Research on Loss-imbalance Equalization of AWG-based OADM

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ABSTRACT

Integrated-Optic Arrayed Waveguide Grating (AWG) NxN multiplexers are a new focus in All Optical Networks (AON) for their unique N input and N output geometry and have been used in a variety of applications.

All AWGs fabricated so far have shown loss-imbalance among FDM channels due to non-uniform diffraction efficiency. It is fatal in AON because it will accumulate after each AWG. Uniform diffraction efficiency obtained in ideal design limit is one ideal solution, but it is nearly impossible to achieve the ideal limit with present fabrication technology.

This paper applies a new method—shifted connection—on equalizing loss-imbalance of AWG-based OADM. The basic idea is simple and the result is of great significance. We theoretically analyze the effect of 8 various shifted configurations and predict each effectiveness. We find the relationship between the loss-imbalance and shift δ is a quadratic equation. We extend the method to cascaded AWGs. Also we deduce the limit of the equalization, which is independent of m and AWG's loss-imbalance parameter α, β. Experiment results accord with theory very well and show that we successfully reduce a worst case loss-imbalance (9.5 dB) to a best case loss-imbalance (3dB) in a single AWG-based OADM. We find that equalization configuration with foldback path is superior to loopback path configurations, when no more than N/2 wavelengths are used. The method is very simple and effective in equalizing AWG's loss-imbalance and the idea can be applied to other equalizations in AON.

keywords: AWG (arrayed waveguide grating), OADM (optical add/drop multiplexer), loss-imbalance, equalization, loopback path configuration, foldback path configuration

I. Introduction

All Optical Networks (AON) are attracting more and more attention because of their flexibility and scalability. An important node in AON is Optical Add/Drop Multiplexer (OADM) which can add/drop desired wavelengths between terminals and network. Among many configurations of OADM, one method is to apply a demultiplexer/multiplexer pair.

A promising device for such a demultiplexer/multiplexer pair is Arrayed Waveguide Grating (AWG) NxN multiplexer. An AWG consists of two star couplers combined with a waveguide array. It is usually integrated in a silicon substrate with Planar Lightwave Circuit (PLC) technology. AWG has a variety of applications in DWDM systems and AON.

Usually, AWG's router equation which reflects the relation between input port *i*, output port *j*, and pass wavelength λ n is $n = i + j - k \bmod N$, $1 \le i, j \le N$, k is a constant. In this paper, we will use a standard AWG with k=1.

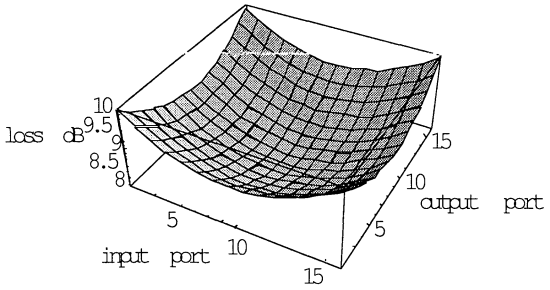


Fig.1. Relation between the loss and the input/output ports of the AWG (Loss-imbalance)

All AWG multiplexers fabricated so far, however, have shown loss-imbalance among FDM channels due to non-uniform diffraction efficiency. In AON, this is fatal because the loss-imbalance will accumulate after each node with AWG. Typical value is 2~3dB per AWG. Uniform diffraction efficiency obtained in the ideal design limit is one solution to get rid of loss-imbalance, but it is nearly impossible to achieve the ideal limit with present fabrication technology.

So it is necessary to do some research on how to reduce the loss-imbalance in system.

We can assume the diffraction efficiency distribution of the AWG to be Gaussian and the transmission loss in the periodic NxN multiplexer depends on the input/output port numbers *i* and *j* as following: [1]

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$$\alpha(i,j)=\alpha_0+\beta\left[\left(i-\frac{N+1}{2}\right)^2+\left(j-\frac{N+1}{2}\right)^2\right]=\alpha_0+\beta f(i,j) \quad (1)$$

where $\alpha(i,j)$ [dB] is the loss of channel $f_{i+j-1 \bmod N}$ from left port i (Li) to the right port j (Rj), α_0 [dB]is the loss between center ports $L_{N+1/2}$ and $R_{N+1/2}$, and β is the multiplication factor determined by N and the normalized spot size of AWG. We can show the relation between the loss and the input/output ports of the AWG as Fig.1, according to Equation (1).

