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Study of Methods of Optical Signal Separation using Passive Optical Fibre Devices

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Abstract

This report describes the project on studying various methods of separating a narrow band optical signal from a broad band source by using passive optical fibre devices. In other words, a notch filter is to be designed to avoid coherent intereference effect in an optical fibre system having a alrge path difference. Four methods have been suggested to be built and tested. The first was done by using a grating monochromator, the second by a fibre grating, the third by a long coupling length optical coupler and the last one using a chemical substance. Out of four, only the first three was actually carried out. The fourth method was skipped due to high toxicity in the chemical substance which needs extremely high precautions and careful steps in order to conduct the experiment. The experiment was aimed to block the narrow band light source at wavelength centred on 1550 nm ± 50 nm. It was found out that the second method which used fibre grating turned out to be the best way in achieving this aim.

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Acknowledgements

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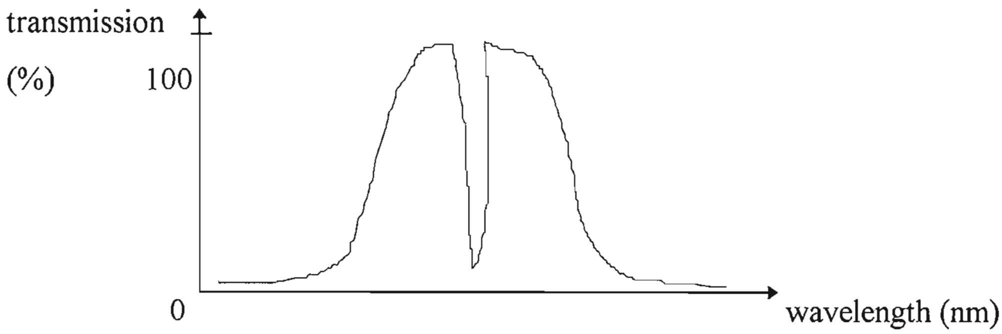
1 Introduction

One of the advantages that an optical fibre offers to the world today is its availability to transmit multiple information using different wavelengths using one path. This technique is known as wavelength division multiplexing (WDM) and it has increased the uses of optical fibres in telecommunication and sensing applications. WDM needs the lights to be able to travel at different wavelengths which provide several channels of transmission. Therefore, there is a need to have devices that can separate the light to travel at wavelengths of interest. The obvious way to achieve this requirement is by using filters. Filters are devices that can allow and stop some wavelengths to be transmitted and four method of designing filters are illustrated in this project.

The aim of this project is to design filters which will remove a narrow band signal from a broad band signal in an optical fibre system. The separation of the signal is very important as it avoids the coherent interference effects in optical fibre systems having a large path difference. Basically, the filter is a notch type which has the following basic characteristic:



There are four types of filter which have been suggested to be prepared and tested:-

1. A Notch filter, using grating monochromator;
2. A Notch filter, using fibre grating;
3. A Filter using long coupling length optical coupler; and
4. A Filter using absorbing chemical substance.

This project was on sensor, where a broad band light source was to be used with an equal path (Sagnac) interferometer. For this sensor, a broad band light source was suitable, as it avoids interference from reflections having unequal path to its optical detector. However, one option of the system also contained a laser source with a Mach-Zender interferometer. We require to suppress this narrow band laser source at the Sagnac detector. For the Sagnac system, an LED light source centred on 1550 nm ± 50 nm wavelength was used, initially presented in an optical fibre of single mode type with 9.4 μm core diameter. The spectrum behaviour of the filter was investigated using a spectrum analyser. Throughout this experiment, the spectrum analyser used was a Hewlett Packard Optical Spectrum Analyser 70004A.

2 Background Information

2.1 Overview on Optical Fibres

Optical fibres are thin cylinder dielectric waveguides which are usually made of silica glass. They consist of a central cylindrical region called the core, surrounded by an outer dielectric material of lower refractive index called the cladding which of typically 125 μm in diameter. The cladding is normally made from pure silica glass but the core is doped with other material usually germanium to raise its refractive index. The physical diagram of a typical optical fibre is in Figure 1:

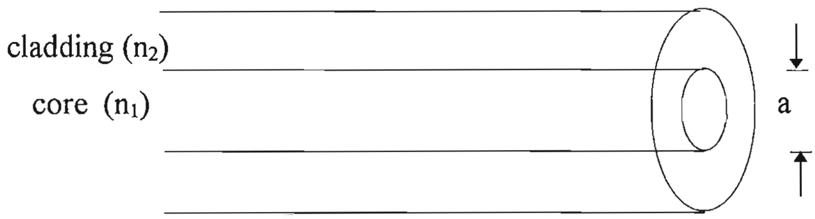


Figure 1: The geometry of an optical fibre

Light propagation in optical fibres is based on the following principles:

- Light is trapped in the core area by total internal reflection at the core-cladding interface.
- Light propagates in the form of distinct modes.

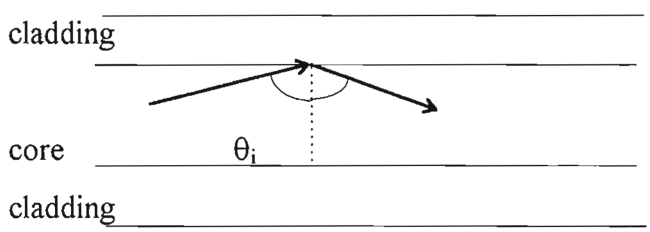


Figure 2: Ray picture showing total internal reflection condition

To satisfy total internal reflection condition,

$$\sin \theta_i > n_2 / n_1 ;$$

where θ_i is the critical angle below which total internal reflection will not occur.

Depending on the shape of the refractive index variation along the fibre diameter, the optical fibres are distinguished into two main categories, that is,

1. Step-index fibres, which refractive index is constant over the core and the cladding but changes abruptly at the core-cladding interface; and
2. Graded-index fibres, which refractive index is constant over the cladding but changes gradually over the core.

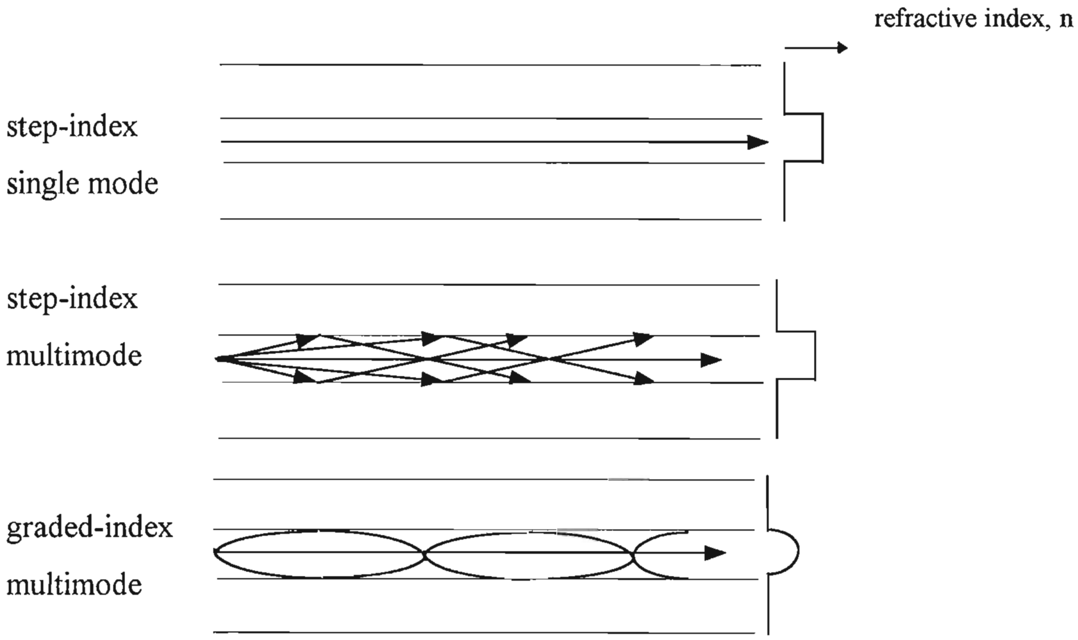


Figure 3: Type of optical fibres with their refractive indexes and modes

There are two types of optical fibres: single mode fibres and multimode fibres. A single mode fibre is a fibre which supports only one waveform which is called as mode to be propagated within the fibre. A multimode fibre allows many modes to propagate inside it and due to this property, it has a larger core than a single mode fibre. The total number of mode that can be carried by a fibre is given by its normalised frequency parameter, which is also known as V-number, and defined as follows:

$$V = k_0 a\sqrt{n_1^2 - n_2^2}$$
$$V = \frac{2\pi}{\lambda} aNA$$

where λ = the operating wavelength;

a = the radius of the core;

NA = the numerical aperture of the fibre.

n_1, n_2 = the refractive indices for the core and the cladding respectively.

k_0 = the propagation constant

The numerical aperture of the fibre is the sine of the maximum angle of incidence θ_i that guarantees total internal reflection at the core - cladding interface.

$$NA = \sin \theta_i = (n_2 - n_1)^{1/2}$$

In optical fibres, light attenuation is caused by three factors: absorption due to impurities; Rayleigh scattering; and microbending. However, optical fibres still offer enormous advantages to the technology and some of them are lower attenuation loss, small in size, light in weight, large data rates for communications, immunity from electromagnetic interference and high bandwidth signal over long distances with low signal dispersion.

