaze" wavelength[6]. The blaze wavelength is the wavelength of light for which the diffracted light follows the same path as a specular reflection from the longer face of the grating groove[6]. The blaze wavelength is dependent on the angle of the groove face with respect to the grating plane (called the blaze angle) and the angle of incidence of the light with respect to the grating normal (θ). Since $\theta = \phi$ at 750 nm a grating should be chosen such that the tooth face is perpendicular to the incoming (and outgoing) light, ie. the blaze angle "α" (see Figure 3-3) must be equal to θ (or ϕ).

Only standard gratings could be used due to the time available for construction. Gratings are specified by the blaze wavelengths and the number of lines per mm. The angular dispersion of a grating increases with an increase in the number of lines per mm whereas the efficiency decreases with an increase in the number of lines per mm. Therefore efficiency must be traded off against angular dispersion when selecting a grating. The most suitable standard gratings were the 1200 l/mm gratings. To obtain the maximum efficiency from the grating it must also have the proper blaze angle as discussed above. The blaze angle α is calculated by setting $\theta = \phi$ in equation 2 with $\lambda = 750$ nm, $c = 1200 \text{ mm}^{-1}$ and $n = 1.55$, then solving for θ. This gives $\theta \simeq 16.9°$, therefore the blaze angle should be 16.9°. Fortunately standard gratings blazed for 500 nm have a blaze angle of 16.6°. Gratings blazed for 750 nm are not as suitable because they have blaze angles of approximately 26.5°. The 750 nm blazed gratings would be best if the grating was in air instead of being cemented to the prism with epoxy (index 1.55).

The prism must hold the grating at the angle required by the Littrow configuration therefore the prism apex angle (see Figure 3-2) must also be equal to "θ". For the 1200 l/mm grating the prism apex angle should therefore be approximately 16.6°.

The gratings and Selfoc lenses were stock items. The fibres were chosen for the proper core size and were etched to reduce their outside diameter. To determine the fibre diameter the grating and lens parameters are entered into equations 1, 2 and 3 (with θ being equal to the prism apex angle) and λ = 790 nm. Solving these equations gives a value for dS which is equal to the required fibre outside diameter. This must be less than or equal to an available fibre diameter. For example if a 1200 l/mm grating blazed for 500 nm and a lens of focal length 2.15 mm are chosen then the required fibre outside diameter is 110 μm.

The diameter of the core of the trunk fibre is 50 μm. The diameter of the cores of the other fibres is determined by the channel shape requirements. Since the channel width (30 nm) is .75 of the channel spacing (40 nm), the core of the fibre should be approximately .75 times the fibre outside diameter (110 μm) or approximately 83 μm. The nearest available fibre had a core of 95 μm.

Construction

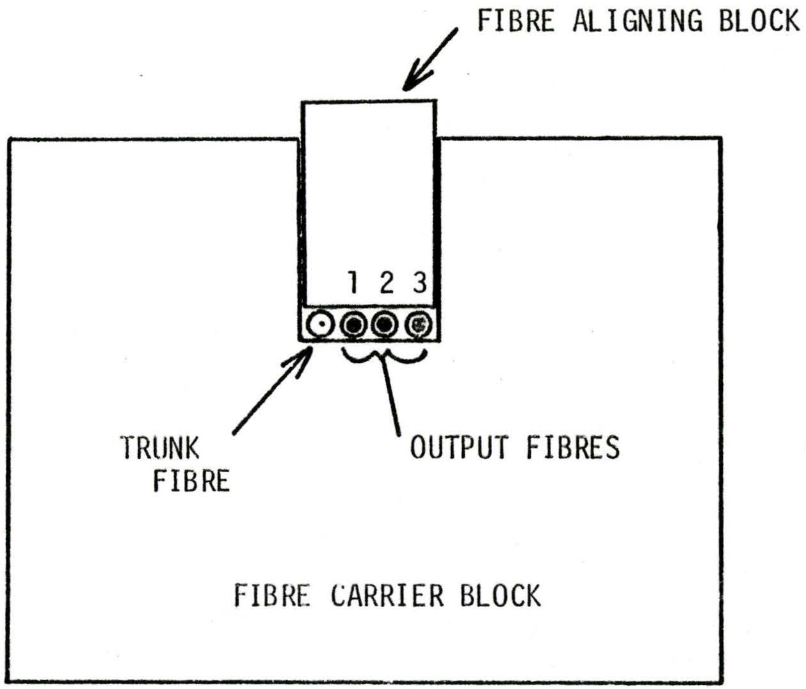
The following paragraphs discuss the construction and packaging of the three channel devices.

The first steps in construction are to cement together the lens and prism grating assembly and to etch the fibres to the correct diameter (110 μm). The fibres are then cleaved and inserted into the fibreholder, such that their ends are flush with the end of the fibreholder and in a straight line. This is shown in Figure 3-5. The fibres are then cemented in place in the fibreholder. The fibreholder is then positioned on the surface of the lens such that the channels are centered at the correct wavelengths and have the best obtainable shape (ie. flat tops and steep sides). Positioning of the fibreholder is critical and requires an accuracy on the order of 5 μm which can be obtained from differential screw type translation stages. When properly positioned the fibre holder is cemented in place. The assembly can then be installed in a package.

The package should protect the device against handling damage but it must not strain the device either during the packaging process or during temperature cycling. Potting of one device in epoxy resulted in approximately .5 dB increase in loss which is believed to be the result of shrinkage of the epoxy during curing. The package must also prevent bending of the fibres where they emerge from the hardened epoxy since they are prone to breakage at such places. Flexible tubing can be used for strain relief.

FIGURE 3-5

FIBRE HOLDER



The package made for the device reported consists of a milled brass box and cover plate. The device is cemented into the box. All fibres are contained in a piece of flexible tubing which exits from one end of the box. The tubing is secured to a flange on the fibreholder and cemented to the inside of the box.

Sources of Loss

The largest single source of loss, excluding manufacturing errors, when the three channel devices are used as demultiplexers is expected to be the grating. Gratings with 1200 l/mm typically diffract 75% to 80% of the incident light into the first order at the blaze wavelength. The efficiency drops to approximately 40% at 0.5 and 1.5 times the blaze wavelength. Since the three channel devices are working with wavelengths ranging from the blaze wavelength to 1.2 times the blaze wavelength the grating can be expected to cause a loss of approximately 1.0 dB for the first channel and less than 2.0 dB for the third channel (assuming that the epoxy has no effect on the grating's efficiency).

The only other major loss is in the lenses. While the transmission of light from a small core fibre through two lenses into a large core fibre, with all adjoining surfaces close to being perfectly index matched, should be greater than 99% it was found to be ≃90% (0.5 dB loss) in other experiments. It is believed that this loss is due to scattering in the lens.

The minimum loss for the first channel of the device is then approximately 1.5 dB due to the available grating and lens. The other channels will suffer additional losses as they are further from the optimum wavelength and focus further from the optical axis of the lens where aberratiions are worse. Errors such as improper positioning of the fibres or fibreholder and poorly cleaved or dirty fibres will increase the loss.

