AN OPTICAL WAVELENGTH MULTI/DEMULTIPLEXING (DWDM/CWDM) BASED ON ARRAY WAVEGUIDE GRATING (AWG) TECHNIQUE

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Special dedicated to:

My beloved family, brothers and sisters

For their never ending support and blessing

To my friends

That is always on my ups and down

Thanks for all

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ABSTRACT

Wavelength splitting (demultiplexing) and combining (multiplexing) are important functions in many optical applications. Wavelength Division Multiplexing (WDM) enable optical multiplexing and demultiplexing in which the signals having different light wavelengths can be separated or combined to transmit in single fibre optic. There are two alternatives in WDM which are, Dense WDM (DWDM) for high capacity and long haul transmission, while Coarse WDM (CDWM) mean for shorter transmission and metro network. CWDM allows the wavelengths to be spaced farther apart, which allows for economical solutions in sparse applications (around 20nm) as compared to DWDM which utilizes very closely spaced wavelengths (around 0.8nm). Arrayed waveguide grating (AWG) multiplexer is a key element for wavelength division multiplexing (WDM) systems in optical telecommunication. The advantages of AWG are the flexibility of selecting its channel number and channel spacing. In this project, conventional AWGs with 4x4 channels structure based on polymer with channel spacing for DWDM/CWDM and core size 3 um x 4 um have been designed which centre wavelength 1550nm. The designs have been carried out by using WDM_phasar design tool from Optiwave Corporation. The performance and optimization of the designed AWGs have been analyzed based on parameters studied.

ABSTRAK

Pemisahan (penyahmultipleksan) dan pencantuman (pemultipleksan) panjang gelombang merupakan fungsi penting dalam aplikasi optik. Pembahagian pemultipleksan panjang gelombang (WDM) membolehkan pemultipleksan dan penyahmultipleksan optik dengan setiap isyarat-isyarat yang mempunyai gelombang cahaya yang berlainan boleh dipisahkan ataupun dicantumkan bagi menghantar dalam satu gentian optik. Terdapat dua alternatif dalam WDM iaitu WDM padat (DWDM) untuk kapasiti yang tinggi dan penghantaran jarak jauh, manakala WDM kasar (CWDM) untuk penghantaran yang lebih dekat dan rangkaian metro. CWDM membenarkan pemisahan panjang gelombang yang besar yang mana memberikan penyelesaian yang ekonomi bagi aplikasi yang rendah (sekitar 20 nm) jika dibandingkan dengan DWDM yang menggunakan jarak panjang gelombang yang sangat dekat/padat (sekitar 0.8 nm). Dalam telekomunikasi optik, pemultipleksan parutan pandu gelombang tersusun (AWG) merupakan elemen utama bagi sistem pembahagian pemultipleksan panjang gelombang (WDM). Kelebihan AWG adalah kefleksibelannya dalam memilih bilangan saluran dan pisahan saluran. Dalam projek ini, 4x4 saluran AWG konvensional yang binaannya berasaskan polimer dengan pisahan saluran untuk DWDM/CWDM serta saiz teras 3um x 4 um telah direkabentuk dengan panjang gelombang tengah 1550 nm. Rekabentuk telah dijalankan dengan menggunakan perisian WDM_Phasar daripada Optiwave Corporation. Prestasi dan pembaikan AWG yang direkabentuk dianalisis berdasarkan parameter-parameter yang dikaji.

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LIST OF ABBREVIATIONS

AWG	-	Array Waveguide Grating
BCB	-	Benzocyclobutene
BPM	-	Beam Propagation Method
C-band	-	Conventional band
CDM	-	Code Division Multiplexing
CWDM	-	Coarse Wavelength Division Multiplexing
DFB	-	Distributed Feedback
d-PFMA	-	deuterated fluoro-methacrylate
DWDM	-	Dense Wavelength Division Multiplexing
EDFA	-	Erbium Doped Fiber Amplifier
FBG	-	Fiber Bragg Grating
FPR	-	Free Propagation Region
FSR	-	Free Spectral Range
GaAs	-	Gallium arsenide
Gbps	-	Gigabits per second
GHz	-	Gigahertz
GUI	-	graphical user interface
IA	-	Input array
ITU	-	International Telecommunication Union
LAN	-	Local area network
L-band	-	Long band
MMI	-	Multimode interference
OA	-	Output array
OADM	-	Optical Add Drop Multiplexer
ORMOCER	-	Organically modified ceramics

PA	-	Phased array
PAWG	-	Phased array waveguide grating
PLC	-	Planar Lightwave circuit
PHASAR	-	Phased array
PDL	-	Polarization dependence loss
Si	-	Silicon/silica?
SMF	-	Single mode fiber
TDM	-	Time Division Multiplexing
TE	-	Transverse electric
TFF	-	Thin film filter
TM	-	Transverse magnetic
WDM	-	Wavelength Division Multiplexing
WGR	-	Wavelength grating router

LIST OF SYMBOLS

ΔL - path length different
$\Delta \lambda$ - channel spacing in wavelength
Δf - channel spacing in frequency
λ - wavelength
m - diffraction order
f_c - centre frequency
λ_c - centre wavelength
N_{ch} - number of channel
${}^{dn}\!/_{dT}$ - Thermo-optic coefficient
$T(f_c)$ - transmission in dB at the channel maximum
$U(s)$ - normalized modal field
N_{eff} - effective index of waveguide mode
d_a - spacing between array waveguide
D - dispersion
d_r - receiver spacing
R - free propagation region length
β - propagation constant
$\Delta \Phi$ - phase different
w_e - effective mode width
Δf_{pol} - polarization dispersion
Ng - group refractive index
$\theta_{\max}$ - maximum dispersion angle
θ_a - aperture width

Na - number of waveguide

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Wavelength splitting (demultiplexing) and combining (multiplexing) are important functions in optical applications. Wavelength Division Multiplexing (WDM) technology enable optical multiplexing and demultiplexing with the individual signals have different light wavelength can be separated or combined to transmit in single fibre optic.