2.2 Essential Principles

Most optical fibre systems do involve some form of multipath operation between the source and the final receiver. Therefore, there is a potential for interference effects to occur. In order to tackle this phenomena, basic concepts like interference and coherence which correspond to the light source need to be addressed.

2.2.1 Interference of light

Interference can be referred to as a combined effect when light waves crossing each other. To explain the interference, the principle of superposition is used; that is, the amplitude at any crossing point or instant is the sum of the instantaneous amplitude of individual waves. The result of adding two waves at a point is dependent on the phase shift between the two waves. Therefore, the resultant sum is minimum or zero for equal amplitude when phase shift is 180° (opposite phase) and it is maximum when phase shift is zero (in phase condition). If the phase shift is between 0° and 180°, the resultant sum takes the value between the maximum and minimum. Therefore, interference effects can only be observed if the phase relationship between the two light waves is constant. In order to maintain this constant phase relationship, it is usual to get the two waves from a single source by dividing the wave to produce the two phase related beams.

Generally, interference can be classified into two types: constructive and destructive. Constructive interference is obtained when the amplitude of the individual wave adds; whereas, the destructive interference occurs when the resultant amplitude is zero. Alternatively, in terms of path difference, it is constructive when path difference from source to the point being considered is zero or an integer multiple of wavelength ($n\lambda$). And, when the path difference is a half wavelength or as odd multiple of half wavelength (i.e. $n\lambda/2$) it is destructive. However, it should be noted that if path difference is large enough, interference will not take place. This difference in optical path length also causes the phase shift between the two points as explained earlier .

2.2.2 Coherence

One of the critical parameters in matching the light source in an optical fibre system is coherence. Coherence is a quantity that implies phase correlation between the points in a light beam. The light is said to be coherent when it is in-phase and incoherent when there is no phase correlation. However, in reality light lies in between these two categories and known as partially coherent. There are also two type of coherence: spatial and temporal.

Spatial coherence is a measure of the phase correlation between two points on the same wavefront. In other words, it is correlated in space.

Temporal coherence is a measure of similarity between wavefront separated in time. It is measured in frequency term and reflects the narrowness of the frequency spectrum of the wavefront.

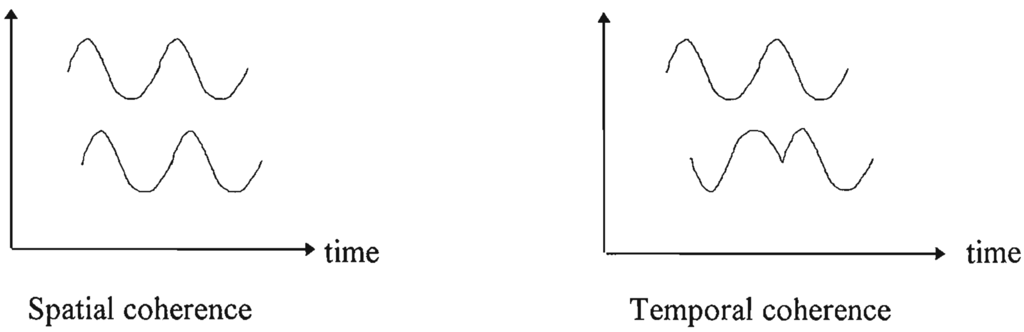


Figure 4 showing the spatial and temporal coherence

When considering a light source, we need to consider the coherence length of the source. Coherence length refers to the maximum length separating two different wavefronts that can be made to produce interference fringe pattern. Therefore, beyond a certain path distance, no interference fringe will be observed. Thus, the path difference less than the coherence length is required to observe the interference effects. Mathematically, the coherence length is defined as

$$\Delta l = c.\Delta t$$

where Δl is the coherence length, c is the velocity of light and Δt is the coherence time.

Thus, it is necessary to know the path difference of a system and the coherence length of the light source being used in order to determine whether coherent interference effects is appreciable or not. To avoid the interference effects in a system having path difference, we have to ensure that the difference of optical path is greater than the coherence length of the light source.

2.2.3 Light sources

Light source also plays an important role in an optical fibre system. The choice of which light source to use depends on the operating principle of the system. The chosen light source must be able to couple a useful amount of power into the fibre and also capable of operating with the required bandwidth of the system. The most used light sources in optical fibber systems are the semiconductor devices; that is, the light emitting diodes (LEDs) and the laser. Besides these two popular sources, there are other useful light sources such as white light source which has a very broad band source that can cover a very large range of wavelengths.

2.2.3.1 Light Emitting Diodes (LEDs)

LEDs are incoherent light sources. They make use of the incoherent light emission from spontaneous recombination of carriers; that is either holes or electrons, injected into an appropriate region across a forward-biased p-n junction. The device structure is arranged to efficiently take the light out of the recombination region of the semiconductor and get into the optical fibre. Physically, LEDs are multilayer devices based on the following semiconductor materials: GaAs (900 nm), AlGaAs (650-850 nm), GaInAs (1200-1700 nm) and InAsP. The number in the brackets is its emission wavelength which coincides with low fibre attenuation spectrum.

There are two kinds of structure used for LEDs: the first is the surface-emitting and the second one is the edge-emitting (ELED). The ELED structure has higher optical power and is also the basis of producing semiconductor laser diode.

The light in LEDs is modulated by varying the current applied to the diode. Some of the characteristics of the optical emission from LEDs are very short coherence length, small optical output power, large spectral width (20 to 100 nm) and small modulation bandwidth. LEDs require only a simple driver circuitry, have a long operating life and inexpensive. Due to these properties LEDs usually are used in a short distance system as a broad band source to couple lights into multimode fibres. Because of its large spectral width, LEDs are not usually used in single mode fibre applications.

2.2.3.2 Lasers

Laser is an acronym which stands for Light Amplification by Stimulated Emission of Radiation. The basic requirements for a lasing action are:

- there exists an active medium that emits radiation in the required region of electromagnetic spectrum;
- a population inversion must be created in the medium; and
- there is a resonant cavity, so that optical feedback occurs at ends of medium to give highly collimated and monochromatic beam.

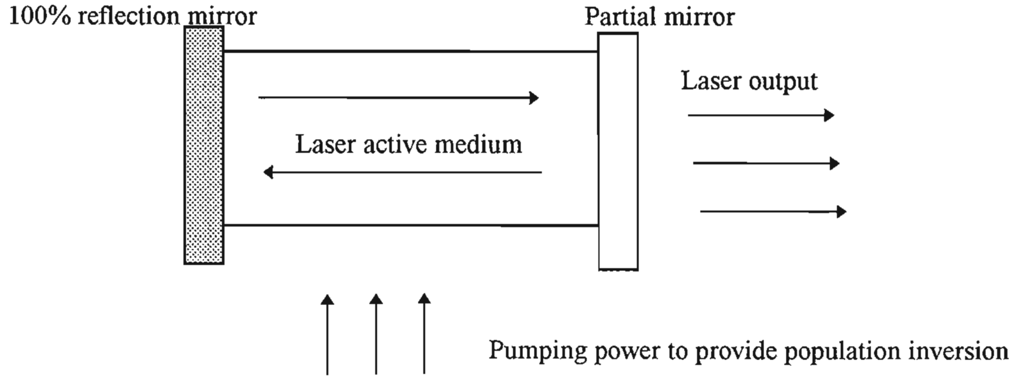


Figure 5: Diagram of laser action

There are many kinds of lasers: semiconductor, solid-state (crystal), gas, and dye; but the most useful one for optical fibre applications is semiconductor laser diode. Laser diode emitters are based on coherent light emission due to stimulated recombination of the injected carriers by internal light. The difference between the laser and the ELED is that there is a form of resonant cavity which provides optical feedback.

Some of laser properties are directional radiation pattern, very narrow spectral width to give highly monochromatic beam, high peak output power that provides high brightness, high modulation bandwidth and has long lifetime. The laser source is also highly coherence where its coherence length depends on its mode structure and the individual modes linewidths.

All in all, lasers are commonly used for coupling light into single mode fibres due to its narrow spectral width and in applications where high power and single mode operation are needed. However, for this project a broadband source is required and this can be either a white light source, a broad band ELED source or laser with a very large spectral width.

3 Experiment 1: **A Notch Filter Using Grating Monochromator**

3.1 Introduction

This method utilises the diffraction theory in optics. The centre of the unwanted wavelength is simply blocked by a thin wire of diameter 10 µm which is placed in front of the receiver fibre to give the required band stop and hence, a notch filter is obtained. The grating monochromator is used to select the wavelength of the reflected light which will then be blocked by the wire.

