Planning of Arrayed Waveguide Grating (AWG) for 16x16 Channels Transmission System of Dense Wavelength Division Multiplexing (DWDM)

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***Abstract*— Arrayed Waveguide Grating (AWG) Technology, one technique of dividing the channel into smaller sub-channels by adjusting the fixed array length increment. AWG techniques can generate coherent transmissions, which are suitable for Wavelength Division Multiplexing (WDM), to be implemented as multiplexer, demultiplexer, filter, add-drop device, and more. This paper discusses the design planning of AWG parameters operating on C-Band channels (1530-1560 nm), to support the needs of WDM channels, especially Dense-WDM (DWDM). Planning is done using WDM-Phasar tool and through theoretical calculations with MatLab. Theoretical calculations aim to produce ideal design parameters, while through WDM-phasar by adding the device size limit, crosstalk and nonuniformity values, it is expected to obtain more realistic design parameters. The parameters observed include the magnitude of the diffraction order (m), the length of the free propagation range (FPR), the difference in array length (ΔL), the number of arrays (Narray), number of I/O (Nmax) and free spectral range (FSR) channels. By using 16 channels of 100 GHz (0.8 nm) in the C-band, the size of the device (15000x9000 µm2), crosstalk (-35 dB) and nonuniformity (0.5), through WDM-Phasar assistance the AWG parameter 1197.347 µm (FPR), 23.764 µm (ΔL), 41 (m), 56 (N_{array}), 16 (N_{max}) and 11.2 nm (FSR). While ignoring the device size, crosstalk and non-uniformity variables, theoretical parameters were generated at 1308.61 µm, 25.1698 µm, 43.7143, 108 pieces, 27 channels and 21.211 nm, respectively for FPR, ΔL, m, Narray, Nmax and FSR. or WDM system capacity (16x16).**

Keywords*— *AWG, WDM, C-Band, crosstalk, non-uniformity

I. INTRODUCTION

Optical operational spectrum can be classified in 3 parts, namely window-1 (800-900 nm), window-2 (1270-1350 nm) and window-3 (1480-1600 nm), each centered at 850 nm, 1310 nm and 1550 nm [2]. Window-1 has been slowly being abandoned due to its considerable damping, so window-2 and window-3 are lately widely used as optical operational ranges. And by ITU-T in G.957 recommendation, dividing the 2 windows into 6 bands namely, bands O, E, S, C, L, and U.

Among the bands that exist, C-Band is the most widely used. The band occupies the 1530-1565 nm spectrum, which is equivalent to a bandwidth of around 4000 GHz. Another advantage of this band lies in window-3, which is more advantageous than window-2. Almost all optical network providers are fighting over this band, because it has low attenuation, larger range and many available amplifiers on the market.

Considering the limited C-Band spectrum, while while the number of users is very much, the band should be used as efficiently as possible, by dividing it into smaller channels through the wavelength division multiplexing (WDM) system. This paper discusses how an Arrayed waveguide grating (AWG) can divide the large bandwidth (C-Band channel) into smaller channels within the WDM scope.

Fig. 1. The C-Band Spectrum

II. WAVELENGTH DIVISION MULTIPLEXING

Wavelength Division Multiplexing (WDM) is a technique of combining multiple signals with different wavelengths. WDM technology is basically a transport technology, to transmit various types of traffic (data, voice, and video) in a transparent manner, using different wavelengths in a single fiber at a time. WDM implementation can be applied either on long haul network (long distance) or for subcriber haul application (short distance).

Based on the amount of channel spacing, WDM can be classified into Dense-WDM (DWDM), Coarse-WDM (CWDM) and Wide-WDM (WWDM), which have bandwidth sizes of ≤8 nm (≤ 1000 GHz), <50 nm (>1000 GHz) and >50 nm. There is even a WDM category with very small channel spacing (<10 GHz), known as Very High Density WDM (VHDWDM). [3]

In WDM technology, there are several techniques for dividing the wavelength (splitting) into several parts or re-combining them into wavelengths with different spacing sizes. Some of these techniques include Fiber Bragg Grating, Thin Film and Arrayed Waveguide Grating.