There are two alternatives for WDM metro networks: dense WDM (DWDM) and coarse WDM (CWDM). In high capacity environments, DWDM is used. In DWDM, the channel separation can be as small as 0.8 or 0.4 nm, for up to 80 optical channels at line rates up to 10 Gbps. DWDM technologies is very expensive, so its application to access networks is difficult. Instead, CWDM is merging as a robust and economical solution. The advantage of CWDM technology lies in its low-cost optical components. CWDM offers solutions for 850, 1,300, and 1,500 nm applications at 10 and 40 Gbps on up to 15 optical channels spaced 20 nm apart. Both CWDM and DWDM technology have their place in current and emerging metro-network infrastructure.

Many technologies are used in optical multiplexing, such as thin film filters (TFFs), array waveguide gratings (AWGs), acousto optical tunable filters, mach-Zehnder interferometers and Fiber bragg gratings (FBGs) in order to overcome problems such as channel spacing, bandwidth, crosstalk and insertion loss. However, arrayed waveguide grating (AWG) multiplexer based on planar lightwave circuit (PLC) is the most likely used in wavelength division multiplexing (WDM) systems in optical telecommunication and it’s been focused to study in this project.

The key advantage of the AWG is that its cost is not dependent on wavelength count as is the dielectric filter solution. Therefore it suits metropolitan applications that require the cost-effective of large wavelength counts. Not only the approach is easily scalable, but the use of fiber-alignment methods depend on the whole wafer photoligraphy, rather than channel-by-channel alignment, further enhances the cost-effectiveness of this approach at higher channel counts. Other advantage of the AWG is the flexibility of selecting its channel number and channel spacing, as a result, various kinds of AWG's can be fabricated in a similar manner (Kien and Shaari 2000).

AWG multiplexers have already been developed using silica, semiconductors such as Si, GaAs, etc and polymers as the waveguide materials. Of the materials, polymers offer excellent potential for the realization of low-cost WDM components because they can be fabricated easily at low temperature on various kinds of substrates. (Kien and Shaari 2000)

AWG multiplexers based on polymeric waveguides have been gaining increasing attention because polymer devices are believed to be produce-able at lower cost than their conventional silica-based counterparts. Moreover, as polymer materials have a thermo-optic coefficient *(dn/dT)* roughly ten times larger than silica, polymeric AWG devices can be thermally tuned over a wider spectral range and may be integrated with polymer optical switches to form an add-drop multiplexer with much lower switching power consumption (Kein et al, 2001)

The first polymer AWG demonstrated by Hida et al 1994 applying deuterated fluoro-methacrylate (d-PFMA) on silicone substrate. However, this AWG only operated at 1300 nm window with some polarization dependence as small as 0.03 nm. Watanabe et al (1997) reported 16 channels polymeric AWG operated at 1550 nm realized using a silicone resin waveguide. This AWG multiplexer has an insertion loss in the range 9-13dB, a crosstalk less than -20dB, and a low polarization dependent wavelength shift.

In 1999, Beelen et al demonstrated 8 channels polymeric AWG with high index contrast of 0.01. By this technique, smaller bend radii can be achieved and it lead to smaller AWG dimension from 66x11 mm to 16x6 mm. Keil et al (2001) reported athermal polymer AWG consisting of polymer waveguide fabricated on a polymer substrate. On the other hand, Ahn et al (2004) proposed and fabricated an all-polymer based cost effective wavelength channel selector by using chip-to-chip bonding of a 16 channels to polymer switch array between two polymers AWG. However, the penalties are large insertion loss and low power of 0.1 dB at 10 Gb/s.

Huang Chang Lin et al (2005) designed a low loss, low crosstalk and low PDL SU-8 polymeric wavelength division multiplexer AWG with temperature variation in range of 0 – 70°C. In year 2006 a compact wavelength division multiplexer based on AWG structures have been fabricated for CWDM using low-loss perfluorocyclobutane-containing polymers by Jiang et al. The device exhibit high thermal stability and low on chip losses.

1.2 Problem Statement

There is demand for high capacity and cost effective for the long and short haul application optical transmission. WDM offers a new dimension for solving capacity and flexibility problems in the telecommunication network. Key motivation for this study is the importance of optical multiplexing and demultiplexing component in optical telecommunication network which are crucial elements in WDM technology, namely the Dense WDM and Coarse WDM. There are also claims for these technologies and the needs of precise design with low cost fabrication process. The polymer waveguide technology is chosen because of low material cost and easy fabrication process. Motivated from the advantages of polymer material, the development of polymer based AWG is initiated in this project.

1.3 Objective

The main objective of this project is to design and simulate conventional four channel AWGs structure based on the BenzoCyclobutene (BCB 4024-40) polymer for DWDM and CWDM application. To employ this objective, thorough studies and researches are to be conducted in order to get relevant informations and also to gain the required knowledge.

1.4 Scope of study

This project is intended for the design and simulation of four channels AWGs structure based on BCB 4024-40 polymer for Wavelength Division Demultiplexing application.

To make this project successful, several scopes are listed to ensure the project is conducted within its intended time frame. The first scope for this project is to understand the concept of DWDM/CWDM and AWG, and also the characteristics of the BenzoCyclobutene (BCB 4024-40) polymer, which is currently being used in the Photonics Research Lab. Literature review was done to find out the related theory.

The second scope of work is to specify the parameters of the design based on mathematical equation of basic design rules for AWG. Suitable numbers of waveguide channel have been studied to figure out the best structure to be implemented in this study. Then, conventional AWGs with 4x4 channels structure based on polymer with varies spacing between the channels for DWDM and CWDM environment will be designed at centre wavelength of 1550nm. Modelling and simulation will be carried out by using WDM_Phasar software, from Optiwave Corporation. With this software, AWG performance such as bandwidth, insertion loss, output power and crosstalk will be analysed.