3.2 Theoretical Background

The principle of operation is that the light is launched through a single mode fibre and then focused onto a reflection grating by using a small thin lens. The single mode fibre has 125 µm in diameter with 9.4 µm core. The small lens is a plano-convex convergent type of 5 mm diameter and is placed in its focal length from the fibres.

The plano-convex convergent lens — The reflection grating

Figure 6: The schematic diagram of the lens and grating used

The grating used in this experiment has the dimension 12.5 mm diameter x 12.5 mm width x 5 mm thickness. It is a 600 lines/mm grating and has a blaze wavelength of 1.6 µm. This reflection grating is made by ruling fine parallel lines on a polished metal plate. The space between the ruled lines is capable of reflecting light while the ruled lines will not. This grating is rotatable in two directions: the first is normal rotation about the grating surface and the second rotation is perpendicular to the plane of incident lights. This rotation also provides the selection of wavelengths that is different angle of rotation of the grating corresponds to the different value of wavelength being reflected.

The grating is placed in the collimated region of the length using Littrow Configuration. Under this configuration, the incident light has the same path as the reflected light. Therefore, the diffraction equation *(sin i + sin r)* = λ / na, is simplified as

$$2 \sin r = \frac{\lambda}{a} \qquad \text{(since i = r)}$$

where i = angle of incidence

r = angle of reflection

a = grating

λ = wavelength of light being used

The angle of incident that will give Littrow Configuration is calculated using the modified diffraction grating at λ_1 = 1555 nm and the value is found to be θ = 27.8° with respect to the normal of the grating.

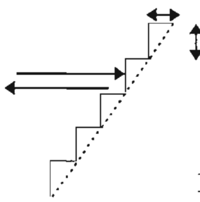
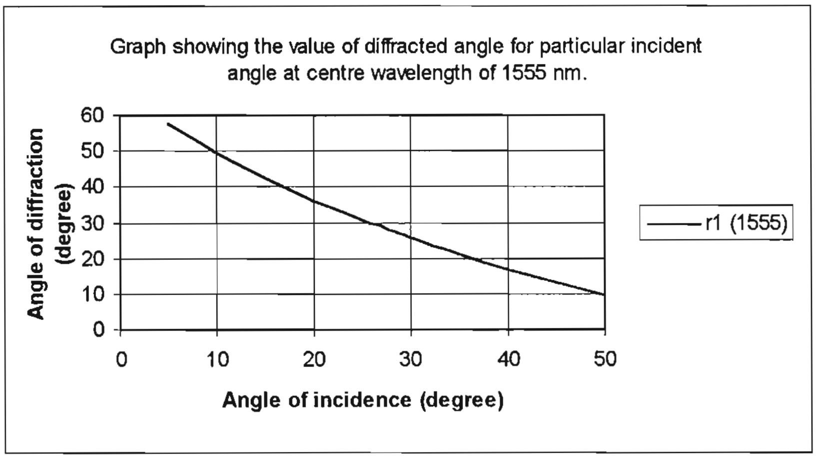


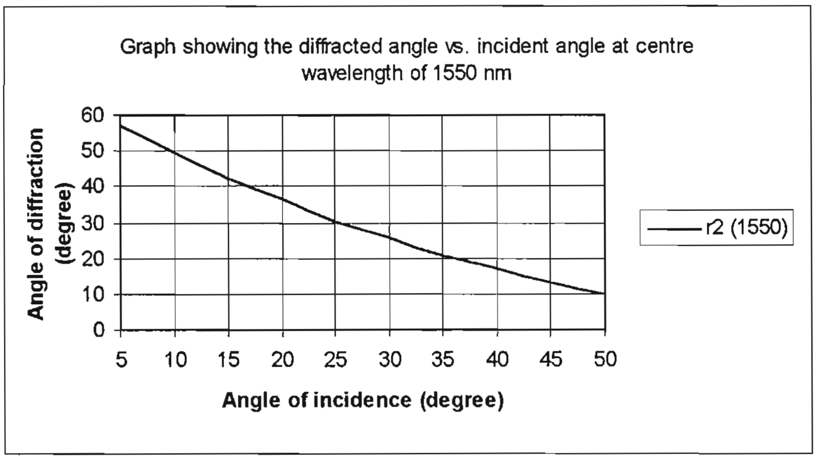
Figure 7: Littrow configuration of the grating

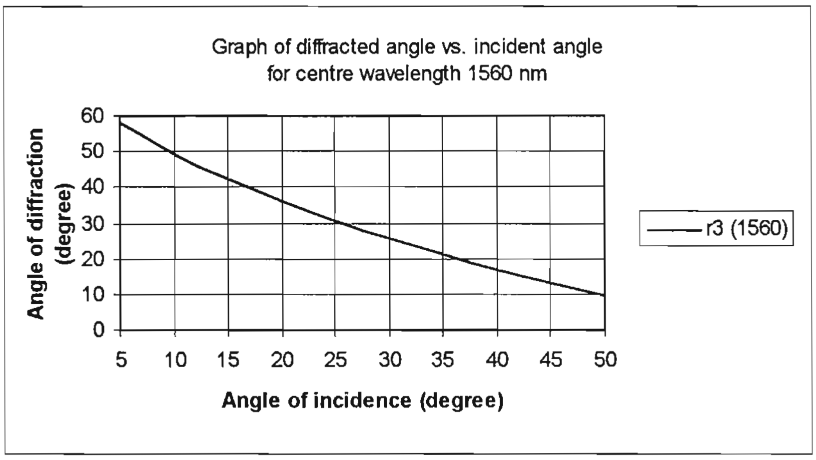
Calculations of the diffracted angle which corresponds to a particular incident angle also have been made using the diffraction equation above for three different values of centre wavelength: λ_1 = 1555 nm, λ_2 = 1550 nm and λ_3 = 1560 nm.

Angle of incident	λ_1 (1555 nm)		Angle of incident	λ_2 (1550 nm)		Angle of incident	λ_3 (1560 nm)
5	57.8		5	57.4		5	58.1
10	49.4		10	49.7		10	49.1
15	42.4		15	42.2		15	42.6
20	36.2		20	36.4		20	36
25	30.7		25	30.2		25	30.6
27.8	27.8		30	25.8		30	25.5
30	25.7		35	20.9		35	21.2
35	21.1		40	17		40	16.7
40	16.9		45	12.9		45	13.2
45	13.1		50	9.8		50	9.4
50	9.6						

The equivalent graphs for these three different values of centre wavelength are then plotted.







The bandwidth of the reflected wavelength is calculated using the following formula:

$$\Delta \nu = \frac{\nu}{qN};$$

No ! !

where $\Delta\nu$ = the bandwidth of the light,

ν = the wavelength of the light,

q = the order of the spectrum,

N = the total number of lines ruled on the grating.

Therefore, in this experiment taking ν = 1550 nm, q = 1 and N = 600 lines/mm, we will get the expected bandwidth of $\Delta\nu$ = 2.58 nm.

The position of spotted focused light from the lens on the grating can be found by using the following formula:

$$\rho = f \tan \theta$$

where f = focal length of the lens

ρ = vertical distance of the point from the optical axis

θ = the angle of light to the focal plane.

The schematic arrangement of the experiment is shown in Figure 7 below:

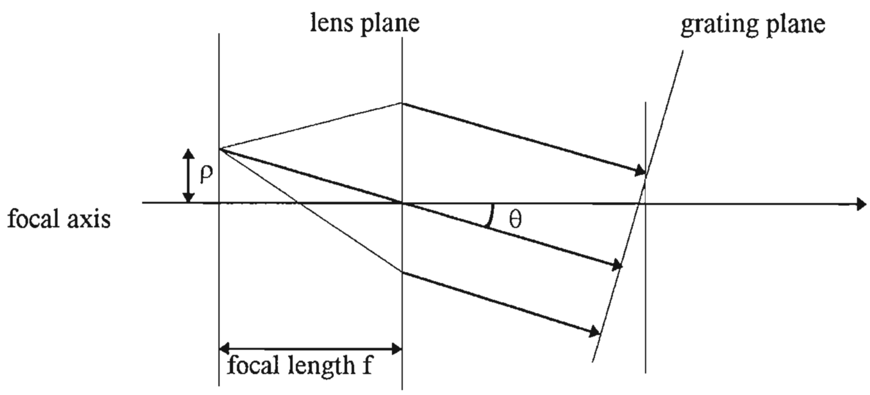


Figure 8 : Ray picture showing the travelling light waves in the experiment

The reflected light then enters a second fibre which is placed next to the first fibre. This second fibre is a multimode type with 82.5 μm core diameter. A thin wire is placed in front of the multimode fibre to block part of the light beam in the narrow region desired by the notch filter.