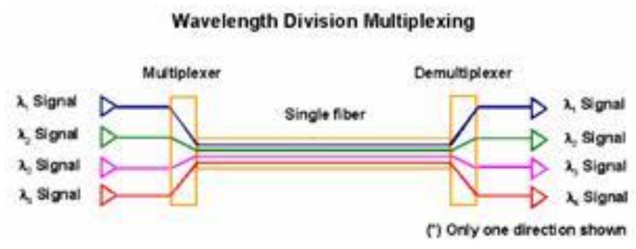

Fig. 2. The Concept of WDM

III. ARRAYED WAVEGUIDE GRATING (AWG)

Arrayed Waveguide Grating (AWG) also called phased array (PHASAR) is an optical network component consisting of 3 main parts of I/O channel, slab (star coupler) and multiple arrays. I/O channels consisting of multiple beams of light are connected into the slab, which consists of the first slab and the second slab contained in the input and output sections. On the input side works as a splitter and the output side serves as a combiner.

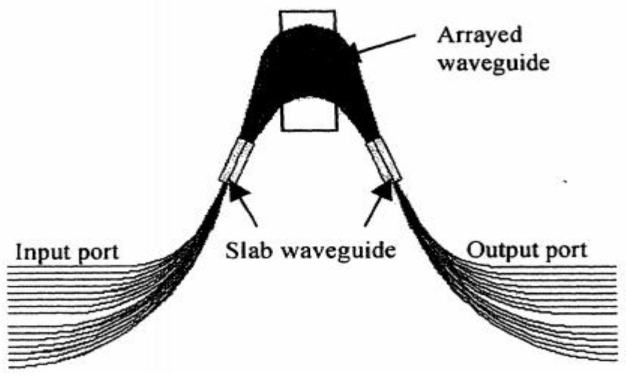

Fig. 3. AWG Basic Components

The main component of AWG are arrays, which have to receive the split result of the first slab divided into multiple arrays, where each array has a constant length difference of ΔL with the next, which depends on the channel space and the size of the device used. Each wavelength will focus on the different outputs in the slab in a region called the free propagation region (FPR), so that in the slab there will be no tangent between light beams.

Some of the advantages of AWG in its integration in optical networks, have very small ransmission losses, more accurate channel spacing, large number of channels and high system stability. AWG techniques can generate coherent transmissions, suitable for wavelength division multiplexing (WDM), as multiplexers, demultiplexers, filters, add-drop devices, etc.

A. Design Parameters

There are a number of AWG parameters that should be set before designing included:

1. Refraction Index
   The refraction index that must be known in the AWG design is the slab refractive index (ns), the refractive index of the array material (nc or neff) and the group index (ng).
2. Wavelength
   This wavelength is related to the desired range of work, so it involves the lower bound (λ_1), the upper limit (λ_2) and the middle wavelength (λ_0).
3. Width of Pitch (Grid)
   The width of grid (d) is inseparable from the existence of the slab, since this slit may be associated with I/O channel or it have to connect between slab and array.

TABLE I. DEFINED PARAMETERS

Parameter	Symbol	Value
Central frequency	λ_0	1550 nm
Frequency range	λ_1 , λ_2	1530-1565 nm
Refraction index of *slab*	n_s	3.06
Refraction index of l*ayer*	n_2	2.638
Effective refraction index	n_c	2.692
Group refraction index	n_g	4.5
Pitch length	d	15 μm

B. Calculated Parameters

Based on predefined parameters, there will be a number of AWG parameters able to be calculated, such as diffraction order (m), array length difference (**ΔL)**, focal length of slab (L_f), Free Spectral Range (FSR), maximum number of waveguide I/O channels (N_{max}), and maximum number of arrayed waveguide (**N_{array}**).

1. Order Diffraction

The order of diffraction (m) is influenced by the frequency range or wavelength in which the AWG is expected to work. The magnitude of the diffraction order is influenced by the upper and lower bounds of an optical spectrum band, as shown in the following formula:

$$\text{Order Diffraction (m)} = \frac{\lambda 1}{\lambda 2 - \lambda 1} \quad (1)$$

where,
m : diffraction order
λ_1 : lower limit of band range (nm)
λ_2 : upper limit of band range (nm).

2. Differences in The Length of an Adjacent Array

Differences in the length of an adjacent (ΔL) array are one of the important characteristics of the AWG system. The magnitude of this parameter, besides determined by the amount of the diffraction order (m) and the refractive index of the array material (n_c), is also influenced by the middle wavelength in which the AWG system will work. Large ΔL parameters, impacting less array spacing and more arched array paths. Of course this can only happen if it has a large diffraction order.

$$\Delta L = \frac{\boldsymbol{m}\,\boldsymbol{\lambda_0}}{\boldsymbol{n_c}} \quad (2)$$

where :
λ_0 : central frequency (nm)
n_c : effective refraction index.