1.5 Research Methodology

Figure 1 shows the overall project activities. The project begins with literature review on fundamental of DWDM/CWDM and AWG characteristics. After the design parameter is determined, the project is followed by proceeding with the design. Following this, the designs will be analysed and its performances will be evaluated.

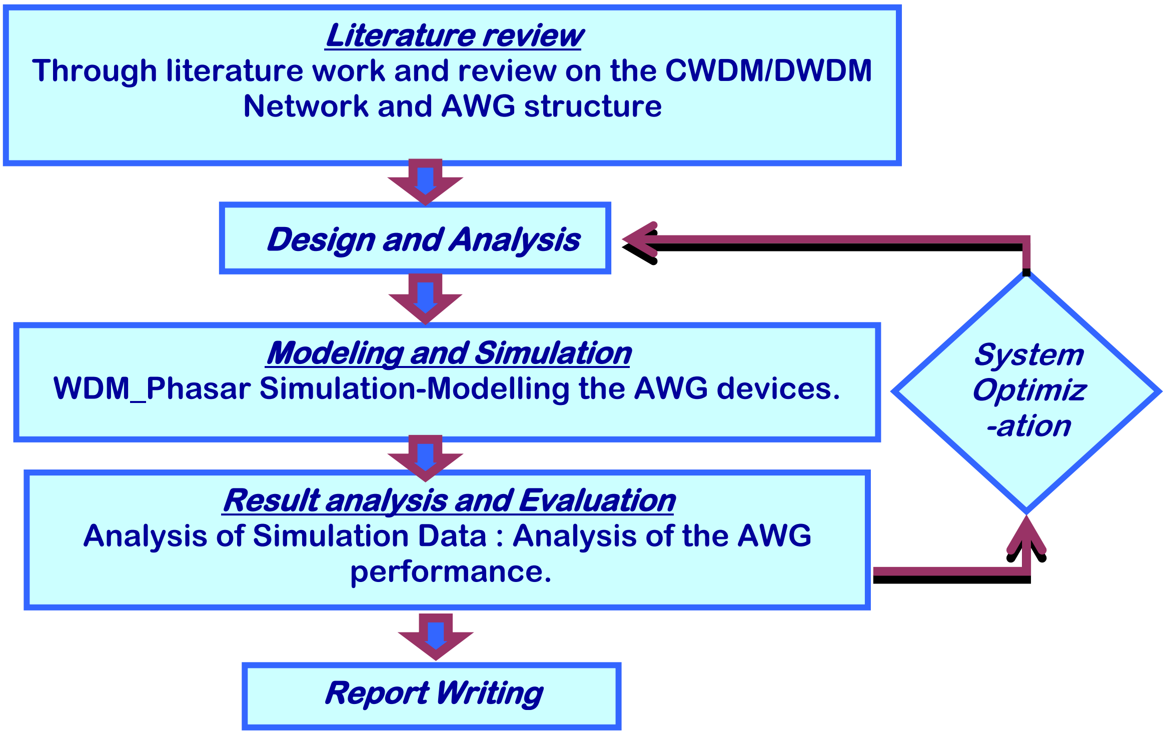

Figure 1 Project Flow Chart

1.6 Thesis Outline

In this thesis the design and simulation AWGs multiplexer/demultiplexer are presented. The background, objectives, scopes and research methodology are discussed in Chapter 1. The literature review of wavelength division multiplexer (WDM) technology, array waveguide grating (AWG) characteristic and polymer material are presented in Chapter 2. The design procedure and AWG simulation are discussed in Chapter 3. The results, analysis and discussion of the simulated results and comparison of the designed devices are presented in Chapter 4. Finally, the conclusion and recommendations for future works are given in Chapter 5.

CHAPTER 1

INTRODUCTION

1.1 Background

The increase in end-user bandwidth demand, along with the decrease in WDM component cost, implies that WDM-based devices are likely to offer performance enhancements in multiple-access networks. Wavelength division multiplexing (WDM) is considered as a promising solution to the demand for tremendous transmission capacity of the optical fiber communications network required in the near future.

Commercial interest in WDM components and systems is rapidly increasing. WDM provides a new dimension for solving capacity and flexibility problems in the telecommunication network. It offers a huge transmission capacity and allows for novel network architectures that offer much more flexibility than the current networks. No new fibre upgrade needed for adding new services (new capacities) to an existing fiber. Key components in WDM systems are the wavelength multiplexers and demultiplexers.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter Outline

In this chapter, fundamental of wavelength division multiplexing (WDM) network and AWG's structure will be described in detail. First part of the chapter explained two alternatives of WDM network which are Dense WDM and Coarse WDM. Then, the chapter continues with the theory of the AWG which is the key element of WDM network and it is the main focused in this thesis. Chapter two end with literature review on BCB-4024 polymer material.

2.2 Wavelength Division Multiplexing

One of important enabling technologies for optical networking is wavelength division multiplexing (WDM). The basic concept of WDM is illustrated in Figure 2.1. WDM technology uses wavelengths to transmit data parallel-by-bit or serial-by-character, which increases the capacity of the fibre by assigning incoming optical signal to specific frequencies (wavelengths) within designated frequency band and then multiplexing the resulting signals out into one fibre. It provides a new dimension of solving the increase demand in high capacity transmission, which poses a serious limitation for the existing carrier technologies by offers a huge transmission capacity and allows for novel network architectures that offer much more flexibility than the current networks.