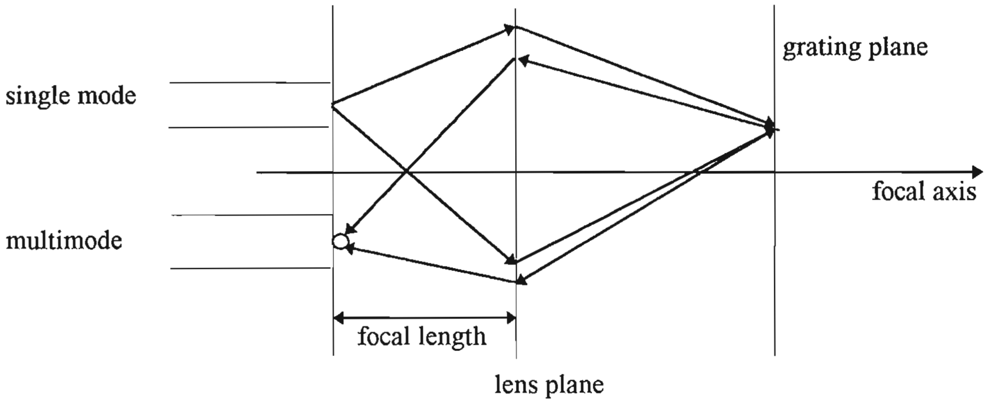


Figure 9: The schematic arrangement of the set-up of the experiment

3.3 Experimental Method

First, both single mode and multimode fibres were glued together side by side in a capillary tube of 500 µm diameter. Then, the surface of the capillary tube was polished to get a flat surface. After that, a small thin wire of 10 µm in diameter was placed across the centre of the multimode fibre. Looking under the microscope, the fibre location is shown in Figure 10 below:

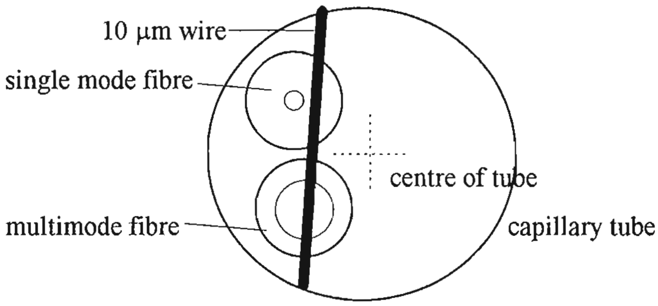


Figure 10 : The sketch of the position of the two fibres inside the capillary tube.

The fibres are offset from the central line of the tube by 125 µm. Although the wire is centrally placed across the multimode fibre, it is offset from the core of the single mode fibre. This offset of wire introduces a problem of centralisation in the filter optic. To compensate this, an additional rotation of the tube about tube axis was made which resulted in the wire was placed horizontally instead of vertically relative to the focal axis.

The capillary tube was then put in a rectangular holder which has the lens glued in front of it. This tube is movable in order to change the distance between the lens and the fibre. When the tube is in the desired distance at focal length, a screw is used to tighten the position of the tube. The diagram of the arrangement is shown below:

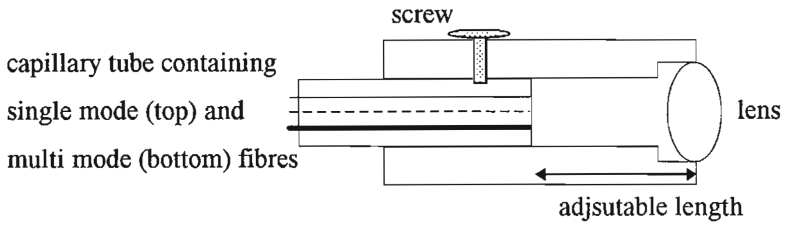


Figure 11: The holder for the lens and the capillary tube containing both fibres

The focal length of the the lens in the system was found by checking the narrowness of the He-Ne laser beam in the labs. This is not the best method of finding the correct value of the focal length. The focal length is an important parameter as it determines whether the reflected light is focused onto the wire or not.

This holder then was inserted to another rectangular block which has a hole drilled at an angle to give the Littrow Configuration. This angle is the complementary angle of θ which has a value of (90° - θ) where θ has been calculated earlier as 27.8°.

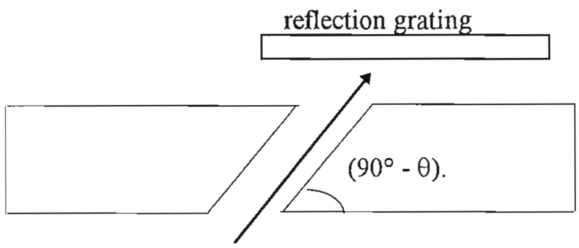


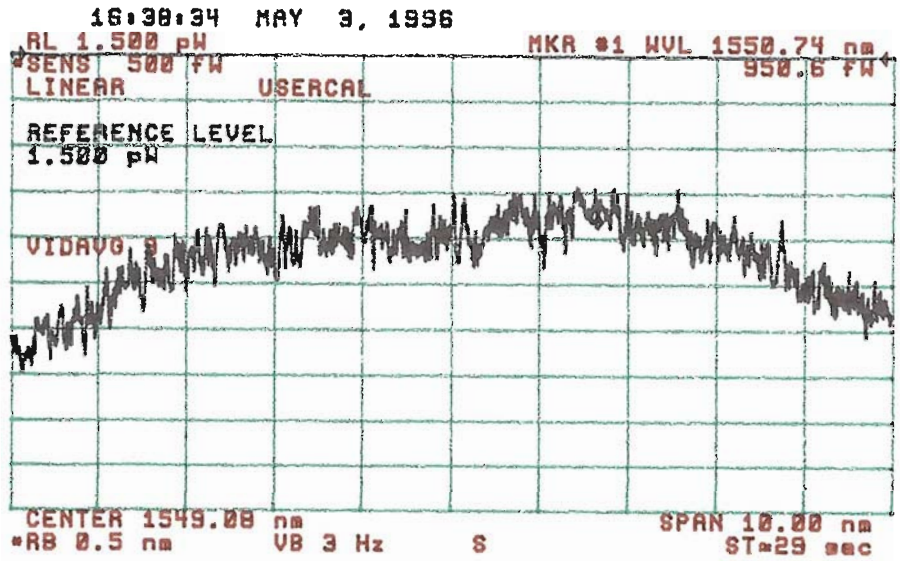
Figure 12: The arrangement to ensure Littrow Configuration

The set-up was then tested using a white light source although initially it should use an ELED source. The waveform of the light was checked using an optical spectrum analyser as shown in the graphs. The grating which selects a particular wavelength was rotated manually until the spectrum analyser shown a notch behaviour of the filter. It is admitted that by doing this rotation manually, the exact value of the angle of rotation of the grating cannot be determined.

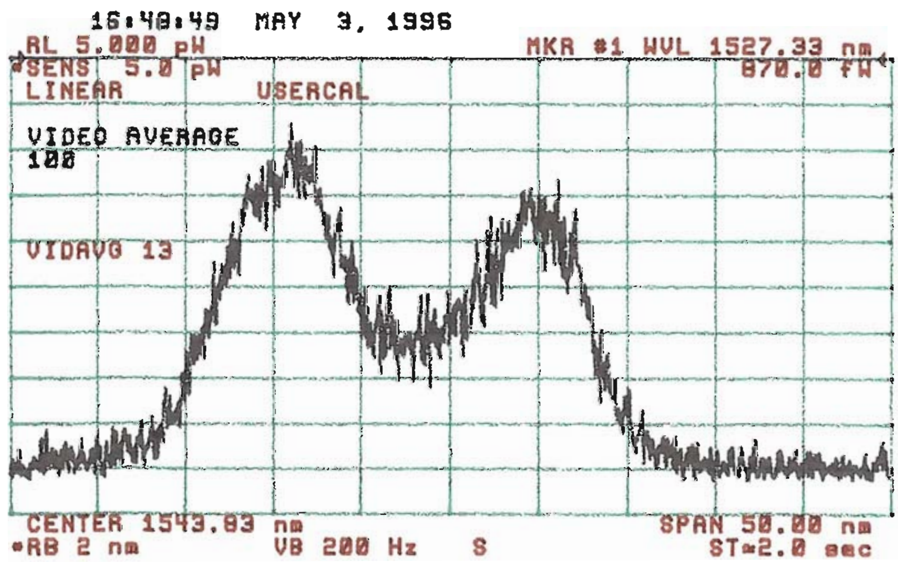
3.3 Results

The following graphs represent the spectrum behaviour of the filter with two different values of the focal length.

Graph of the transmission of light vs. the light wavelength for a focal length around 5 mm:



Graph of the transmission of light vs. the light wavelength for a focal length longer than 5 mm:



3.4 Discussion of Results

As shown in the graphs there is a notch region in each graph although it is not quite clear in the first graph. It is suspected that the first measurement made was not using the accurate value of the focal length. In the second measurement, it can be clearly seen the notch region near the centre wavelength of the filter, i.e. at wavelength around 1543 nm. This wavelength is not the specified centre wavelength for the experiment. From the graph also, the bandwidth of the notch is given approximately as 15 nm which is large compared with the calculated value 2.58 nm.