3. Focal Slab Length

The length of the slab path or so-called focal slab waveguide (L_f) is sometimes referred to as the Free Propagation Region (FPR). It is the length of the slab path formed by the divergent light beam, which radiates from the first slab input grid to the array. Or it could also be associated with the length of the second slab path generated by the light coming out from the converging array convergently to the output of the second slab corresponding to the output channel.

$$\mathrm{Lf} = \frac{n_s d^2 n_c}{m\,\Delta\lambda\, n_g} \quad (3)$$

where,

n_s : slab refractive index
d : the width of grid spacing in the slab(μm)
n_g : refraction index of array group
Δλ : desired channel width spacing

4. *Free Spectral Range*

Free Spectral Range (FSR), can be roughly understood as an effective bandwidth that is ready to be divided into bandwidth channels with smaller sizes. The FSR value must be greater than the bandwidth requirement of all channels. For example, if desired 8 channels each with 200 GHz (1.6 nm) spacing, then the available FSR should be larger than 1600 GHz (12.8 nm).

$$\mathrm{FSR} = \frac{\lambda_0 n_c}{m\, n_g} \quad (4)$$

5. Maximum number of I/O channels

As mentioned earlier, the FSR value must be greater than the total number of all the channels served. Therefore, if it is known that the magnitude of the FSR will be able to calculate the number of I / O channels that can be formed (Nmax) with the desired specific spacing width (Δλ).

$$N_{max} = \text{integer}\left(\frac{FSR}{\Delta_\lambda}\right) \quad (5)$$

6. Arrayed Waveguides Number

As seen in the forming equation, the FSR parameter is influenced by the array material and the range of wavelengths in which the AWG system is to be operated. As a result, the FSR value will also affect the number of arrays that can be formed, as seen in the following equation:

$$N_{array} = 4N_{max} = 4\ \text{integer}\left(\frac{FSR}{\Delta_\lambda}\right) \quad (6)$$

TABLE II. CALCULATED PARAMETERS

Parameter	Symbol
Diffraction order	m
Difference of adjacent channel length	ΔL
Focal slab length	L_f
Free spectral range (FPR)	FSR
Maximum number of I/O channels	N_{max}
Arrayed waveguides number	N_{Array}

C. Additional Parameters

To get better design results, there are several other parameters that need to be added as more realistic planning considerations, such as device size, insertion loss, non-uniformity and crosstalk.

IV. DESIGN PLANNING STAGES

To get more comprehensive planning results from AWG parameters, besides theoretical calculations also use tool in the form of software tools. The steps taken are as follows:
- Setting all desired parameters.
- AWG planning with WDM-Phasar.
- Visualization of planning result.
- Calculation of AWG parameters.

WDM-Phasar is a tool that is selected to help display the visual representation of the design based on the design parameters those have been entered. But theoretical calculations also need to be done as a comparison that reflects the ideal conditions.

Initial planning begins with the selection of possible device sizes after a number of semiconductor parameters related to the AWG are entered, then viewed their effects on other parameters of the AWG as a consequence of selecting the specified semiconductor material. In addition to the device size variations, observations are also made by varying the number of different I/O channels and the width of channel spacing.

By inserting the device length of 15000μm, non-uniformity = 0,5 and crosstalk -35 dB, while the insertion loss is ignored (0 dB). Furthermore, using WDM-Phasar, their effects will be observed on other parameters, among others:
1. The effect of the size of the device.
2. The influence of the number of I /O channels.
3. Effect of the width channel spacing.

After obtaining initial observations, the desired schemes (16 I/O channels) are then selected for further study, including performing theoretical calculations as a comparison.

V. RESULTS

A. Initial Testing

By selecting a 15000μm length of device while the width is changed from 4000μm, 6000μm, 9000μm, 10000μm and 15000μm, the AWG parameters are obtained as shown in Table 3.

TABLE III. DEVICE SIZE EFFECTS

Device Width (μm)	4000	6000	9000	10000	15000
FPR length (μm)	690.77	690.77	**690.77**	690.77	690.77
Diffraction order	71	71	**71**	71	71
ΔL (μm)	41.15	41.15	**41.15**	41.15	41.15
Jumlah Array	64	64	**64**	64	64
Array putus	0	0	**0**	0	0
Cut I/O	15	9	**0**	0	0
FSR (nm)	21	21	**21**	21	21

B. Parameters of WDM-Phasar

Given the size of 4000μm and 6000μm many I/O channels are unserved (disconnect), therefore for further tests using a width of 9000μm. Furthermore, with the size of the device 15000μm x 9000μm with other parameters that are still the same, affecting the number of I/O channels (100 GHz spacing) to AWG parameters tested and produce output data as in Table 4.