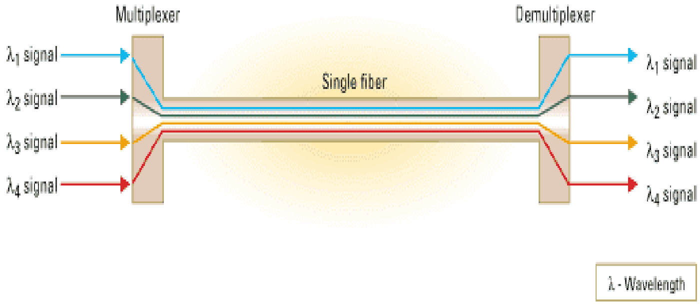

Figure 2.1 Wavelength Division Multiplexing

In WDM, different end users operate only at electronic speed but huge opto-electronic bandwidth mismatch is overcome by multiplex many WDM channels from different users onto a fibre. By contrast, time division multiplexer (TDM) and code division multiplexer (CDM) required for end users to operate at rate higher than electronic speed which made them less interest to be employed in network compare to WDM. Furthermore, it is cost effective to employed WDM technologies into network as there is no new fibre upgrade need for adding new services (new capacities) to an existing fibre.

Research and development on optical wavelength division multiplexing (WDM) networks have matured considerably. Its have been applied for local, access, metro and long haul network architecture.

2.3 Dense Wavelength Division Multiplexing

Dense Wavelength Division Multiplexing (DWDM) technology was developed for large number of channels of lights with different wavelengths that need to be transmit within one single fibred. This increases the bandwidth capacity of a single fiber by tens or even hundreds of times. DWDM has been deployed for long-haul transmissions and will surely change the landscape of fiber-to-the-home network architecture and protocols. The DWDM technology can be applied to different areas in communication networks, which includes the backbone networks, the Local Area Networks (LANs) and also the residential access (Song and Wua).

DWDM has been popular with carriers for some time. It was originally used to mitigate bandwidth issues in backbone long-haul voice applications, but is now used for a broader spectrum of applications, where high bandwidth is needed. Extended distances of up to 600km are supported, but require expensive EFDAs (Erbium Doped-Fiber Amplifiers) to boost power.

DWDM uses expensive narrow-bandwidth (0.8nm) filters and requires specialized cooling to stabilize laser temperatures. The standard calls for up to 80 channels, but typical DWDM implementations support 16-40 wavelengths or channels, at speeds from 2.5 Gbps to 10 Gbps per wavelength (Lounsbury, 2007).

DWDM technology is very efficient for long-haul networks. It not only supports long distances, a multitude of channels and high aggregate bandwidth, but it offers the sophisticated end-to-end management tools required in carrier networks. A far larger number of customers can be supported concurrently, spreading the infrastructure costs over a larger group of users (Lounsbury, 2007).

DWDM is a “hot” technology in every sense of the word. The high density of channels over a narrow frequency range from 1530 - 1620nm (spanning the C- and L-bands) requires expensive filters and cooling and consumes a lot of power. However, all this makes for larger engineering and manufacturing efforts bundled in a larger-than-optimum package. Complexity, cost, colossal equipment footprints combine to leave room for alternative WDM transmission facilities to emerge.

2.4 Coarse Wavelength Division Multiplexing

Coarse wavelength division multiplexing is a form of wavelength division multiplexing that has wider spacing between the wavelengths used than Dense WDM. Also, unlike other forms of WDM, it uses a far broader photonic band spectrum than other such systems, which often are confined to one or two bands. Up to 18 wavelengths can be sent using some schemes of CWDM. CWDM can be used over multimode and single-mode fibres although signal distances are generally shorter than DWDM. The costs of deploying CWDM are significantly lower than DWDM (*RBN Inc., 2002*).

CWDM technologies have been in use since the early 1980s, long before the general acceptance of WDM into the telecom network. Initial deployments involved multiple wavelengths with 25 nm spacing in the 850 nm window over multimode fibre local area networks (LANs). Applications included multi-channel video distribution and bi-directional, latency sensitive telemetry and control information transmitted over a single optical fibre (*ADC whitepaper*).

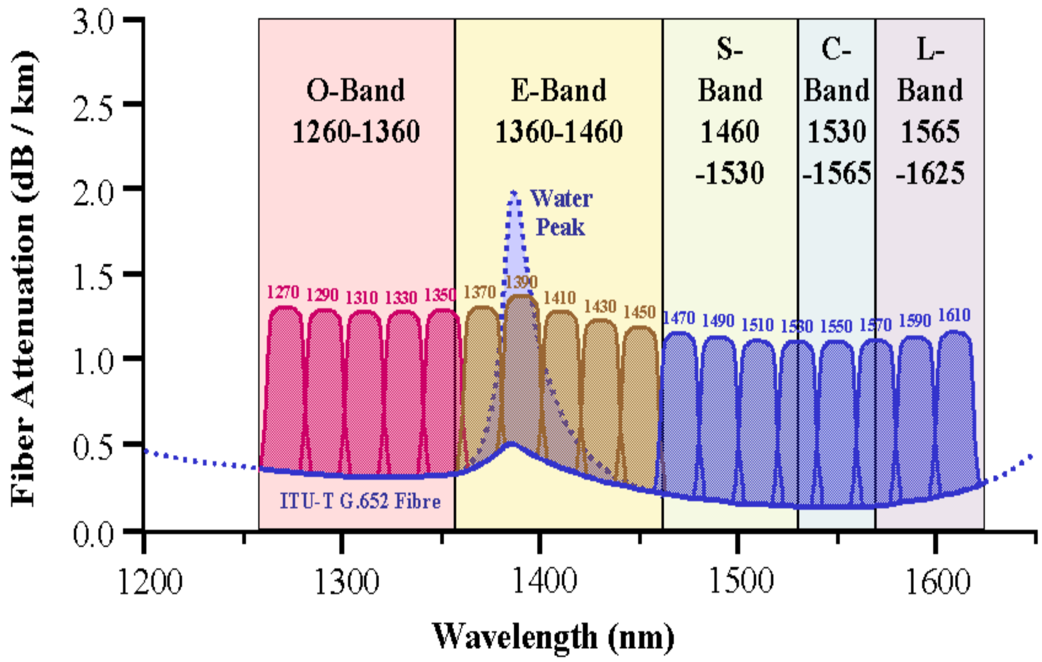

Figure 2.2 Metro CWDM Wavelength Grid as specified by ITU-T G.694.2

The ITU has set the standards of 20-nm channel spacing starting from 1270-nm and ending at 1610 nm, giving up to 18 channels.