The main problem in this experiment was to find the correct value of the focal length of the lens used. This was probably a result of the system set-up which used manual adjustment to find the focal length of the lens. It is suggested here that a better system set-up should be equipped by using a micrometer which has a better precision to get the focal length.

The other problem encountered was the small amount of reflected light found in the launched single mode fibre. Although it was small, it is thought that it may affect the accuracy of the filter. This reflection light may come from the glue that might cover the lens.

3.5 Conclusion

This experiment has shown a method of designing a notch filter by using grating monochromator where the unwanted wavelength is reflected by the grating and blocked by a thin wire. Although the result obtained did not indicate the best performance of the filter mainly due to the focusing problem, it is believed that with a better equipment set-up a more accurate and precise result will be produced.

4 Experiment 2: **A Notch Filter Using Fibre Grating**

4.1 Introduction

In this method a narrow band fibre filter is produced by incorporating a photorefractive fibre grating in a single mode fibre. This technique allows a permanent filter to be produced without the use of bulk elements such as diffraction gratings. The bandwidth of the filter is determined at the fabrication stage and can be anything from << 1 nm to 100 nm. The centre wavelength of the grating must also be determined at this stage, but tunability of $\geq$ 10 nm is possible in service.

4.2 Theoretical Background

The fibre which was used in this experiment is HD 283_01. This fibre has the following specifications:

Numerical Aperture (NA) = 0.23
Cut-off wavelength = 1350 nm
Diameter of fibre = 100 μm

This fibre has been designed specifically to avoid coupling to cladding modes at wavelength shorter than Bragg wavelength. Such a fibre is necessary if interference with the short-wavelength light source is to be avoided. The centre wavelength of the grating is to be at λ = 1555 nm, with a bandwidth of between 3 nm and 6 nm. This will be done either by adding several gratings together, each with a slightly different wavelength, or by using hydrogenation to increase the photosensitivity of the fibre, thus enabling the filter to be made with only one grating. Hydrogenation is the preferred option, but care must be taken when using the fibre as there may be some long-term drift in the properties of the grating.

The grating is formed by exposure to two interfering beams of coherent UV lights through the cladding. The beam is split into two and then recombined coherently at the core of the fibre. In the core, the nodes and antinodes of the interference periodically change the refractive index of the glass, and thus gradually building up a Bragg grating. This technique is also known as holographic exposure.

4.3 Experimental Method

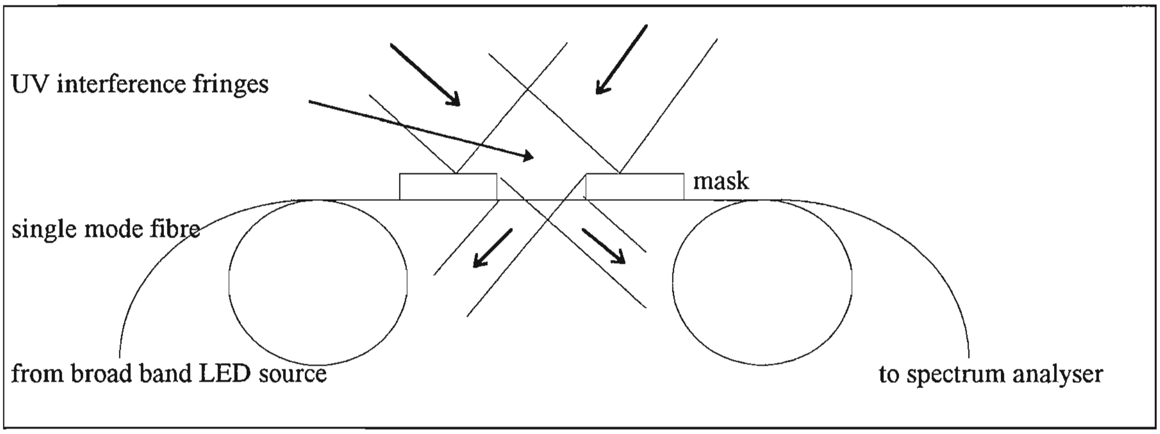


Figure 13: The experimental set-up

The grating was made by exposing the photosensitive core of the fibre to intense, coherent UV light which is capable of modifying the refractive index of the core. If this is done with a small enough periodicity, grating will be set up which will reflect light over a small band of wavelengths. The reflection efficiency can easily exceed 99.9 % in practice, with very small attendant loss. For this experiment, a KrF excimer laser was used to expose the fibre. This is a pulsed laser, with a pulse duration of approximately 20 ns, a repetition rate of up to 80 Hz (20 Hz in this experiment), and an operating wavelength of 248 nm. The beam from the laser was divided into two and recombined at an angle of approximately 29° to produce a grating at the desired wavelength.

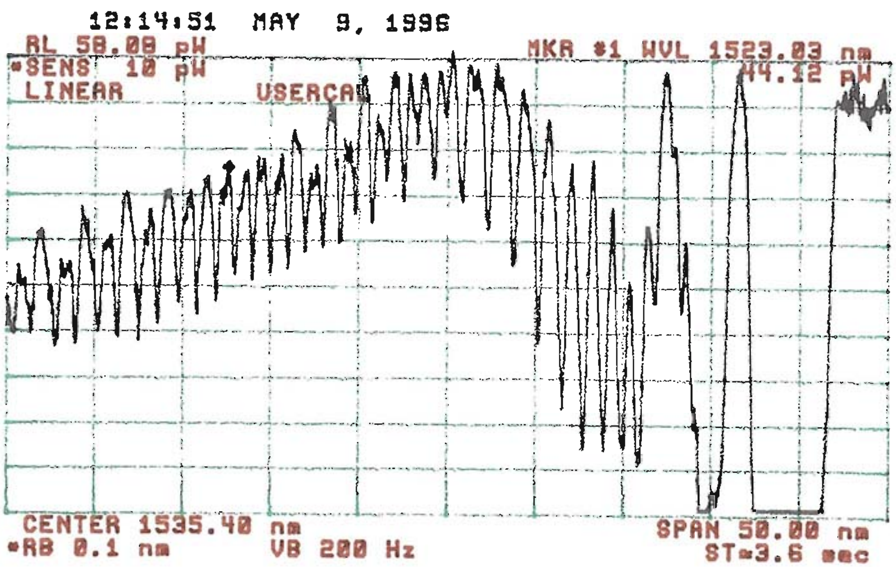
In order to meet the specification of relatively broad bandwidth, it was necessary to increase the photosensitivity of the fibre by soaking it in hydrogen. This was carried out at 160 bar and room temperature for two weeks. This allows a substantially greater index modulation to be achieved over what is obtainable using the untreated fibre. After soaking in hydrogen, the fibre was stored at -60°C in order to prevent outgassing. The fibre had a numerical aperture of 0.22 and a cut-off wavelength of 1.4μm. It was designed specially to avoid coupling to cladding modes at wavelengths shorter than the grating wavelength, which can lead to substantial losses in this region of the spectrum.

Three gratings were made at a nominal centre wavelength of 1555nm. The fibre was exposed to the laser for between 5 and 10 minutes, longer exposure leading to stronger and hence broader gratings.

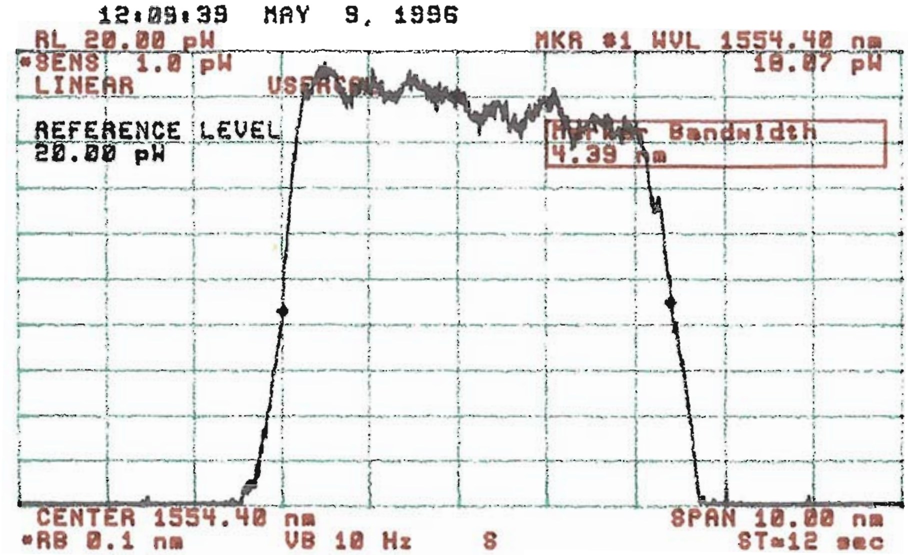
4.4 Results

The graphs that follow show the behaviour of the best two grating made. The first grating made does not meet the required bandwidth specification and therefore its graphs is not presented here.