TABLE IV. THE IMPACT OF THE NUMBER OF CHANNELS

Channel Number	2	4	8	16	32	40
FPR length (μm)	46.052	138.15	322.36	**690.77**	1427.60	1796.02
Diffraction order	1059	353	151	**71**	34	27
ΔL (μm)	613.80	204.60	87.52	**41.15**	19.70	15.64
Jumlah Array	5	14	30	**64**	131	164
Array putus	0	0	0	**0**	86	116
Cut I/O	0	0	0	**0**	21	40
FSR (nm)	1.4	3	10	**21**	45.5	57

As shown in Table 4, it can be seen that for the number of channels 32 and 40, there are partially unserved I/O channels and some arrays are not eligible, so for further tests using the number of I/O channels is 16 pieces, as the maximum number of secure I/O channels.

The next test is done by selecting the number of I/O channels as much as 16 pieces, but the magnitude of the channel spacing is changed and the results can be seen in Table 5.

TABLE V. CHANNEL SPACING EFFECTS

Channel Spacing (GHz)	8	10	50	100	200	500
FPR Length (μm)	690.77	690.77	690.77	**690.77**	690.77	690.77
Difraction Order	883	706	141	**71**	35	14
ΔL (μm)	511.79	409.20	81.72	**41.15**	20.28	8.11
Arrays Number	64	64	64	**64**	64	64
Cut Arrays	2	2	0	**0**	0	29
Cut I/O	4	3	0	**0**	0	0
FSR (nm)	1.7	2.1	10.9	**21**	44	110

Considering the C-band channel only has a width of about 4000 GHz, if it is to be divided into 16 I/O channels then the ideal maximum channel spacing is only 250 GHz. This is reinforced in the test results with 500 GHz channel spacing, it turns out there are a number of broken arrays. And the number of I/O channels selected for the AWG design is 16 channels of 100 GHz, so it is safe enough to used.

C. Theoretical Calculation Results

To obtain an ideal condition picture of the AWG parameters, still using the same parameters, theoretical calculation of parameters is also created using Matlab program. And the results can be seen in table 6.

TABLE VI. THE PARAMETERS CALCULATED IN THEORY

Channel Spacing						
Δf (GHz)	**8**	**10**	**50**	**100**	**200**	**500**
Δλ (nm)	**0.064**	**0.08**	**0.4**	**0.8**	**1.6**	**4**
m	43.7143	43.7143	43.7143	**43.7143**	43.7143	43.7143
ΔL (μm)	25.1698	25.1698	25.1698	**25.1698**	25.1698	25.1698
Lf (μm)	16358	13086	2617	**1308.61**	654.305	261.72
FSR (nm)	21.211	21.211	21.211	**21.211**	21.211	21.211
N_{max}	331	265	53	**27**	14	6
N_{array}	1324	1060	212	**108**	56	24

However, for 16 I/O channels, the channel widths suitable for AWG applications on C-Band bands are 50 GHz, 100 GHz and 200 GHz. And to get a safe planning result for the device size 15000μm x 9000μm selected with 100 GHz channel spacing.

D. Design Comparison

As indicated in the previous tables, both calculation with WDM-Phasar and theoretical calculations can be compared to each other. The special result of planning parameters AWG for 16x16 channels each has 100 GHz (0.8 nm) channel spacing as shown in Table 7.

TABLE VII. AWG DESIGN COMPARISON (16 X 16 CHANNELS)

Parameter	Symbol	Theory	WDM_ Phasar
Channel spacing	Δf (GHz)	100	100
Diffraction order	m	43.7143	41
Path-length difference	ΔL (μm)	25.1698	23.764
Focal length of the slab	L_f (μm)	1308.61	1197.347
Free Spectral Range	FSR (nm)	21.211	11.2
Number of I / O channels	N_{max}	27	27 (16) *
Number of arrays	N_{array}	108	110 (56) **

As seen in Table 7, there are some differences in the results of AWG parameters planning using WDM-Phasar software compared with theoretical calculation. This can happen because there are some conditions requested to enter in WDM-Phasar, such as the value of crosstalk, non-uniformity and the size of the device, which for theoretical calculations it does not exist.

Likewise for the maximum number of I/O channels successfully passed theoretically there are 27 channels, while the WDM-Phasar visual results have 27 I/O lines as well but only 16 are successfully missed, the rest are disconnected. This can be explained because when entering data in WDM-Phasar, the desired number of I/O channels is set to 16 pieces. Thus the maximum amount that can be passed only 16 lines.