Such large channel spacing delivers the following advantages (*VPI photonics*):

- Temperature control is not required for laser sources, even for outside plant, giving lower power consumption
- Transmitters are cheaper (typically 1/5 of Dense-WDM)
- Muxes, Demuxes and OADMs are cheaper (1/3 cost of DWDM)
- Each wavelength can carry a broadband service without crosstalk, (analog and digital services on the same fiber without degradation of the analog service)

Metro CWDM technologies now comprise optical filters and un-cooled lasers with 20 nm spacing. There are 18 wavelengths currently specified with nominal wavelengths ranging from 1270 nm to 1610 nm inclusive. Figure 2 shows a mapping of the ITU-T G.694.2 CWDM wavelength grid. A typical attenuation curve for the installed base of ITU-T G.652 fibre is also shown. The mapping of CWDM wavelengths onto the fibre attenuation curve has been done for greater clarity and to highlight the higher loss incurred by some wavelengths.

2.5 Array Waveguide Gratings

In recent years, the arrayed waveguide grating (AWG) has become increasingly popular as a wavelength multiplexer and demultiplexer for WDM applications. This popularity is largely due to the fact that AWG device have been proven capable of precisely de(multiplexing) a high number of optical signals. AWG also known as the optical phased array (PHASAR), phased array waveguide grating (PAWG) or waveguide grating router (WGR).

The arrayed waveguide grating was first proposed a solution to the WDM problem by Smit in 1988 and was further developed in the following years by Takahashi who reported the first devices operating in the long wavelength window. Dragone, extended the concept from 1 x N demultiplexers to *N* x N wavelength routers which play an important role in multi-wavelength network application. Since then, researchers have designed many AWGs seeking to improve them by increasing the number of channels, decreasing the wavelength spacing, increasing transmission, lowering crosstalk, and reducing the size of the device. These AWGs have many applications in addition to simple demultiplexing applications, including add/drop filters, cross-connects, channel equalization, and multi-frequency lasers (Smit, 1996).

2.5.1 Basic Operation

Generally AWG device serve as multiplexers, demultiplexers, filters and ad-drop devices in optical WDM applications. Figure 2.3 (a) shows a schematic layout of an AWG demultiplexer. The device consists of three main part which are input and output waveguide, two slab waveguide star couplers (or free propagation region (FPR)), connected by a dispersive waveguide array with the equal length difference between adjacent waveguides. The operation principle of the AWG multiplexer/demultiplexer is described as follows.

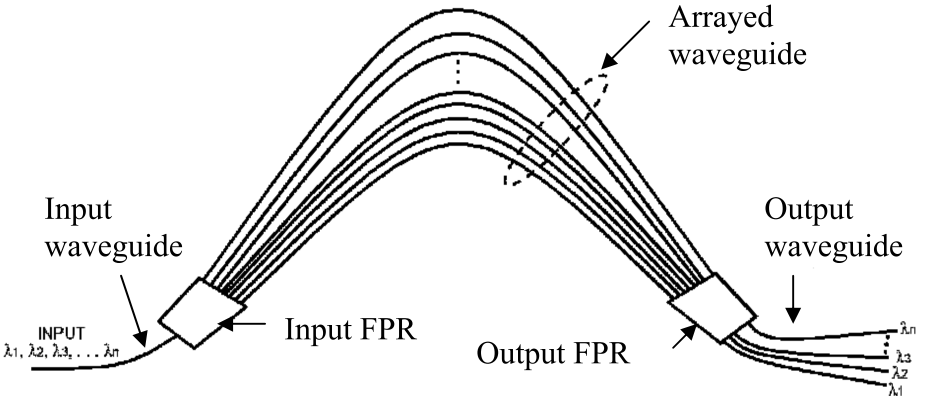

Figure 2.3 (a) The structure of AWG demultiplexer

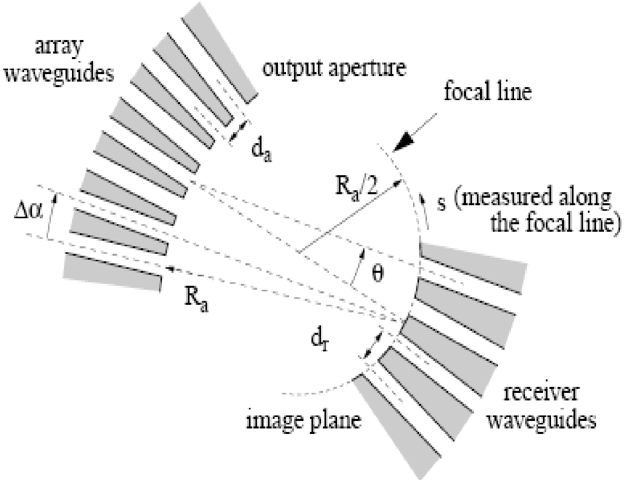

Figure 2.3 (b) Output free propagation region (FPR) (Smit, 1996)

Light propagating in the input waveguide is diffracted in the slab region and coupled into the arrayed waveguide by the first FPR. The length of the array waveguides has been designed such that the optical path length difference (ΔL) between adjacent array waveguides equals an integer (*m*) multiple of the central wavelength (λ_c) of the demultiplexer. As a consequence, the field distribution at the input aperture will be reproduced at the output aperture. Therefore, at this centre wavelength, the light focuses in the centre of the image plane (provided that the input waveguide is centred in the input plane) (Amersfoort, 1998).