When used as a multiplexer the three channel device will experience a large loss due to the input fibres being larger than the outputs. This loss can be estimated as:

$$L = SG - 20 \log[NA_O \cdot D_O/(NA_I \cdot D_I)] \qquad (4)$$

where NA_I - numerical aperture of the image of the input fibre
NA_O - numerical aperture of the output fibre
D_I - diameter of the image of the core of the input fibre
D_O - core diameter of the output fibre
SG - loss caused by going from a step index fibre to a graded index fibre (approximately 3 dB)(8)

The loss is approximately 7 to 8 dB for the fibres used in the three channel device (discussed later in this chapter). This loss is inevitable in this multiplexer configuration since the different fibre sizes are required to obtain the specified spectral characteristics.

Evaluation

The first three channel devices constructed were designed to have the optical axis between the second and third channel fibres, not centred on the trunk fibre. This was done to minimize the effects of lens aberrations by keeping the light as close to the optical axis as possible. However, these devices had added crosstalk from channel three into channel one. It is believed that this crosstalk is the result of a reflection inside the device. A device constructed with the trunk fibre on the optical axis (prism apex angle of 16.6°) did not show any extra crosstalk from channel three into channel one. The components used to build the later device are listed in Table 3-1. Detailed test results for this device are given and discussed below.

The demultiplexing capability of the three channel devices was tested by injecting nearly monochromatic light (filtered by a monochromator) into the trunk fibre and measuring the output from each of the three channel fibres as a function of wavelength. The input power to the trunk fibre was measured (after the 3 outputs) by breaking the trunk fibre 0.5 m from the monochromator and measuring the output from the short piece of trunk fibre. The output power was recorded on both linear and log scales to produce accurate loss and crosstalk values.

A typical linear output graph is given in Figure 3-6. Only channel 2 has a flat top, the other two channels both have peaked tops. This is the result of positioning the fibre holder while

FIGURE 3-6

THREE CHANNEL DEMULTIPLEXER OUTPUT (LINEAR)

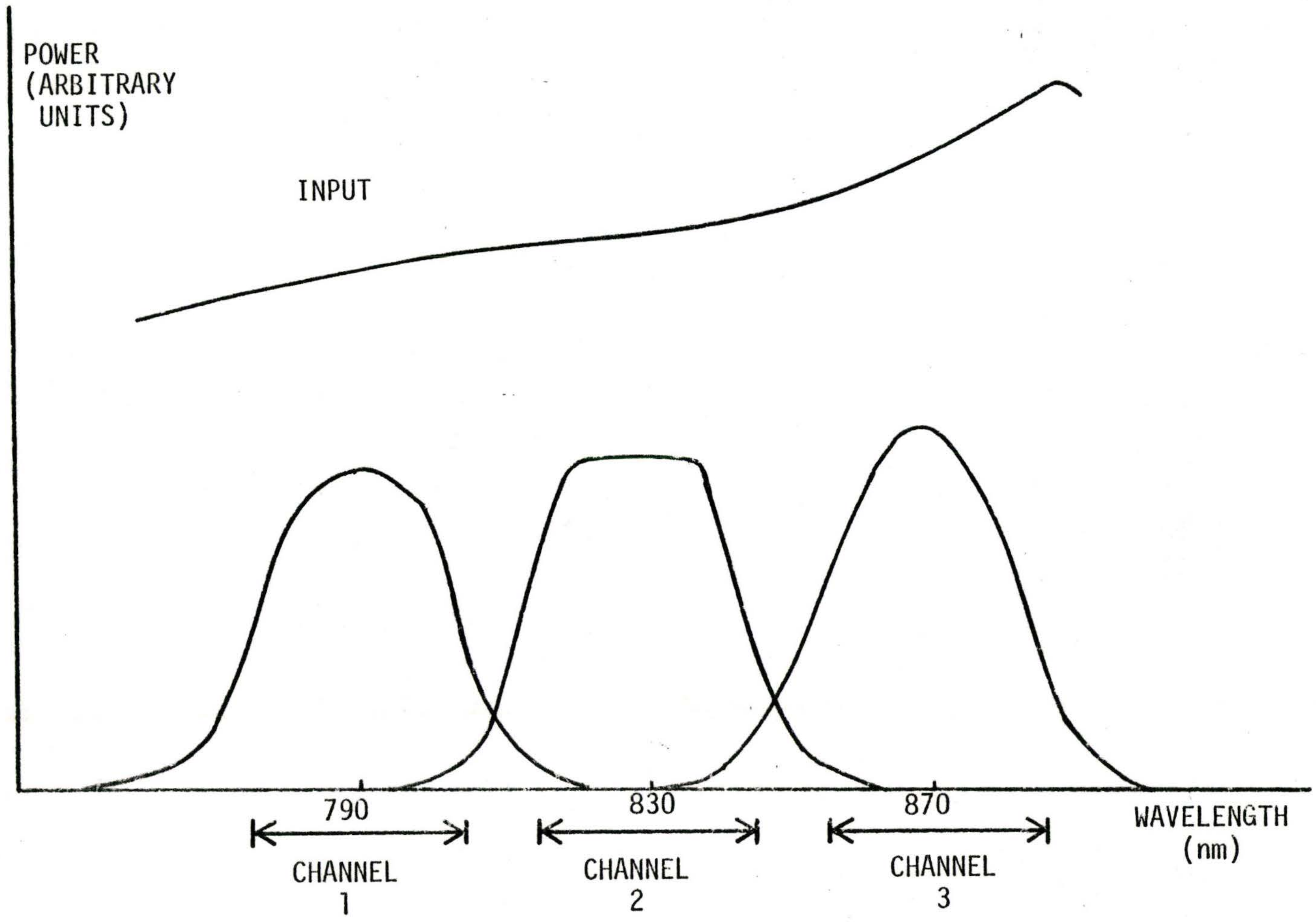


TABLE 3-1

3 Channel Device Components

Grating	gold coated replica, 1200 l/mm, blazed for 500 nm.
Lens	focal length 2.15 mm, 2 mm diameter (SLW 2.0 - .25)
Prism	apex angle 16.6°
Trunk Fibre	BNR graded index, 125 µm OD[*], 50 µm core with NA = .16
Channel Fibre	BNR step index 140 µm OD[*], 95 µm core with NA = .24

[*] etched to 110 µm

monitoring only the number two channel fibre which was approximately 25 μm out of line with the rest of the fibres. The losses of channels 1 through 3 are 2.2, 2.2 and 2.5 dB. The channels centre wavelengths match their nominal values within the limitations of the monochromator wavelength drive. The log of the output of the same device is given in Figure 3-7. The crosstalk, taken from Figure 3-7, is less than -10 dB at the channel edges and less than -30 dB at the channel centres. Crosstalk is measured with respect to the interfering channels peak output. The channel width of channel 2 is about 25 nm at the -1 dB points and 33 nm at the -3 dB points. The channels are wider than intended because a 95 μm core fibre was used instead of an 83 μm fibre. The crosstalk at the channel edges would be considerably reduced if the channel width was 30 nm, not 33 nm. Other devices tested as demultiplexers has losses ranging from 2.0 to 3.0 dB, the latter value only occuring on the device which was potted in epoxy.

The multiplexing performance of the three channel device was tested by injecting light into the channel fibres and measuring the output from the trunk fibre. The loss values ranged from 10 to 11 dB. The loss due to the mismatch between the high NA, large diameter input fibres and the low NA, small diameter trunk fibre is between 7 and 8 dB (see equation 4) depending on the diameter and NA assumed for the image of the input fibre. The remainder of the 10 dB loss (3 dB) can be accounted for by the lens, grating and any manufacturing errors.