The loss-imbalance of a configuration of AWG is the difference between the greatest loss and the least loss of all wavelengths in this configuration.

Two basic configurations in the application of AWG are loopback path configuration and foldback path configuration, as shown in Fig 2 and Fig 4 respectively. In the former configuration, input and output ports are at different sides of AWG while in the latter configuration, input and output ports are at the same side.

II. Theoretical Analyze on Loss-imbalance Equalization of AWG-based OADM

In theoretical analyze, we suppose a 16x16 AWG with Maximum Insertion Loss≤10dB, and loss-imbalance≤2dB. Actually, the maximum and minimum insertion is $\alpha(1,16)$ and $\alpha(8,8)$, respectively, so $\alpha(1,16)-\alpha(8,8)\le 2dB$. Thus we deduce α_0=8.0dB and β=0.0178571 respectively.

We find from Fig.1 that if the input port is the center port, the loss of the wave at the center output port is the least, and the loss of the wave at the edge output port is the biggest. The loss-imbalance curve of is symmetric. AWG is usually used both as multiplexer and de-multiplexer in optical systems, i.e., it is used bi-directionally, so a wave will pass AWG twice.

If we let wavelengths with larger (less) loss at the first path to pass a second path with less (larger) loss, we can reduce the difference of the total loss. So, it is possible to realize wonderful equalization by simply shifting the connect ports.

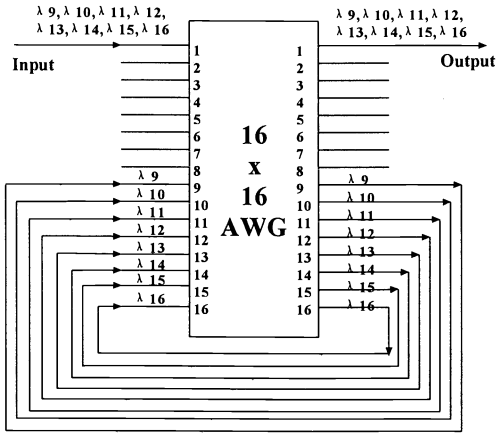


Fig.2. Conventional AWG-based OADM with loopback path

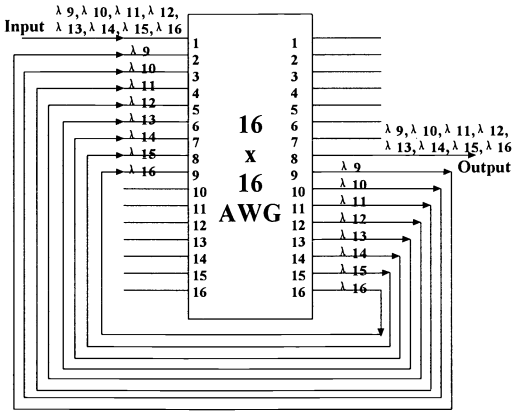


Fig.3. Shift connected OADM with loopback path (δ =7)

A). Loss-imbalance Equalization of Loopback Path Configuration

A conventional AWG-based OADM is shown in Fig.2. Wavelengths can add/drop at every loopback path by cutting the path into two ports, one used as add port and the other drop port. We do not show the add/drop ports in Fig.2,3,4 because the locations of add/drop ports have no impact on our equalization.

Fig. 2 can add/drop each of the 8 wavelengths λ 9— λ 16, which are inputted at left port 1 (L1), and are outputted at right port 9-16 (R9-R16) with losses $\alpha(1,9)-\alpha(1,16)$ respectively and $\alpha(1,9)<\alpha(1,10)<\cdots<\alpha(1,16)$. So in order to realize equalization we should make the loss of λ 9— λ 16 to descend in their second pass after looped back to AWG's left side. We propose the following ameliorated configurations (let loopback paths shift δ ports), as shown in Table 1. Where Config.8 (δ =0) is the conventional configuration. Fig 3 shows Config 1 (δ =7).