If the input wavelength is detuned from this central wavelength, phase changes occur in the array branches. Due to the constant path length difference between adjacent waveguides, this phase change increases linearly from the inner to outer array waveguides, which causes the wavefront to be tilted at the output aperture. Consequently, the focal point in the image plane is shifted away from the centre (Amersfoort, 1998). By placing receiver waveguides at proper positions along the image plane, spatial separation of the different wavelength channels is obtained.

2.5.2 Focusing

Focusing is obtained by choosing the length difference ΔL between adjacent array waveguides equal to an integer number of wavelengths, measured inside the array waveguides (Smit, 1996):

$$\Delta L = m \cdot \frac{\lambda_c}{N_{eff}} \qquad (2\text{-}1)$$

Where *m* is the order of the phased array

λc is the central wavelength

N_{eff} is the effective index of the waveguide mode

With this choice the array acts as a lens with image and object planes at a distance R_a of the array apertures. The input and output apertures of the phased array are typical examples of Rowland-type mountings. The focal line of such a mounting, which defines the image plane, follows a circle with radius $R_a/2$ as shown in Figure 2.3 (b).

2.5.3 Dispersion

By referring to Figure 2.3 (b) it can be seen that the dispersion angle **θ** resulting from a phase difference **$\Delta\Phi$** between adjacent waveguides follows as (Smit, 1996):

$$\theta = \arcsin\left(\frac{(\Delta\Phi - 2m\pi)/\beta_{FPR}}{d_a}\right) = \frac{\Delta\Phi - m2\pi}{\beta_{FPR} d_a} \qquad (2\text{-}2)$$

Where $\Delta\Phi = \beta\, \Delta L$

B *and* β_{FPR} are the propagation constants in the array waveguide and Free Propagation Reion (FPR)

d_a is the lateral spacing(on centre lines) of the waveguides in the array aperture

The dispersion D of the array is described as the lateral displacement ***ds*** of the focal spot along the image plane per unit frequency change. From Figure 1(b) it follows:

$$D = \frac{ds}{df} = R\frac{d\theta}{df} = \frac{dr}{\Delta f_{ch}} \tag{2-3}$$

Where d_r is the receiver spacing
R is the length free propagation region (FPR)
Δf_{ch} is the channel spacing in GHz

2.5.4 Free Spectral Range

An important property of AWG is the free spectral range (FSR), also known as demultiplexer periodicity (Amersfoort, 1998). This periodicity is due to the fact that constructive interference at the output FPR can occur for a number of wavelengths. The free spectral range ($\boldsymbol{\Delta\lambda_{FSR}}$) denotes the wavelength and frequency spacing between the maxima of the interference pattern because of the periodic characteristic of the AWG transfer function, and can be obtained after ignoring material dispersion of the core refractive index n_c.

$$\Delta\lambda FSR = N\Delta\lambda \approx \lambda_c / m \tag{2-4}$$

Where $\boldsymbol{N}$ is the number of wavelengths
$\Delta\lambda$ is the wavelength channel spacing in nm
m is the diffraction order

To prevent different orders from overlapping it is significant to make sure that larger or equal the no of channel multiplied by channel spacing. For a fixed Free Spectral Range (FSR), the diffraction order can be calculated by using expression:

$$m = \frac{\lambda_c}{N_{ch}\Delta\lambda} = round\left(\frac{\lambda_c}{\Delta\lambda_{FSR}}\right) \qquad (2\text{-}5)$$

2.5.5 Insertion Loss and Non-uniformity

The primary cause for insertion loss in the AWG is due to inefficient coupling at the interface between the first FPR and the AWs. Due to reciprocity, identical loss occurs at the second AW - FPR interface into higher diffraction orders. Coupling efficiency, and therefore insertion loss is largely determined by the separation of the AWs at these interfaces, where smaller separations increase the coupling efficiency (McGreer, 1998). However, at small separations, coupling between the AWs becomes significant. This effect has to be carefully quantified through the Finite Difference- Beam Propagation Method (FD-BPM) or another simulation method to avoid phasing errors in the AWs. Other areas that cause loss may include:

- Material losses
- Scattering due to fabrication errors and waveguide roughness
- De-focussing of the spot on the output plane due to phase errors, decreasing coupling efficiency into the output waveguide.

Channel non-uniformity is defined in (Smit, 1996), as the difference in intensity of the central and edge channels of the AWG, and is the result of the variation of the waveguide mode far field with angle. Channel non-uniformity can be estimated analytically or determined through numerical simulation.

2.5.6 Channel Bandwidth

If the wavelength is changed the focal field of the PHASAR moves along the receiver waveguides. The frequency response of the different channels follows from the overlap of this field with the modal fields of the receiver waveguides. If we assume that the focal field is a good replica of the modal field at the input, and that the input and output waveguides are identical, the (logarithmic) transmission $T(\Delta f)$ around the channel maximum $T(f_c)$ follows as the overlap of the modal field with itself, displaced over a distance $\Delta s(\Delta f) = D\Delta f$ (Smit, 1996).

$$T(\Delta f) = T(f_c) + 20\log \int_{-\infty}^{+\infty} U(s)U(s - D\Delta f)ds \qquad \text{(2-6)}$$

Where *U(s)* is the normalized modal field
D is the dispersion
$T(f_c)$ is the transmission in dB at the channel maximum

For small values of Δs (smaller than effective mode width w_e) the overlap integral can be evaluated analytically by approximating the modal fields as Gaussian fields:

$$T(\Delta f) - T(f_c) = 20\log\left(e^{-\frac{D\Delta f^2}{w_o{}^2}} \right) \approx -6.8\left(\frac{D\Delta f}{w_e}\right)^2 \qquad \text{(2-7)}$$

The L-dB bandwidth Δf_L is twice the value Δf for which $T(\Delta f) - T(f_c) = L$ dB

$$\Delta f_L = 0.77 \frac{w_e}{D} \sqrt{L} = 0.77 \frac{w_e}{d_r} \Delta f_{ch} \sqrt{L} \qquad (2\text{-}8)$$

The latter identity follows by substitution of $D = {dr}/{\Delta f_{ch}}$. If we substitute ${w_e}/{d_r} \approx 0.4$ as a representative value (crosstalk due to receiver spacing <-40 dB), the 1-dB bandwidth is found to be 0.31 Δf_{ch}. For a channel spacing of 100 GHz we thus find a 1-dB bandwidth of 31 GHz (Smit, 1996).