The number of arrays required theoretically 4 times the number of I/O channels. With the number of I/O channels of 27 channels, then the number of arrays required can reach 108 lines. While the simulation results using WDM-Phasar seen there are 110 lines of the array, but only 56 that can be enabled. It can be explained that, since the number of I/O channels is 16, indeed required number of arrays is about 64 only. If WDM-Phasar only functions 56 of the 110, it is understandable because of the effect of crosstalk and non-uniformity values that can not reach the maximum, 64 lines (4x16).

E. Design Visualization

To know the magnitude of each channel power, using WDM-Phasar can be visualized the response of each I/O channel (16x16) with channel spasing 100 GHz (0.8 nm) on C-Band band can be shown in Fig.4.

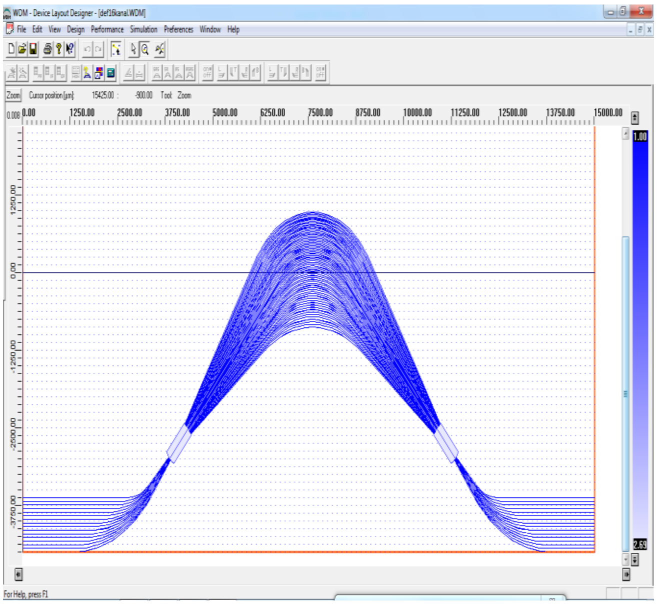

Fig. 4. AWG Design Result (16x16 Channels)

It can be seen in the figure that, for 16 channels of I/O channels it can be implemented on the planned AWG device, as evidenced by none of the I/O channels being broken. And when operated on a C-band channel, it can simulate the channel response as shown in Fig. 5.

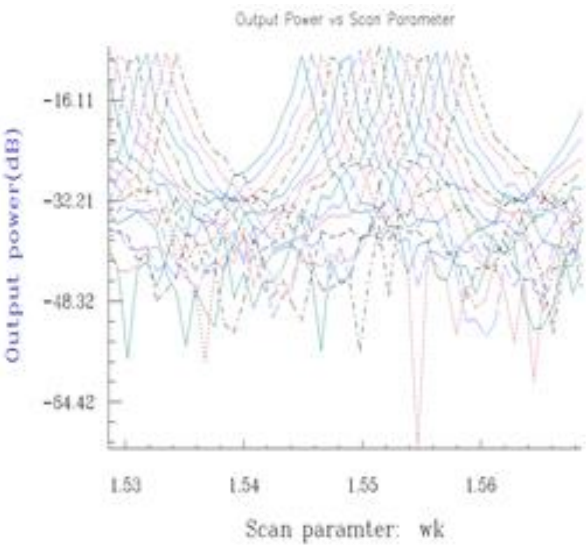

Fig. 5. Channel Response (16x16)

VI. CONCLUSIONS

From planning of Arrayed Waveguide Grating (AWG) parameters can be drawn some conclusions, such as diffraction order (m), Free Propagation Range (FPR), difference of array length (ΔL), number of arrays (N_{array}), number of I/O channels (N_{max}) and Free Spectral Range (FSR):

1. The size of the device is large, facilitating the planning of the desired AWG parameters, but clearly less efficient.
2. The larger the number of I/O channels requires a lot of large FPR, resulting in a smaller array spacing, making it more potentially broken.
3. The narrow working bandwidth causes a high diffraction sequence (m) and produces an increasingly curved array path. Because it has to maintain a constant array increase, so that more and more potentially damaged arrays.
4. For 100 GHz channel spacing, via WDM-Phasar with device size limit 15000x9000 μm^2, crosstalk -35 dB and nonuniformity 0.5, yielding AWG parameters 1197.347 μm (FSR), 23.764 μm (ΔL), 41 (m), 56 lines (N_{array}), 16 I/O channels (N_{max}) and 11.2 nm (FSR).
5. For 100 GHz channel spacing, in theoretical calculations giving results of 1308.61 μm (FPR), 25.1698 μm (ΔL), 43.7143 (m), 108 (N_{array}), 27 (N_{max}) and 21.211 nm (FSR).

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