Table 1. Various Equalization Configuration of Loopback path

Input port L1, 1st Output R9-16	Config.1	Config.2	Config.3	Config.4	Config.5	Config.6	Config.7	Config.8
	δ =7	δ =6	δ =5	δ =4	δ =3	δ =2	δ =1	δ =0
Loopback to	L2—L9	L3—L10	L4—L11	L5—L12	L6—L13	L7—L14	L8—L15	L9—L16
Final Output port	R8	R7	R6	R5	R4	R3	R2	R1

Because $n=i+j-1 \bmod N$, $1\le i,j\le N$, then j=n-i+1 mod N. Because signal λ n is first inputted in L1 port, i.e.:

i=1, it will output at Rn port (because j=n-1+1 mod 16=n) with a loss $\alpha(1,n)$. Then λ n is looped back to L(n- δ) port, and it will be outputted at R(δ +1) (because j=n- (n- δ) +1 mod 16= δ +1) port with a loss $\alpha(n-\delta,\delta+1)$. Thus, we get the total loss of λ n:

$$\alpha_T = \alpha(1,n)+\alpha(n-\delta,\delta+1)=2\alpha_0+\beta[f(1,n)+f(n-\delta,\delta+1)]=2\alpha_0+\beta f_T \quad (2)$$

The loss-imbalance is:

$$\Delta\alpha_T = \max\alpha_T - \min\alpha_T = \beta(\max f_T - \min f_T) = \beta\Delta f_T \quad (3)$$

and $$f_T = 2\left(n-\frac{N+1}{2}\right)\left[\left(n-\frac{N+1}{2}\right)-\delta\right]+\delta^2+\left(\delta-\frac{N-1}{2}\right)^2+\left(\frac{N-1}{2}\right)^2 = 2x(x-\delta)+C \quad (4)$$

while $x = n-\frac{N+1}{2}$ and $0 < x \le \frac{N-1}{2}$ ($\frac{N+1}{2} < n \le N$), and $C = \delta^2+\left(\delta-\frac{N-1}{2}\right)^2+\left(\frac{N-1}{2}\right)^2$ is constant for each δ. The function of f(x) is shown in Fig 5.

For $0 \le \delta < \frac{N}{2}$, the maximum and minimum value of function f_T is obtained when $x = \frac{N-1}{2}$ (n=N) and $x = \frac{\delta}{2}$ ($n = \frac{N+1}{2}+\frac{\delta}{2}$) respectively. Because n is integer, $\min f_T$ is obtained when $n = \frac{N+1}{2}+\frac{\delta}{2}$ (if δ is odd) or $n = \frac{N+1}{2}+\frac{\delta+1}{2}$ (if δ is even). Thus we get the loss-imbalance of our loopback path AWG-based OADM:

$$\Delta\alpha_T = \beta\Delta f_T = \beta(\max f_T - \min f_T) = \begin{cases} \beta[\frac{1}{2}(N-1)(N-1-2\delta)+\frac{1}{2}\delta^2], \delta: odd \\ \beta[\frac{1}{2}(N-1)(N-1-2\delta)+\frac{1}{2}\delta^2]-\frac{1}{2}\beta, \delta: even \end{cases}, \quad (5)$$