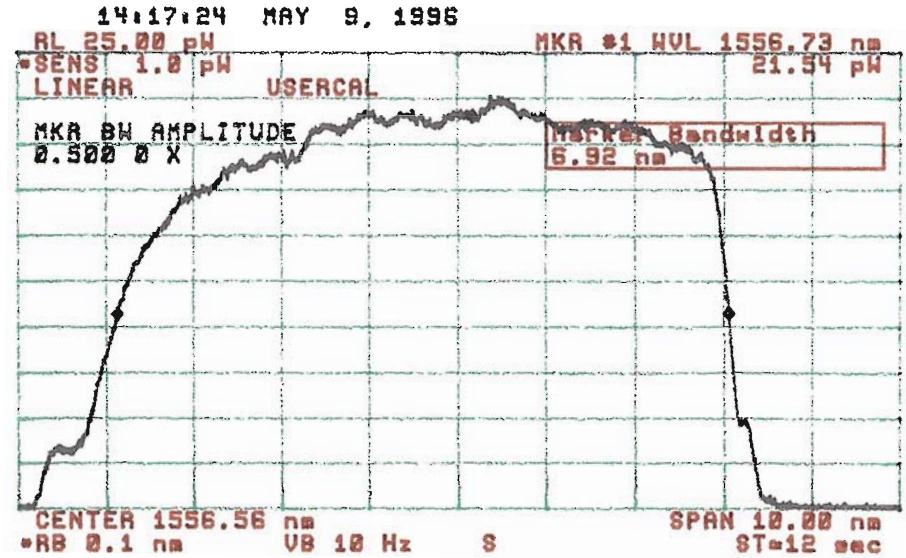
Graph showing the transmission of light (%) vs. the light wavelength (nm) for the second grating:



Graph showing the reflection of light (%) vs. the light wavelength (nm) for the second grating:



Graph showing the reflection of light (%) vs. the light wavelength (nm) for the third grating (the largest bandwidth):



4.5 Discussion of Results

The first graph shows the transmission characteristic of the filter. It can be seen clearly that almost 100% reflection was obtained at wavelength 1550 nm. The largest bandwidth which was achieved was approximately 7 nm. The transmission of these gratings at or near the peak wavelength could not be measured, but would be at least 50 dB down on the off-peak transmission of the fibre. The second grating has bandwidth of 4.39 nm.

Unfortunately, strong coupling to cladding modes at wavelengths shorter than the Bragg wavelength was observed for all gratings, even though cladding mode coupling had been successfully suppressed in weaker gratings. It is thought that a fibre will need to be specifically designed to suppress coupling when such strong gratings are required.

4.6 Conclusion

This experiment has demonstrated the use of fibre grating which was made by holographic exposure, as a notch filter. From the performance shown in the results obtained, it is found that this filter has performed the best characteristic of almost 100% reflection at the required wavelength.

5 Experiment 3: **A Filter Using Long Coupling Length Optical Coupler**

5.1 Introduction

In this experiment, an optical coupler which has bitapered region is used as a narrow band notch filter. To act as a notch filter, the coupler will need the wavelength rejection band which will be provided by absorption. This absorption in the tapered fibre is mainly caused by a dopant in the core of the fibre. The coupling efficiency in the tapered region gives the response of the filter.

5.2 Theoretical Background

A coupler is one of the optical components that works as a function of wavelength. It is a four port device which light energy transfer will occur between the coupling region of the two fibres, that is, the light transfers from an adjacent fibre to another fibre. Ideally it will split the input signal (port 1) into two channels (port 2 and 3) as shown below:

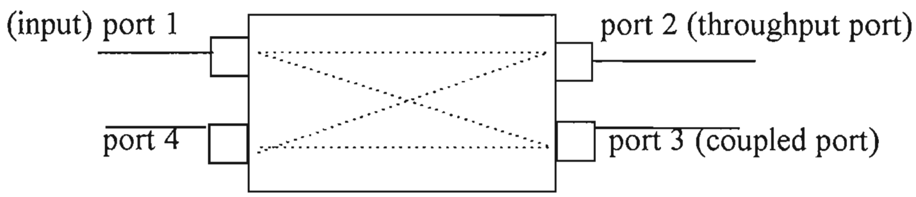


Figure 14: The schematic of a coupler

The coupler is usually characterised by its coupling ratio. The coupling ratio is defined as the amount of energy that is coupled from the input port to the coupled port (port 3). As an example, a 50:50 or 3 dB coupler will transmit 50% of light to the first fibre (port 2) and another 50% to the second fibre (port 3). This coupling ratio is affected by polarisation effects of the signal.

The light transfer that occurs between adjacent fibre cores happens by evanescent wave coupling. When two fibre cores are in close proximity, the evanescent field of the light in the throughput fibre gets into and excites the mode in the coupled fibre. At the time the modes of the two fibres have the same phase velocity, resonant interaction occurs and total energy transfer takes place after some interaction length known as the coupling length. Therefore, it is possible to completely transfer all the light from one fibre to another as long as it is within the coupling length. However, over-coupling will occur when the interaction continues after the coupling length.

The coupling length of the coupler is given by

the coupling length, $L_c = \dfrac{\pi}{2\chi_c}$;

where χ_c= the coupling coefficient. Therefore, the coupling coefficient is inversely proportional to the coupling length.

The light signal will experience a phase shift of 90° when transfered to the coupled fibre. This phase shift is important as it affects interference between the guided waves in the coupling region. For example in full coupling, the coupled signal is 180° out of phase with the throughput signal when coupled back to the throughput port where it interferes destructively with the throughput signal.

The coupling back and forward of the power in the coupling region between the fundamental core and cladding modes is wavelength dependent. The signal here varies almost sinusoidally with wavelength with a half period or linewidth which is a function of the coupling length. The rejection ratio in a fibre filter decreases as the length is increased. The filter rejection ratio is defined as the ratio of the transmitted power at the rejected wavelength to the transmitted power at the nearest peak transmission wavelength. The tuning of the centre wavelength of the filter is done by twisting while polarisation effect is reduced by applying additional longitudinal strain.

It is intended that the troughts of the sinusoidal wave are in the unwanted wavelength region as the trought reperesents the destructive interference in the coupler; whereas, the crests represent the constructive interference in the coupler.

5.3 Experimental Method

In this experiment, two long coupling length constant cladding index single mode fibres were used. This type of fibre was chosen because they have low loss. Usually in a normal telecommunication fibre, the materials used for doping in the core region are germanium (GeO_2) or silica (SiO_2). And there is a depressed region in between the core and the cladding where boron (B_2O_3) or silica (SiO_2) is doped here. This fibre is good except than it cannot be used to make low loss couplers. That is why the fibre for this experiment has non-depressed cladding. The fibre has only germanium doped core.

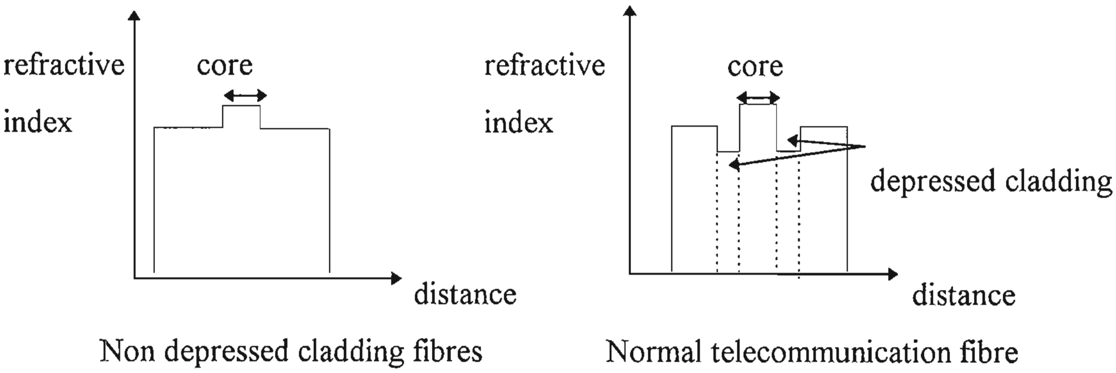


Figure 15: Comparison between the fibre used for coupling with normal telecommunication fibre

The couplers made are fused type, formed by twisting the two fibres together, pulling them and then fusing the mid region. This is one of the simplest and fastest methods of making a coupler where the heat source is a flame. The coupling ratio of the coupler is monitored during the fabrication and adjusted during drawing process. Three such couplers with different values of coupling length have been made with the following specifications:

Coupler	Coupling length, x /mm	Coupling ratio	Insertion loss /dB
A	65	50:50	0.13
B	60	50:50	0.15
C	55	50:50	0.18

Table 1 showing the properties of the couplers made

The insertion loss is a quantity represents the attenuation loss in the couplers. It can be seen that the longer the coupling length, the lower the value of the insertion loss.