2.5.7 Channel crosstalk

Crosstalk may be caused by many mechanisms (Smit, 1996), which are receiver cross-talk, truncation, mode conversion, coupling in the array, phase transfer incoherence, and background radiation. The first four can be kept low through efficient design. The other two follow from imperfections in the fabrication process and are more difficult to reduce. The major source of the cross-talk is caused by the coupling between the receiver sides of the star coupler. Using the overlap between the exponential tails of the propagation field and the waveguide mode profile, the cross-talk can be easily calculated (*Apollo Photonics*).

Another source of cross-talk is caused from truncation of the propagation field by the finite width of the output array aperture. This truncation of the field produces the loss of energy and increases the output focal field side-lobe level. To obtain sufficiently low cross-talk, the array aperture angle of AWG should be larger than twice the Gaussian width of the field. The truncation cross-talk should be less than –35dB when this requirement is met (*Apollo Photonics*).

Cross-talk by mode conversion is caused by a “ghost” image may occur due to the array waveguides are not strictly single mode, a first order mode excited at the junctions between straight and curve waveguides. It can be kept low by optimizing the junction offset by avoiding first mode excitation. The cross-talk caused by coupling in the array can be avoided by increasing the distance between the arrayed waveguide. However, due to imperfections of the fabrication process, the incoherence of the phased array, caused by the change of optical path length (in the order of thousands of wavelengths), may lead to considerable phased error, and, consequently, to increase the cross-talk. For this reason, on a practical level, the reduction of cross-talk for an AWG device is limited by imperfection in the fabrication process (*Apollo Photonics*).

2.5.8 Polarisation Dependence

Phased arrays are polarisation independent if the array waveguides are polarization independent, which are the propagation constants for fundamental TE- and TM-mode are equal (Smit, 1996). Waveguide birefringence is a difference in propagation constant, will result in a shift Δf_{pol} of the spectral response with respect to each other, which is called the polarization dispersion.

Waveguide boundary conditions cause quasi- TE and quasi-TM polarised modes to propagate at different speeds (birefringence), particularly in the case of strongly confining waveguides. As well as birefringence due to waveguide geometry, stresses within the structure may occur due to fabrication processes that can cause anisotropy and stress birefringence (McGreer, 1998).

Birefringence causes a second “shadow” spot on the output plane of the FPR, where the TE- and TM- like polarisations have experienced different phase shifts, potentially coupling with the wrong output waveguide and causing inter-channel crosstalk. Several methods have been presented to reduce this polarisation dependence, such as making the Free Spectral Range equal the difference between the phase change between TE and TM polarized modes, hence overlapping the TE/TM spots (Amersfoort, 1996), or using a polarisation converting lambda half-plate half way along the arrayed waveguides (Takahashi, 1992), causing both polarisations to undergo the same phase change.

2.5.9 AWG Design

This section looks at the analytical methods used to design an AWG. Before the AWG is designed, some basic parameters such as materials and device functions, centre wavelength, core and cladding refractive index, and the size of the core channel with the interface need to be determined. These are used to calculate the effective N_{eff} and group refractive index N_g of array channel and slab waveguides. An AWG is specified by the following characteristics (Smit, 1996):

- Number of channels
- Central Frequency f_c, and Channel spacing Δf_{ch}
- Free Spectral Range Δf_{FSR}
- Channel bandwidth
- Maximum insertion loss
- Maximum non-uniformity
- Maximum crosstalk level
- Polarization dependence

2.5.9.1 Channel Spacing and Number of Ports

Wavelength channel spacing $\Delta\lambda$ and the number of channels *M* and *N* are the most important parameters to design the AWG wavelength multiplexer. Usually the wavelength channel spacing $\Delta\lambda$ is selected according to the ITU-grid standard such as 50 GHz, 100 GHz, or 200 GHz. The numbers of the wavelength channels M are determined according to the requirements of the type of network (WDM/DWDM/CWDM) and its customers. Generally there are two kinds of AWG: 1x*N* (*M*=1) and *N*x*N* (*M*=*N*). The number of the wavelength channels *N* is selected with the exponent of 2 such as 16, 32, 64, and 128 (*Apollo Photonics*).

2.5.9.2 Receiver Waveguide Spacing

First, start with the crosstalk specification. Crosstalk puts a lower limit on the receiver waveguide spacing d_r. As with today's technology cross talk levels lower than -30 to -35 dB are difficult to realize, it does not make sense to design the array for much lower crosstalk. To be on the safe side, we take a margin of 5-10 dB and read from Figure 2.4 the ratio d_r/w required for -40 dB cross talk level (Smit, 1996). It is noted that the crosstalk for TE- and TM-polarization may be different as the lateral index contrast and, consequently, the lateral *V*-parameter can differ substantially for the two polarizations. However, since BCB polymer has a low birefringence, crosstalk for TE- and TM-polarization would give nearly the same result.