B). Loss-imbalance Equalization of Foldback Path Configuration

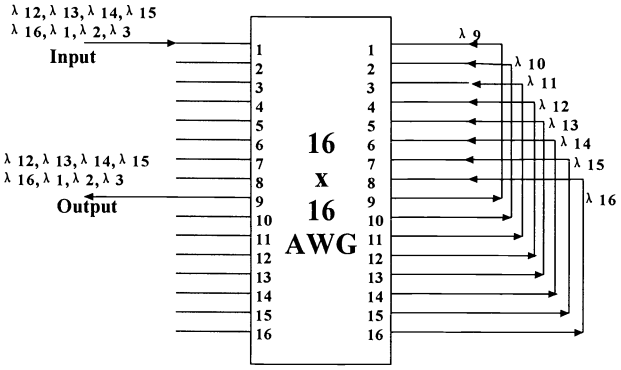


Fig. 4. Loss-imbalance Equalization of Loopback path Configuration

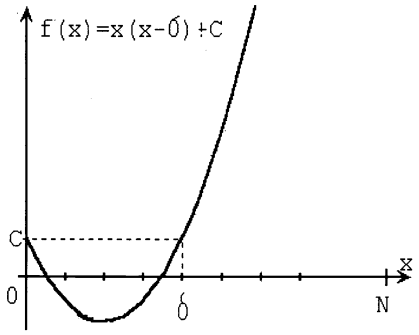


Fig.5. The relation between f(x) and δ

For NxN AWG and N/2 (suppose N is Even) continuous wavelengths (Wavelength Set ($\lambda_{N/2+1}$,...., λ_N)), only one shifted-connection foldback configuration is available, as shown in Fig.4, where δ =N/2. Wavelengths are inputted in AWG's L1 port and is outputted at L(N/2+1) port. We deduce the loss-imbalance as following:

Wavelength λ n passes AWG at the following sequence $L1 \to Rn \to R(n-\frac{N}{2}) \to L(\frac{N}{2}+1)$ with a total loss:

$$\alpha_T = \alpha(1,n)+\alpha\left(n-\frac{N}{2},\frac{N}{2}+1\right)=2\alpha_0+\beta\left[f(1,n)+f\left(n-\frac{N}{2},\frac{N}{2}+1\right)\right]=2\alpha_0+\beta f_T, \quad (6)$$

We find if we let δ =N/2 in (2) then we get (6). So we get:

$$f_T = 2\left(n-\frac{N+1}{2}\right)\left(n-\frac{2N+1}{2}\right)+\left(\frac{N}{2}\right)^2+\left(\frac{N-1}{2}\right)^2+\left(\frac{1}{2}\right)^2 = 2\left(n-\frac{N+1}{2}\right)\left(n-\frac{2N+1}{2}\right)+C \quad (7)$$

The roots of function $f = 2\left(n-\frac{N+1}{2}\right)\left(n-\frac{2N+1}{2}\right)=0$ is $n_1 = \frac{N+1}{2} = \frac{N}{2}+\frac{1}{2}$ and $n_2 = \frac{2N+1}{2} = N+\frac{1}{2}$. Because $n_1 = \frac{N+1}{2} < n \le N < n_2 = \frac{2N+1}{2}$, the minimum and maximum value of f_T is obtained when

$n=\frac{1}{2}(n_1+n_2)=\frac{3N+2}{4}$ (because n is integer, then $n=\left\lfloor\frac{3N+2}{4}\right\rfloor$, where the bracket means Integer) and $n=\frac{N+2}{2}=\frac{N}{2}+1$ (or $n=N$) respectively. So we get the loss-imbalance

$$\Delta\alpha_T=\beta\Delta f_T=\beta(\max f_T-\min f_T)=\beta\left[-\frac{N-1}{2}-2\left(\left\lfloor\frac{3N+2}{4}\right\rfloor-\frac{N+1}{2}\right)\left(\left\lfloor\frac{3N+2}{4}\right\rfloor-\frac{2N+1}{2}\right)\right], \quad (8)$$

If N is the multiple of 4, then $\left\lfloor\frac{3N+2}{4}\right\rfloor=\frac{3N}{4}$, and $\Delta\alpha_T=\beta\Delta f_T=\frac{N(N-4)}{8}\beta$. (9)

For NxN AWG (N is the multiple of 4), the minimum loss-imbalance of loopback path is obtained when δ=N/2 (Equation (5) gets its minimum value), and the loss-imbalance of foldback path is Equation (9). Because:

$$\frac{\Delta\alpha_T^f}{\min\Delta\alpha_T^l}=\frac{N(N-4)}{8}\beta\Big/\beta[\frac{1}{2}(N-1)(N-1-2\delta)+\frac{1}{2}\delta^2]-\frac{1}{2}\beta\Big|_{\delta=N/2}=1 \quad (10)$$

then we can say the loss-imbalance of foldback path configuration equals to the minimum loss-imbalance of loopback path configurations. But in fact, when N/2 continuous wavelengths are used, the maximum shift loopback path configurations can achieve is N/2-1. So we can say foldback path is better than the best configuration of loopback path.