Each coupler was then connected to a light source in port 1 and to a spectrum analyser in port 2 to check the spectrum behaviour of the couplers. In this experiment, the light source used was a white light source because the white light has less distortion compared to the initial suggested LED source. The centre wavelength of the signal to reject is 1560 nm. The experiment done was based on trial and error, in which the way the connection was made is illustrated below:

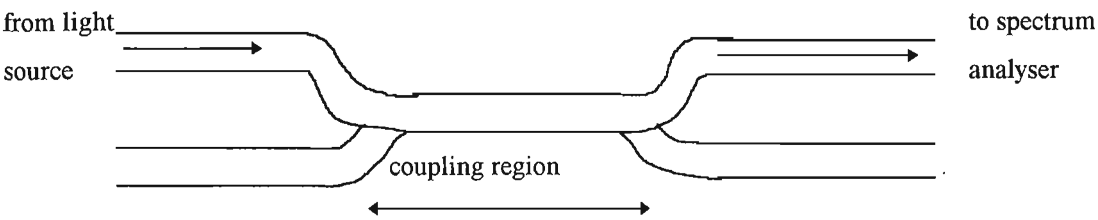


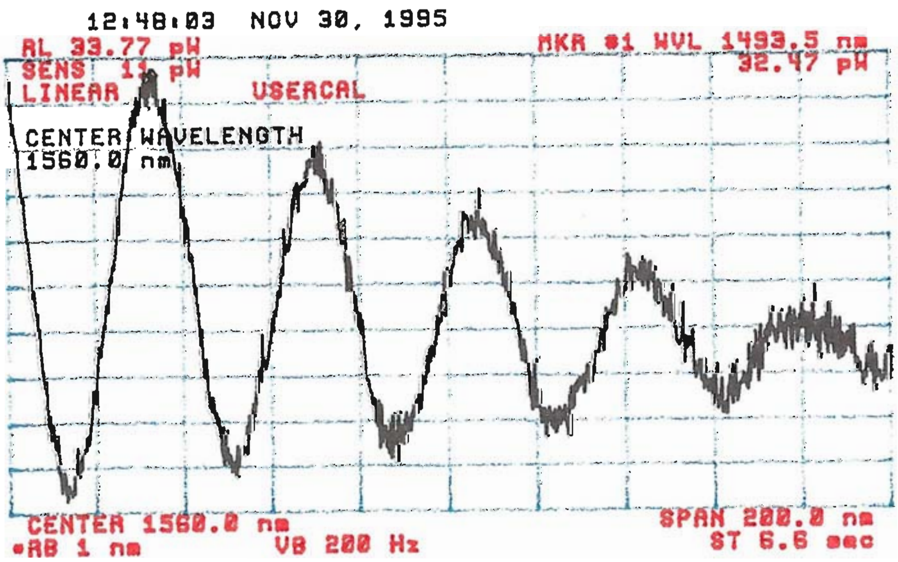
Figure 16 showing the connection for the couplers

In dealing with couplers, careful step has to be taken to ensure that the coupling region does not break. The coupling region is very sensitive and can easily be broken by small vibration and for this reason it is usually protected with some form of packaging.

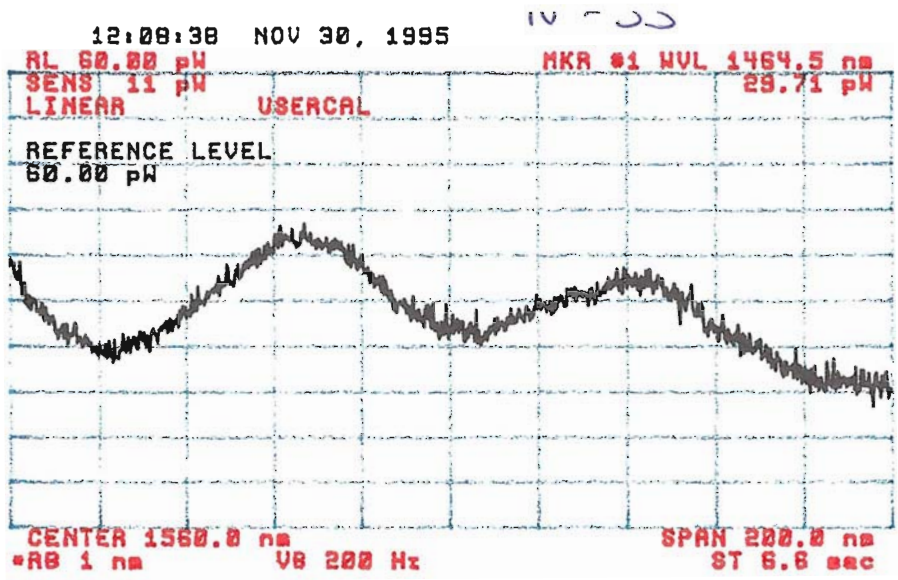
5.4 Results

The graphs below show the transmission of light (%) vs. the wavelength of the light (nm):

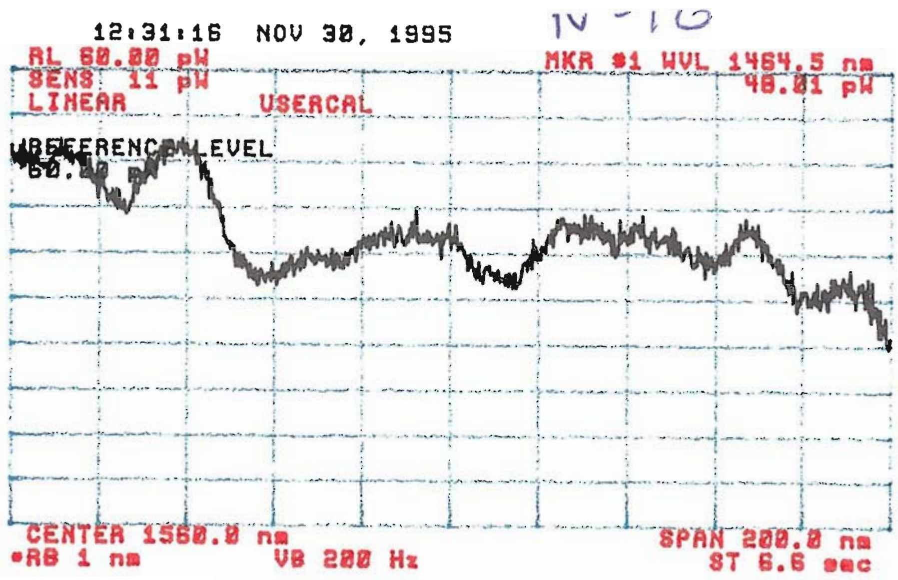
Graph A: Coupler at 65 mm coupling length



Graph B: Coupler at 60 mm coupling length



Graph C: Coupler at 55 mm coupling length



5.5 Discussion of Results

It can be noted from the graphs that all couplers did not show a good characteristic as a notch filter. Although all of the them showed the expected sinusoidal wave behaviour as a coupler, they had a very poor rejection ratio at the interested wavelength centred on 1560 nm. All the trougths which represent the destructive interference in the coupler and where the notch region should be, were not obtained at the value of the specified wavelengths for this project. The closest characteristic of a notch filter was obtained by coupler A which has the longest coupling length at 65 mm. This also indicates that the longer the coupling length is, the lower the filter rejection it has. The discrepancy of the result may be due to the poor coupling efficiency of the coupler, the polarisation effects and backscattering of the signal into the input port.

5.5 Conclusion

This experiment has demonstrated that a notch filter was designed by using optical coupler with long coupling length. The long coupling length is chosen as it is an important parameter in making the coupler to have low loss and low value of the filter rejection ratio. However, the filters did not give the notch region that is the trougths of the sinusoidal wave at the specified wavelengths of the project.

6 Experiment 4: **A Filter Using Absorbing Chemical Substance**

6.1 Introduction

This experiment manipulates the absorption characteristic of a radiation at a certain wavelength in a chemical substance. When light passes through an absorbing medium, the intensity of the light changes. The change is due to the light energy being lost or transformed as other form of energy like heat. This energy loss is said to be absorbed by the material. Therefore, suitable materials that have an absorption peak at specific wavelengths are used to absorb the unwanted wavelengths, and thus a notch filter is built.

6.2 Theoretical Background

The Near Infra-Red region, which is defined between 1000 to 3000 nm, is a significant portion of the electromagnetic spectrum because many compounds including almost all organics and inorganics have numerous absorbance peaks. This absorption may be due to the intrinsic material absorption, the impurities consisting of primarily of metal and OH ions in the medium and also the atomic defects in the medium.