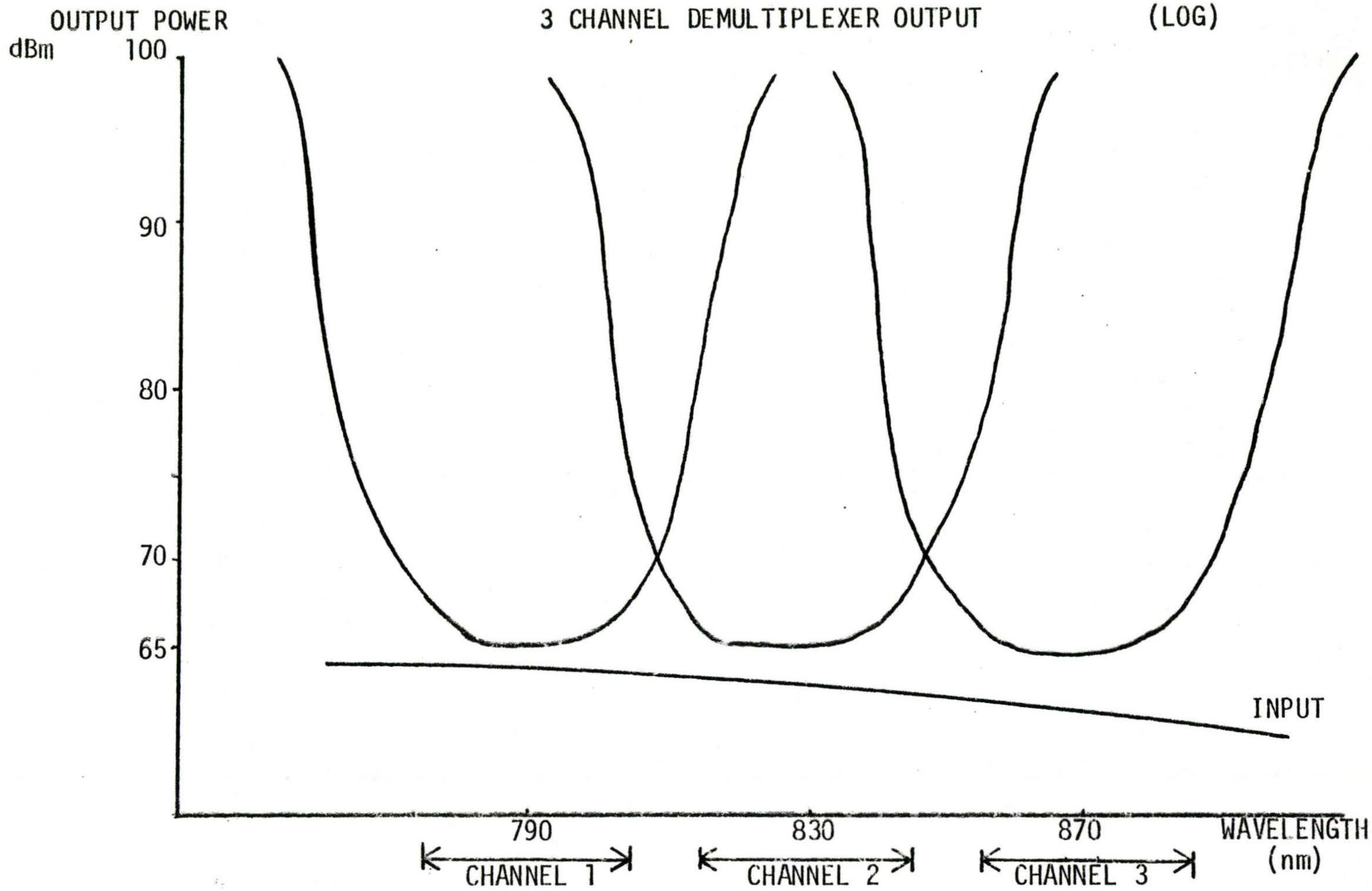

3 CHANNEL DEMULTIPLEXER OUTPUT
(LOG)
OUTPUT POWER
dBm
100
90
80
70
65
INPUT
790
830
870
WAVELENGTH
(nm)
CHANNEL 1
CHANNEL 2
CHANNEL 3

FIGURE 3-7

Experiments indicate that approximately 3 dB extra light is captured by the large fibre therefore the net loss is on the order of 7 to 8 dB.

Temperature tests have not yet been performed on the three channel devices.

CHAPTER 4

TWO CHANNEL MULTIPLEXER/DEMULTIPLEXER

The two channel multiplexer/demultiplexer is required to separate the short wavelength band (750 to 900 nm) from the long wavelength band (1100 to 1400 nm). It is shown schematically in Figure 4-1. The short wavelength information is always travelling in the opposite direction to the long wavelength information thus the two channel device is in a sense bidirectional. However, the device used at the subscriber end will be different to that used at the Central Office end to optimize performance as explained later.

Principle of Operation

The operation of the two channel device is similar to the filter device described briefly in Chapter 2. The operation will be explained here, in more detail, for the Central Office version of the device. The subscriber device functions similarly except that the signals flow in opposite directions. The two types of two channel devices are shown in Figures 4-2A and 4-2B.

In the Central Office device the short wavelength channel is an input and the long wavelength channel is an output. Short wavelength information entering via the short wavelength channel fibre is collimated by the Selfoc lens, reflects from the filter and is imaged onto the trunk fibre. Long wavelength light enters