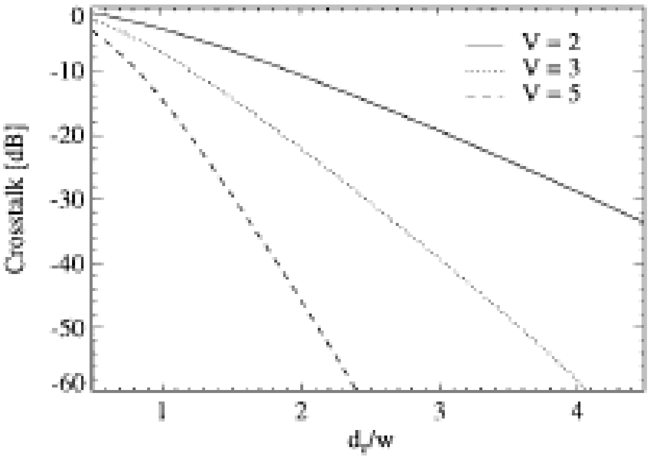

Figure 2.4 Crosstalk resulting from the coupling between two adjacent receiver channels (Smit, 1996)

2.5.9.3 FPR Length Ra

The length of the Free Propagation Region is determined by the maximum acceptable channel non-uniformity (expressed in dB). Channel non-uniformity is defined in (Smit, 1996) as the difference in intensity of the central and edge channels of the AWG, and is the result of the variation of the waveguide mode far field with angle. Channel non-uniformity can be estimated analytically or determined through numerical simulation. By specifying the maximum channel non-uniformity, a value for the maximum dispersion angle (θ_{max}) can be obtained. If the distance to the outermost output waveguide, S_{max}, is known, then the minimum length of the Free Propagation Region. The minimal length $Ra_{\min}$ of the Free Propagation Region then follows as (Smit, 1996):

$$Ra_{min} = S_{max} / \theta_{max} \qquad (2\text{-}9)$$

whereby $S_{\max}$ is the s-coordinate of the outer receiver waveguide refer to Figure 2.3 (b).

2.5.9.4 Length increment ΔL

First we compute the required dispersion of the array from,

$$D = \frac{ds}{df} = \frac{d_r}{\Delta f_{ch}} \tag{2-10}$$

The waveguide spacing d_a in the array aperture should be chosen as small as possible, since a large spacing will lead to high coupling losses from the FPR to the array and vice versa (Smit, 1996). With d_a and R_a fixed, the divergence angle $\Delta\alpha$ between the array waveguides is fixed as $\Delta\alpha = d_a / R_a$ as shown in Figure 2.3(b) and the length increment ΔL of the array follows equation as discussed in subtopic of 2.3.3.

2.5.9.5 Aperture width θa

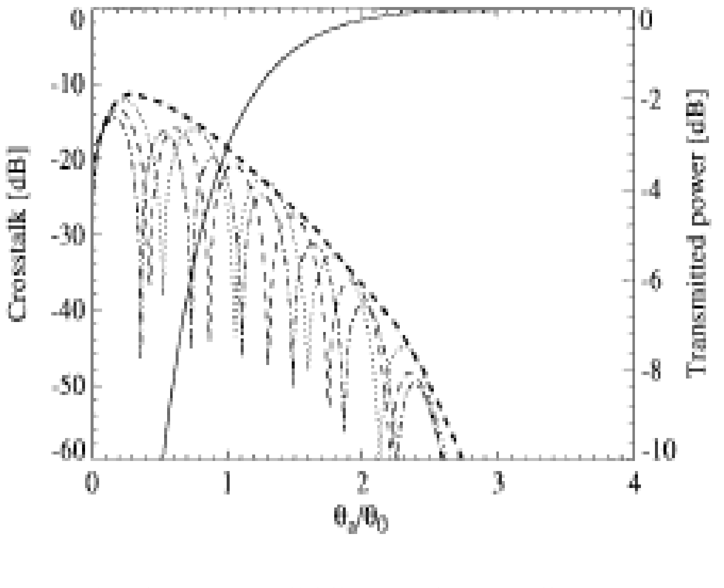

Figure 2.5 Transmitted power (solid line) and crosstalk as a function of the relative array aperture θ_a / θ_o (Smit, 1996)

The angular half width θ_a of the array aperture should be determined using a graph like Figure 2.5 (adapted for the specific waveguide structure used).

2.5.9.6 Number of array waveguides *N*a.

The choice of θ_a fixes the number of array waveguides (Smit, 1996):

$$Na = 2\theta_a R_a / d_a + 1 \qquad (2\text{-}11)$$

where *Na* is number of waveguide
da is spacing between array waveguide
Ra is the length of FPR

2.6 Polymer Material

Polymer waveguide technology has a great potential for economic mass production of complex planar photonic circuits that comply with the severe requirement imposed by applications in communication systems. Due to its low cost from the availability of a wide range of cheap optical polymer and simplicity of fabricating waveguides from them, polymer has been widely use for optical devices.

Polymer can be deposited over most subtracts including semiconductor material. Polymer material has low refractive index spreading rate in millimetre and infrared wave. Optic polymer waveguide structure is made by fabrication techniques suitable with electronic semiconductor such as lithographic photo and RIE (N. Razali, 2005).

For this design, AWG based on WDM system the Benzocyclobutene (BCB 4024-40) polymer has been used. This polymer has several advantages as follow (Liu et al, 2005):

- Low optical losses.
- Low wavelength dispersion.
- Low birefringence which indicate a lack of molecular orientation in the optical properties. Birefringence is the difference between the refractive indices of a material at two different polarizations (eg. TE and TM polarization).
- Good thermal stability (Tg >350^{o}C).
- Propagation loss of 0.8 dB/cm at 1300 nm and 1.5 dB/cm at 1550 nm.
- Resistant to humidity.
- Good adhesion properties.
- Simplicity and flexibility of waveguide fabrication process.
- Low cost.

Since BCB-4024 polymer offers advantages such as low birefringence, good thermal stability and low wavelength dispersion (Liu et al, 2005), it has been chosen as material in this project. BCB polymer becomes an attractive material and has been used for fabrication various optical devices for instance optical switching (Cao et al), polymeric optical waveguide (Gang et al, 2005) and multimode interference optical splitter (M. H. Ibrahim et al, 2006).

Cao et al demonstrated optical bistability and all-optical switching in BCB polymer micro-ring resonators. 2 pm on- and off-switching responses in frequency domain were achieved using a tunable *cw* laser through a high Q BCB micro-ring

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