The absorption property in a material can be explain by considering the energy levels in the atoms or molecules of the material. These energy levels have discrete values which usually denoted by E_0, E_1, E_2 ... E_N. The relationship between two energy levels is expressed by Boltzmann equation:

$$\frac{P(E_i)}{P(E_j)} = \frac{\exp[-(E_i - E_j)}{kT}$$

where,

k = Boltzmann's constant of value 1.38×10^{-23}; and

T = the absolute temperature in Kelvin.

This energy level can only absorb photon of light when the frequency of the light, ν is equivalent to the value of ν_{ij} where

$$h\nu_{ij} = E_j - E_i \quad (j > i)$$

and h is a Planck constant of value 6.625 x 10^{-34} Js. Therefore, one photon which has energy $h\nu_{ij}$, is said to be absorbed by the atom when the photon has transfer from energy level E_i to energy level E_j.

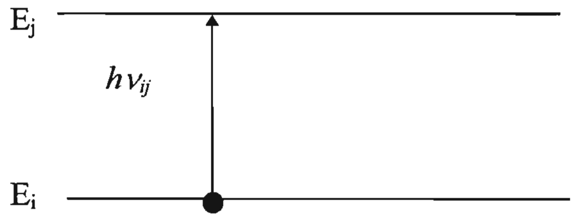


Figure 15: The absorption phenomenon from energy level diagram

The behaviour of the absorption in materials depends on the following parameters:

- the absorption cross-section of the molecule;
- the optical path length involved; and
- the illumination wavelength used.

The change in the intensity of light beam measured at a distance z into an absorbing material is given by

$$I(z) = I(0) \exp(-\alpha z)$$

where α is the absorption coefficient which relates the cross-section c_s (unit = m^2) of the molecule and the concentration c_m (unit moles per cubic meter) of the molecule by

$$\alpha = \frac{(c_s c_m)}{N}$$

where N is Avogadro's number of value 6.022 x 10^{-23} mol^{-1}. The concentration of material used can be calculated using the following formula:

$$\text{concentration (in ppm)} = \frac{\text{required absorbance}}{\text{(path length) (molar absorbance)}}$$

6.3 Experimental Method

Several materials which have the absorbance peak at around 1550 nm have been considered. In general, these are materials which made of N-H bond, like ammonium hydroxide solution NH_4OH, iodomethane and di-iodomethane. At first, Hydrazine was also considered since it has a very close spectrum that is required in the experiment. However, it is a particularly unpleasant material, so it has been decided not to use it. The spectrum of the chosen material, Iodomethane (CH_3I) is shown in Appendix A, as based from the spectra's book.

The substance chosen is then stored in a 10 mm cell. The set up of the experiment is shown below:

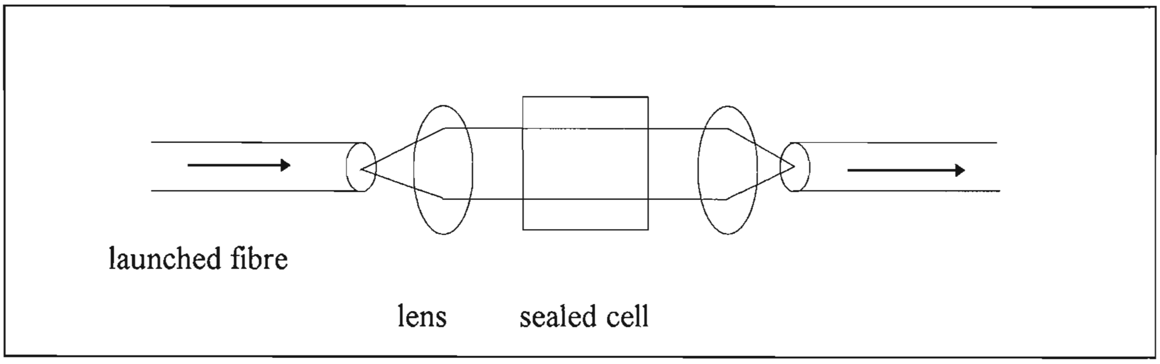


Figure 16: The experimental set-up

This arrangement is known as transmission approach. A sealed liquid glass cell containing the chemical substance will be placed in the collimated region between two identical lenses. The light from the fibre will pass through the two lenses and the glass cell. The centre of the required narrow band wavelength of the light at 1550 nm will then be absorbed by the chemical substance in the cell. This absorption provides the stop band region of the notch filter. The other end of the fibre is spliced to a spectrum analyser where the behaviour of the light is checked.

6.4 Problem

The main problem in conducting this experiment is the high degree of toxicity in the chemical substance. Most of the substances that have near infra red absorption bands have high toxicity which can be extremely hazardous to the experimenter. For example, the iodomethane can cause toxic by ingestion, inhalation and skin contact. It is also extremely irritating to eyes and causes burns if splashed in eyes. When used in high concentration it vapours narcotic. Therefore, due to this high toxicity of the chemical substance, it is agreed between me and the supervisor to skip this experiment.

6.5 Conclusion

The experiment was not carried out mainly because of the high toxicity in the materials to use which needs special treatment and extremely high precautions. Obviously, this is not the best way to design a filter. However, it is proven that this arrangement of using absorption is used in real applications especially in sensing area.

7 Discussion of Results

This chapter reviews all the suggested methods. The advantages and disadvantages of each method are discussed before the recommendation is made.

In optical fibre systems, it is highly beneficial to use all fibre devices. This is because all fibre optical devices have the advantages of increased thermal and mechanical stability since the light never leaves the confinement of the fibre core, better noise immunity, electrical isolation and very low intrinsic loss and scattering of single mode fibres. In this project, two devices have such properties and both of them are the fibre grating and the optical couplers.

In the first method using grating monochromator, the performance of the filter is the second best. A major problem was encountered in getting the right focal length of the lens used. The focal length is very crucial because the reflected light from the grating will not be blocked exactly by the thin wire if the lens is not in the focal length. Therefore, a better equipment like a micrometer should be used to get the reflected light to focus onto the thin wire. The other disadvantage of the system besides poor precision of the equipment is the bulk elements used in the experiment like the diffraction grating and the holder for the fibres. This will result in uneasy set-up for the experiment in order to get the optimum performance of the filter.

In method two which used fibre grating, 99.9 % of reflection was obtained at the centre of the unwanted wavelength. This is obviously a very good notch filter and came out as the best performance of all the filters tested in this project. It is one of the all in fibre devices which is very useful in designing optical fibre system as it does not need any signal processing outside the fibre. Moreover, this filter takes less time to build, around 5 to 10 minutes of exposure to the UV light. However the problem of strong coupling to cladding modes at wavelength shorter than the Bragg wavelength was observed.

Method three which made use of an optical coupler with long coupling length is another all fibre device. Out of the three filters, this filter has the poorest performance as a notch filter. The poor performance may be due to the poor coupling efficiency of the coupler and it is hard to ensure taht the notch region of the unwanted wavelength is obtained at the trough of the sinusoidal wave of the coupler.

The suggested fourth method by using an absorbing chemical substance was not conducted. The main problem in this approach was that the high degree of toxicity of the chemical substance used. If the substance used is not so toxic, then there is a possibility that this approach will give a satisfactory result.

In summary, the best method for making a narrow band filter is by using fibre grating because it can give reflection up to 99.9%. Then the second best performance was obtained using the grating monochromator and the long coupling length optical couplers gave the worst filters.

8 Conclusions

This project has demonstrated successfully three methods of designing narrow band filters. The filters are to remove a narrow band signal from a broad band source, which are needed in order to avoid coherence interference effect in an optical fibre system. Although initially there were four approaches have been suggested, the other method which uses an absorbing chemical substance, was not carried out due to the high toxicity in the chosen material. Two of the method tested, that is fibre grating and optical coupler were all in-fibre devices which are very useful since they reduce a lot of component cost and maintain the quality of the signal as the light never leaves the fibre core. In this project, the best characteristic of a notch filter was obtained by using fibre grating, followed by a grating monochromator approach and the couplers were the third.

9. References

1. J Dakin and B Culshaw, *Optical Fiber Sensors: Principles and Components Volume 1.* (Artech House Inc, 1988)

2. P St J Russell, J-L Archambaut and L Reekie, *Fibre Gratings.* (Physical World, Oct 1993, pp 41-46)

3. M Born, and E Wolf, *Principle of Optics.* (Pergamon Press)

4. M C Hutley, *Diffraction Grating.* (Academic Press Inc, 1982)

5. A J Schuman, *Optical Data Processing.* (Wiley, 1970).

6. Sadtler, *The Atlas of Near Infra Red Spectra.*

7. Helmut F Wolf, *Handbook of Fibre Optics: Theory and Applications.* (Garland Publishing, Inc. 1979)

8. Martin H Weik, *Fiber Optics and Lightwave Communications Standard Dictionary,* (Van Nostrand Reinhold Co., 1981)

APPENDIX A: The spectrum of the iodomethane (CH_3I) for experiment 4.