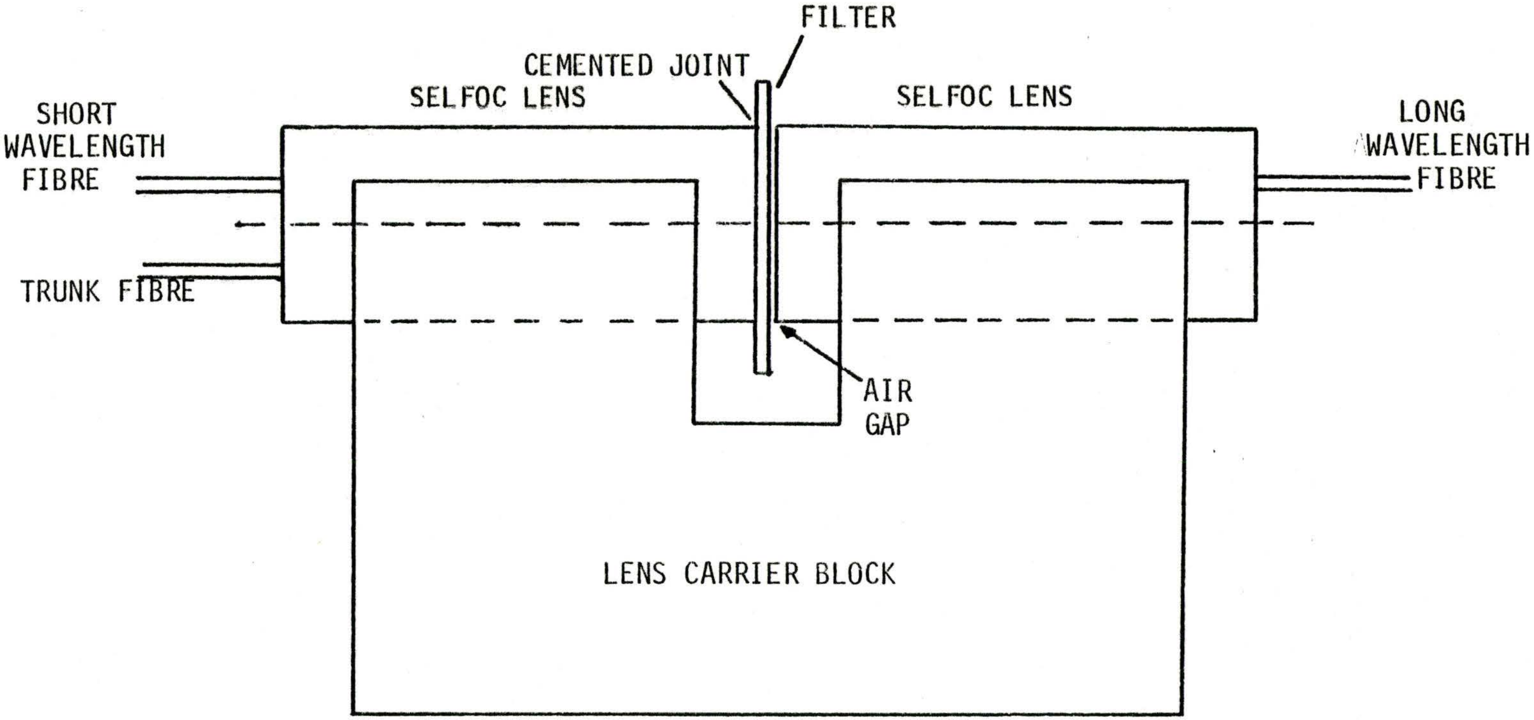
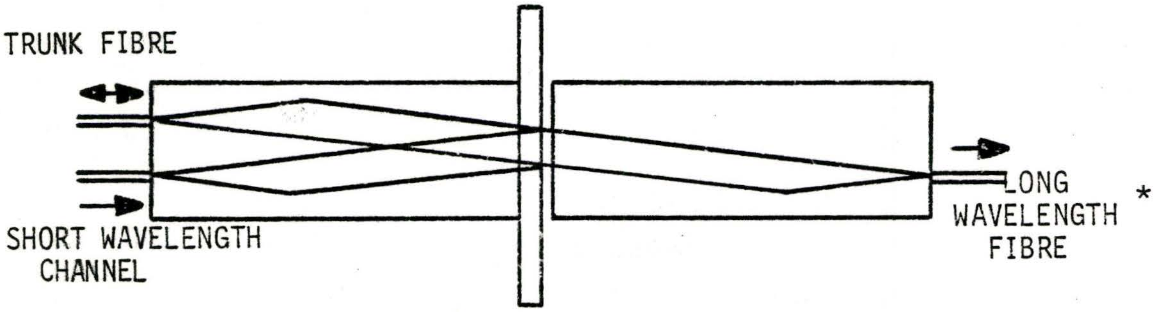


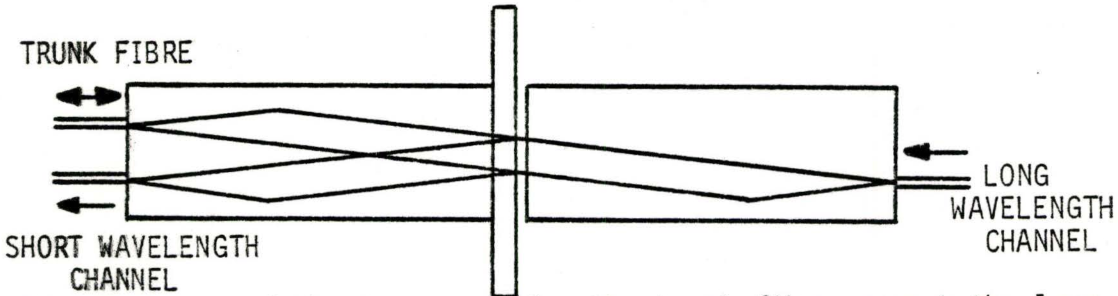
FIGURE 4-1
THE TWO CHANNEL DEVICE

FIGURE 4-2

A CENTRAL OFFICE DEVICE



B SUBSCRIBER DEVICE



All fibres are of the type used for the trunk fibre except the long wavelength channel fibre on the Central Office version (marked with an *) which is a large core step index fibre.

from the trunk fibre and is collimated by the first lens. It is transmitted by the filter and imaged onto the long wavelength channel fibre by the second lens.

The two channel device has no dispersive elements therefore the filter totally controls the device's spectral characteristics assuming that there are no noticeable absorption bands in any of the components.

Detailed Design

The most important element in the two channel device is the filter. The ideal filter characteristics, shown in Figure 4-3, are 100% transmission in the long wavelength band, 100% reflection in the short wavelength band and a very narrow transition region. Available filters have characteristics similar to those shown in Figure 4-4. In general the "ripples" in the transmission band become larger as the transition region is narrowed and long wavelength filters have smaller ripples for a given slope than do short wavelength filters(9). It is also generally true that the reflectivity of the filter in the stopband can be made larger than it's transmission in the passband(9). Thus the longpass filter gives the lowest loss for the short wavelength channel and lowest crosstalk in the long wavelength channel as required by the system considerations of Chapter 2.

The short wavelength channel fibre must be the same type as the trunk fibre since the short wavelength channel is connected

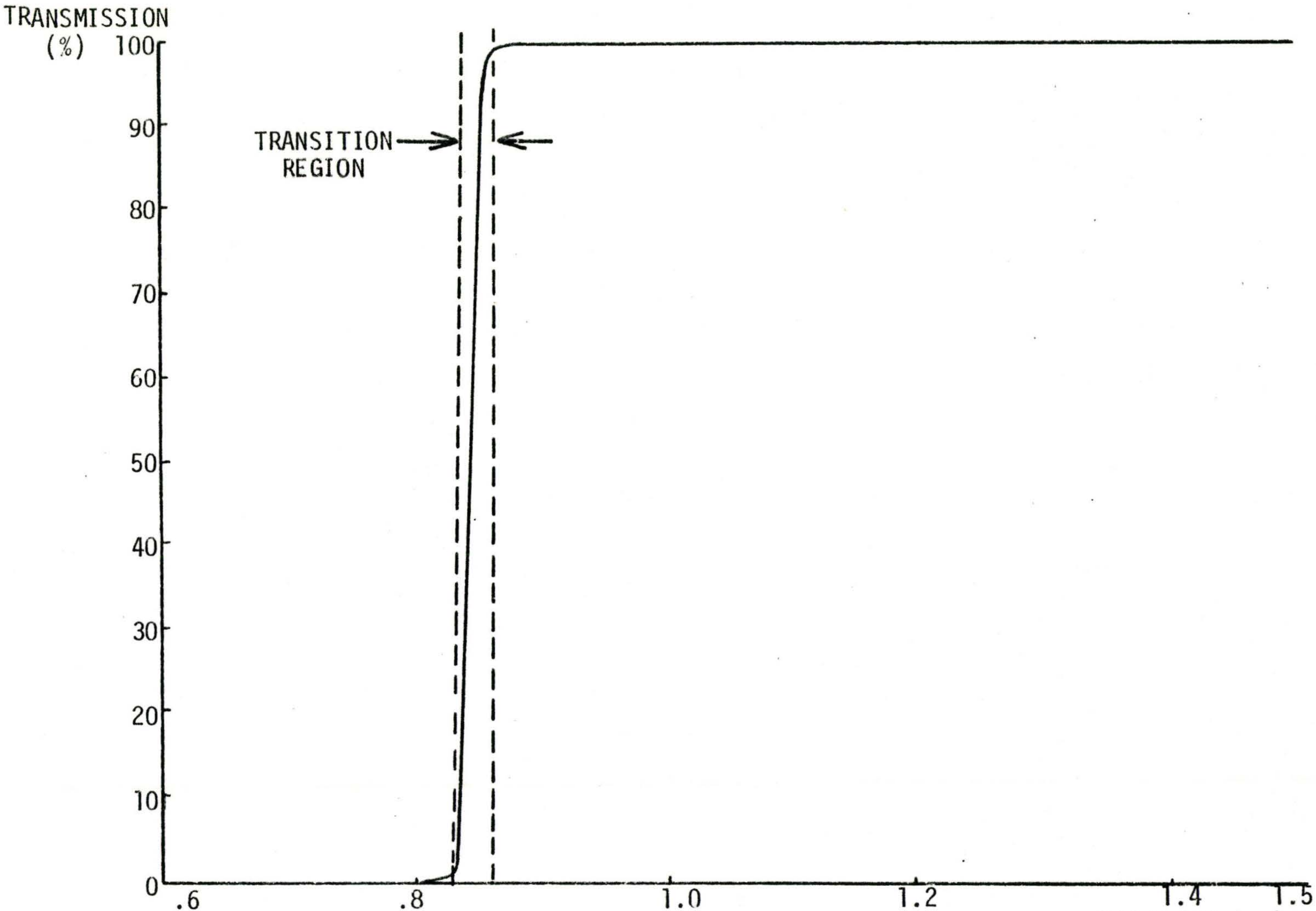


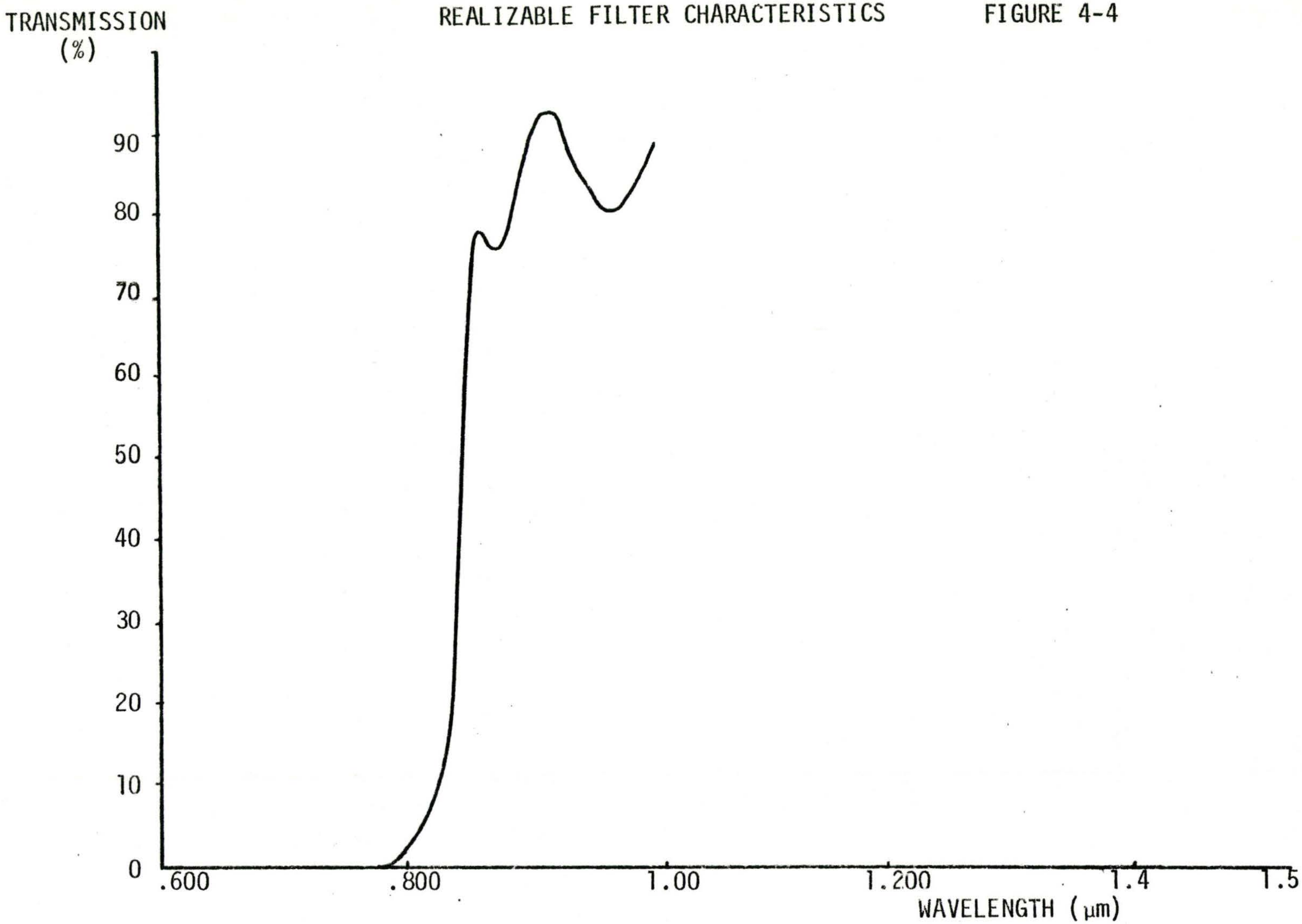
FIGURE 4-3 IDEAL FILTER CHARACTERISTICS

to the 3 channel device. The subscriber two channel device will also have the same fibre (as the trunk) for the long wavelength channel since it is an input. The Central Office device could use a large core fibre for the long wavelength channel since it is an output to a detector. Figure 4-2 shows the subscriber and Central Office versions of the two channel device as well as the fibre types and direction of signal flow.

Sources of Loss

The two major sources of loss in the two channel device, other than manufacturing errors, are the loss in the filter and the loss due to the lens. The latter is the major source of loss in the short wavelength channel. It results from a combination of the effects of lens aberration, which makes the image of the trunk fibre larger than the output fibre, and the "excess loss" believed to be a result of scattering. The excess loss is also discussed in Chapter 3. The loss due to the lens aberrations is expected (on the basis of other experiments) to be 0.5 to 1.0 dB. The loss due to the filter affects mainly the long wavelength (transmitted) channel. Multilayer dielectric filters have very little absorption but do, in the case of a long wavelength pass filter, have significant reflectivity in the passband. The filter reflection loss is approximately .33 dB at the transmission peak near 950 nm (see Figure 4-4). There are also Fresnel reflections at the gap between the filter and lens which appear as losses (approximately .36 dB) in the long wavelength channel. The filter and Fresnel reflection losses could appear

REALIZABLE FILTER CHARACTERISTICS FIGURE 4-4



as crosstalk in the short wavelength channel if other than silicon detectors were employed. The long wavelength channel also has the same loss due to lenses as the short wavelength channel.

The loss of the two channel device is wavelength dependent. This is because the available Selfoc lenses are optimized for 830 nm and exhibit considerable chromatic aberration which causes the focal point of a quarter period lens to be considerably off the back surface of the lens. The long wavelength fibre can therefore only be positioned for minimum loss at one wavelength and other wavelengths, which focus ahead of or inside the fibre, will suffer an additional loss.

Construction

The construction of the two channel device is relatively simple by comparison to the three channel (grating) device. The uncoated side of the filter substrate is cemented to a lens. Both lenses are then cemented into the lens carrier block so that there is a slight gap between the coated side of the filter and the second lens. The filter is not cemented to the second lens since it is not yet known whether the cement will change the filter properties. The trunk and short wavelength fibres are positioned on the face of the first lens. Light of approximately 830 nm wavelength, which is selected by a monochromator, is transmitted down the trunk fibre. The short wavelength channel is established by simultaneously moving the trunk fibre and the short wavelength fibre to maximize the short wavelength channel output. The trunk and short wavelength fibres are then cemented to the lens. The monochromator output is shifted to about 1300 nm and the long wavelength fibre is positioned to maximize it's output. It is then cemented in place. The lens carrier is then cemented into a brass holder which serves as the package base.

Alignment of the fibres of the two channel device (during construction) is relatively simple as only the output need be maximized; there is no adjustment of the channels spectral characteristics as these are controlled by the filter.

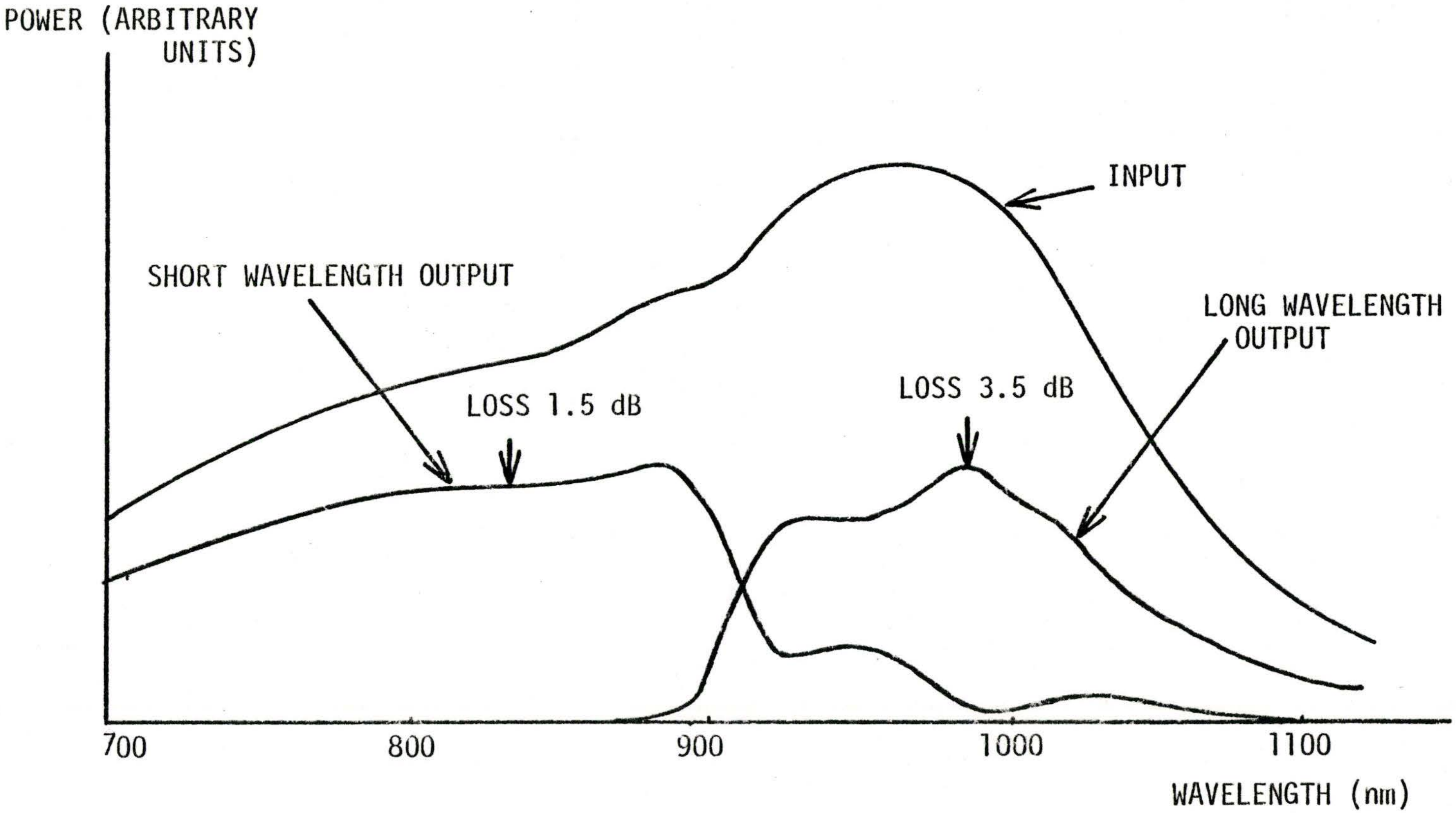
One two channel device has been constructed. This device was the type used at the subscriber end of the system and employs only 50 μm core graded index fibres. The lenses used were Nippon Sheet Glass SLS 2.0 - .25. The filter characteristic is that given in Figure 4-3. At the time of construction no germanium detectors were available so the long wavelength channel was aligned for 1000 nm and could only be tested to approximately 1100 nm.

Evaluation

The transmission of the long wavelength and short wavelength channels as a function of wavelength are shown in Figure 4-5. The transmission of both channels was measured by injecting light filtered by a monochromator into the trunk fibre and

FIGURE 4-5

TWO CHANNEL DEVICE PERFORMANCE



recording the output from each channel. The ripples in the passband can clearly be seen near 1000 nm. The short wavelength channel loss is 1.5 dB and the long wavelength channel loss is 3.5 dB. The crosstalk was not measured. The loss in the long wavelength channel is believed to be mostly the result of improper positioning as the fibres were not properly mode stripped during construction. It is expected that the performance of two channel device will be improved as a result of current efforts.

CHAPTER 5

CONCLUSIONS

The devices necessary to construct the WDM system described in Chapter 2 have been demonstrated. The measured characteristics of the two devices reported in Chapters 3 and 4 are summarized in Table 5-1. The insertion loss for two each of the devices reported would be 7 dB for the long wavelength channel and approximately 16 dB average for the short wavelength channels not including splicing loss. The loss in the short wavelength channel makes no allowance for the increase in source coupling efficiency which would be obtained by using a large core step index fibre to couple light from the source. Including this the short wavelength channel could be expected to exhibit an insertion loss of approximately 13 dB. The crosstalk for a system of two each of the reported devices adds up to less than -30 dB (-60 dB electrical) from the centre of any short wavelength to any other short wavelength channel and less than -10 dB from the edge of any short wavelength channel into any other short wavelength channel.

The reported losses, particularly for the short wavelength channels, are large and would limit the use of these devices to short links or to retrofitting of installed systems where some other components such as sources or receivers could also be upgraded. However, these devices are the first of their type made by the author (except for several three channel devices with

TABLE 5-1

WDM Component Losses

Three Channel (Grating Type)	Measured (dB)	Predicted (dB)
Subscriber (demultiplexer)	2.2, 2.2, 2.5	2.0
Central Office (multiplexer)	10→11**	10→11**
Two Channel (Filter Type)		
Subscriber Long Wavelength	3.5	2.1
Subscriber Short Wavelength	1.5	1.5
Central Office Short Wavelength	1.5*	1.5
Central Office Long Wavelength	3.5*	1.5

* Not measured but expected to have equal to or less than that of the subscriber device.

** There is no allowance made here for the increase in source coupling efficiency (see text).

different prism apex angles). It is certain that the two channel device suffers from misalignment resulting from improper mode stripping of the fibre cladding and that the three channel device has non-optimum performance as a result of the fibres being out of line in the fibreholder. There are also improvements which could be made to the design of the multiplexer and in the construction of all of the devices. These are discussed in the following section.

Improvements

One method which should reduce the loss and greatly reduce the variation of loss from channel to channel of both types of devices would be to improve the method of aligning groups of fibres. Currently the fibres are first cleaved and then cemented into a fibreholder (3 channel device) or cemented side by side (2 channel device). With these processes it is difficult to keep the fibre ends clean and aligned. A better method would be to form the fibres into a "ribbon", cast them rigidly in epoxy and then polish their ends flat. Any slight scratches left by the polishing would be index matched by the epoxy which holds the fibres to the lens. It is expected that by polishing the fibres the loss of all three channels of the grating device could be 2.0 dB or less (as mentioned before some early devices have had one channel with 2.0 dB loss). The two channel device should benefit from having the trunk and short wavelength fibre polished. However, no quantitative reduction in the loss can be predicted.

The loss of the long wavelength channel of the two channel device would be reduced by at least .35 dB by cementing the filter to the second lens. It is estimated that an improvement of approximately 0.5 dB is possible when the long wavelength channel is properly aligned and a further 0.5 dB improvement could be made by using a large core step index fibre for the long wavelength channel of the Central Office two channel device.

Table 5-1 also summarizes the losses predicted for the two and three channel devices after improvments in the construction process and optimization the performance of the two channel device (at the central office end). The predicted insertion losses have been reduced to 4 dB in the long wavelength channel and to 15.5 dB in the short wavelength channels (or 12.5 dB if 3 dB is assumed for the increase in source coupling efficiency).

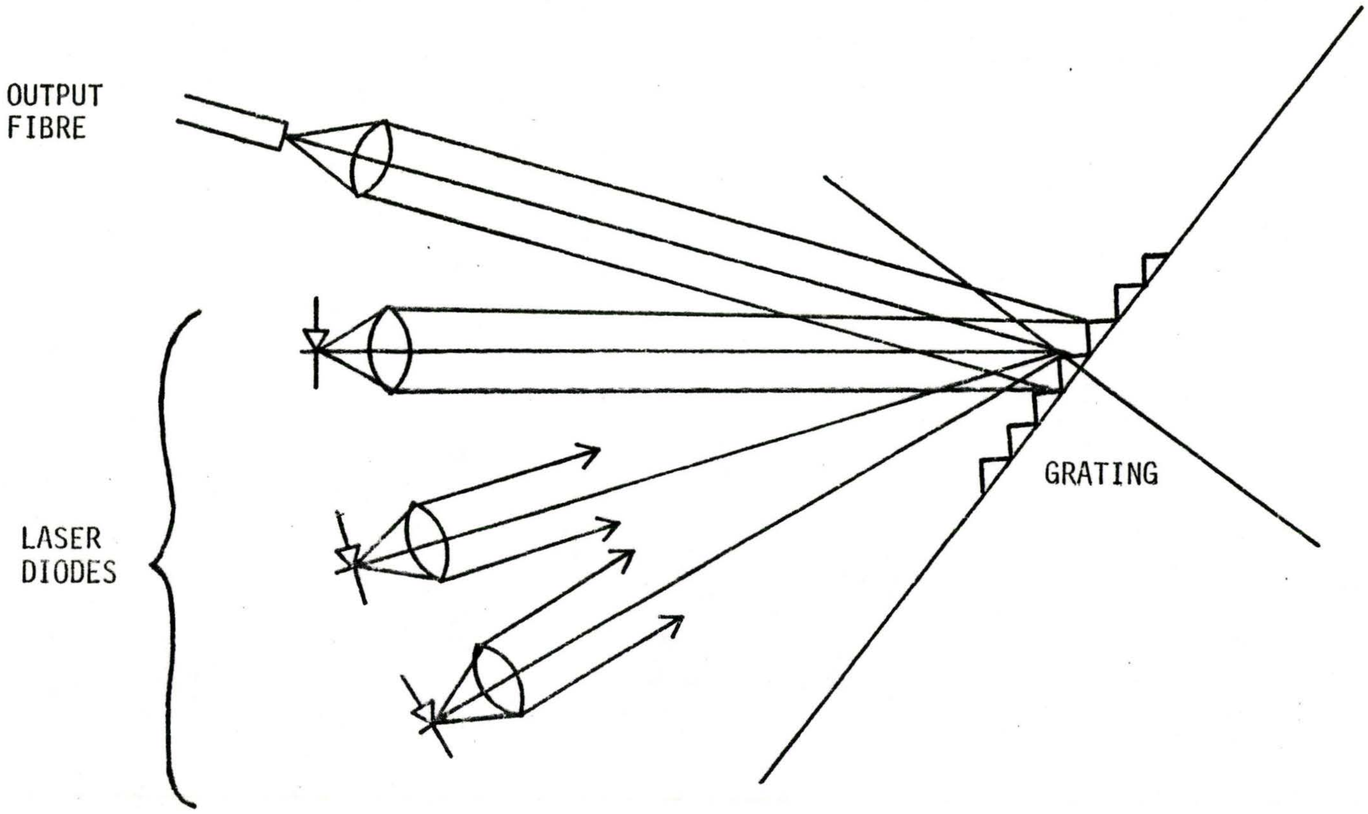
The bulk of the loss in the short wavelength channels is caused by the multiplexing of the three channels at the Central Office end of the system. Approximately 6 dB of this loss is a result of the input fibres being larger than the trunk fibre. However, that requirement only pertains if the multiplexer must have a spectral response such as that given in Figure 2-3A. Other multiplexers which combine sources together, regardless of the spectral content of the sources, could be expected to have much better performance. An example of this type of device is the twisted fibre combiner. In this device three fibres are twisted together and fused which causes the light in the fibre cores to mix. G. Duck[8] has demonstrated that this type of a device can multiplex three sources with a loss of 6.0 dB. It has a minimum loss of 4.8 dB (that is at most 1/3 of the input light will be coupled into the output fibre) if the same fibres are used for inputs and the output. Similar devices can be constructed by using 3 short focal length and 1 long focal length lens[4] but, do not have any advantage in performance and might cost significantly more. The minimum loss of 4.8 dB for multiplexing only applies if the sources are coupled into the same fibre type used for the multiplexer output.

A lower loss, although less easily constructed, grating multiplexer could be fabricated by multiplexing the laser diodes directly into a fibre and not using a fibre between the laser and the multiplexer as shown in Figure 5-1. The inefficiency of the grating, aberrations of the lenses and light not captured by the lenses and fibres due to NA mismatch would cause a loss of which is expected to be less than 3 dB (relative to the coupling of the laser directly to the output fibre). It retains the advantage of spectrally filtering the inputs. A recently reported[10] filter type multiplexer has a loss of approximately 2.0 dB but no information on the fibre type is given. It seems likely therefore at a three channel multiplexer with a loss of 3 dB or less can be fabricated.

Development of the devices reported, particularly the three channel multiplexer is expected to allow construction of practical WDM systems in the near future. These will allow more efficient utilization of the information carrying capacity of

FIGURE 5-1

IMPROVED MULTIPLEXER



optical fibres with a consequent reduction in system cost. The gain may be even larger when the 1.1 to 1.5 μm spectral region, where fibres have minimum loss and dispersion, is used more extensively.

APPENDIX A

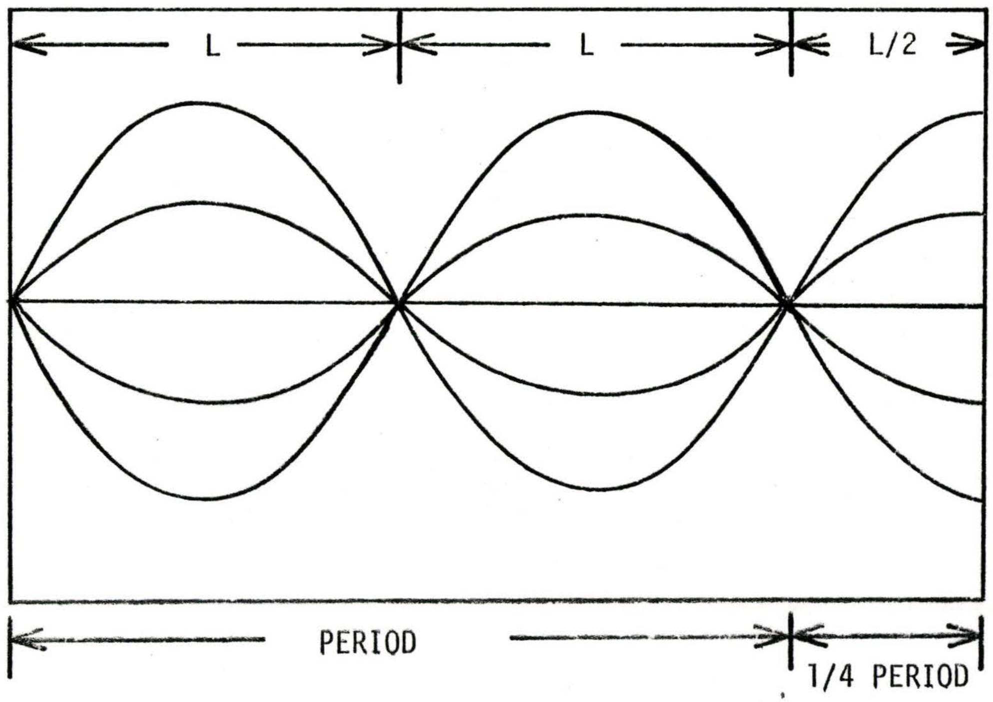
GRADIENT INDEX LENS

A gradient index lens obtains its focussing power from a radial change in the index of refraction not from an abrupt change of index at a curved boundary. The gradient index lens is very similar in principle to a graded index fibre but does not require a cladding layer. Because of the lack of a cladding, gradient index lenses are made by ion exchange on the outside of a rod not by soot deposition on the inside of a tube. The only commercially available gradient index lenses known to the author are the "Selfoc" lenses manufactured by Nippon Sheet Glass Company. Reference 7 gives detailed information on these lenses.

The path which a light ray follows in a Selfoc lens is determined by the index profile of the lens. Rays entering on axis follow the nearly sinusoidal paths shown in Figure A-1 while off axis rays follow skewed sinusoidal paths. All rays lauched from a point focus back to a point after passing through a distance "L" or any integer multiple of L (see Figure A-1). The distance 2L is a full period of the sinusoid and a piece of gradient index rod of length 2L is known as a full period lens while a piece of gradient index rod of lentgh L/2 is called a quarter period lens etc.

FIGURE A-1

RAY TRACE IN A GRADED INDEX MEDIUM



One of the most useful features of the Selfoc lens is that the faces through which light enters and exits are flat. An object can therefore be placed against either face of the lens and cemented to the face.

The imaging properties of a lens depend on its length. With a object placed against the entrance face of a full period lens an erect, real, unit magnification image will be formed on the exit face whereas under the same conditions a quarter period lens forms an image at infinity, ie. it collimates the light from a point source.

Selfoc lenses are specified by numerical operture (NA) not f/# as used for conventional lenses. The two specifications are approximately related by:

$$f/\# = 1/(2.NA) \tag{A-1}$$

The NA of a Selfox lens is a function of the radial position on the lens and falls to zero at the edge of the lens[7]. Therefore only on the optical axis does a Selfoc lens have a high NA or, equivalently, low f/#. The Selfoc lens can be modelled as having two principal planes and a focal length in exactly the same fashion as a conventional lens.

The quarter period Selfoc lens was used as a collimating element in all of the devices reported in this thesis because of its unique combination of properties, in particular the low f/#, small size and practicallity of cementing fibres to the lens faces.

BIBLIOGRAPHY

1) Tomlinson, W.J. "Wavelength Multiplexing in Multimode Optical Fibres", Applied Optics, 16, 2180 (1977).

2) Aoyama, K. and Minowa, J. "Optical Demultiplexer for a Wavelength Division Multiplexing System", Applied Optics, 18, 1253 (1979).

3) Kobayashi, K. and Seki, M. "Micro-Optic Grating Multiplexers for Fibre-Optic Communications "Proc. Optical Fibre Communication, March 7, 1979, Washington, DC.

4) Miki, T. and Ishio, H. "Viabilities of the Wavelength-Division-Multiplexing Transmission System Over an Optical Fibre Cable", IEEE Trans. on Communications, Comm. 26, 1082 (1978).

5) Kobayashi, K. et al, "Micro-optic Devices for Fibre Optic Communications, Fibre and Integrated Optics, 2, No. 1, Crane, Russak and Co., 1979.

6) Bausch and Lomb, Diffraction Grating Handbook, Jan. 1977.

7) Nippon Sheet Glass Co., "Selfoc" Single Microlens, April 1977.

8) Duck, G., Private Communication, Bell-Northern Research.

9) Bertram, B., Private Communication, Ontario Research Foundation.

10) Nosu, K. et al "Multireflection Optical Multi/Demultiplexer Using Interference Filters", Electronics Letters, Vol. 15, No. 14, 5 July 1979.