III. Theoretical Result

We draw the total loss of each configuration in Fig 6, where the maximum value subtract the minimum value of each curve means the loss-imbalance of each configuration. Fig 7 shows the equalization effectiveness of each configuration when N=16 and β=0.0178571. We find the larger the δ, the better the equalization. The loss-imbalance of loopback path configuration is reduced from 2dB (δ=0, Conventional connection) to 0.57dB (δ=7). The loss-imbalance of fold-back path configuration is 0.43dB (δ=8).

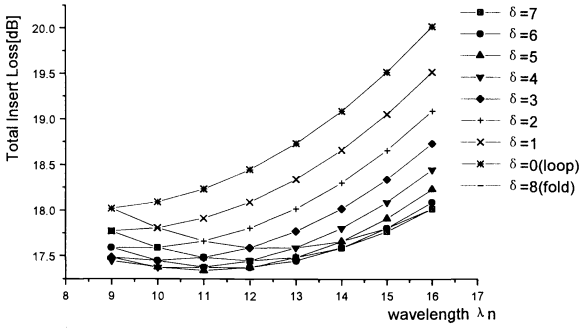


Fig.6. Total loss of each wavelength in each configuration

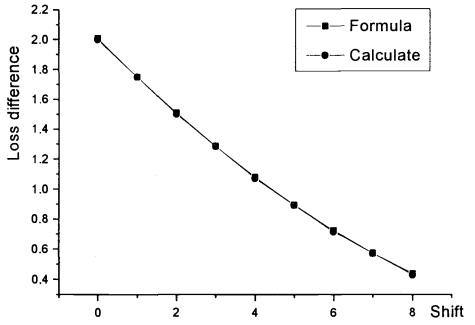


Fig.7. Effectiveness comparison of each shifted-connection

We can realize the loss-imbalance equalization of m ($m \geq 2$) AWG-cascaded configurations as Fig 8 and Fig 9. In these configurations, we reduce the loss-imbalance from 2×2=4dB to 0.43×2=0.86dB, which is only 21.4% of the former.

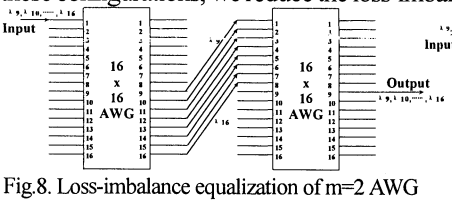


Fig.8. Loss-imbalance equalization of m=2 AWG cascaded configuration

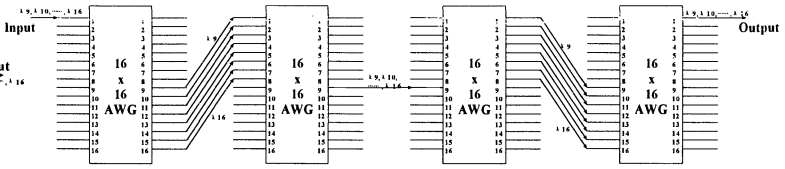


Fig.9. Loss-imbalance equalization of m=4 AWG cascaded configuration

Actually we can easily deduce the minimum loss-imbalance (limit) of the shifted connection configurations as Equation (11) by simply letting δ=0 and δ=N/2 in Equation (5).

$$\frac{Min(\Delta\alpha_T\,AfterEquqlization)}{\Delta\alpha_T\,BeforeEqualization}=\frac{1}{4}\cdot\frac{N(N-4)}{(N-1)^2} \quad (11)$$

If N=16, then Equation (11)=21.4%. We can get the following significative conclusion from Equation (11):

1). The limit is solely determined by N, no matter what m is. That means, the minimum loss-imbalance of equalization is the same no matter in a single AWG-based OADM or in m (m=2,m=4,…,m=2k, k is integer) AWG cascaded chains.

2). The limit is solely determined by N and independent of AWG's loss-imbalance parameter α and β. This is because our equalization is entirely a geometrical method.

IV. Experiments

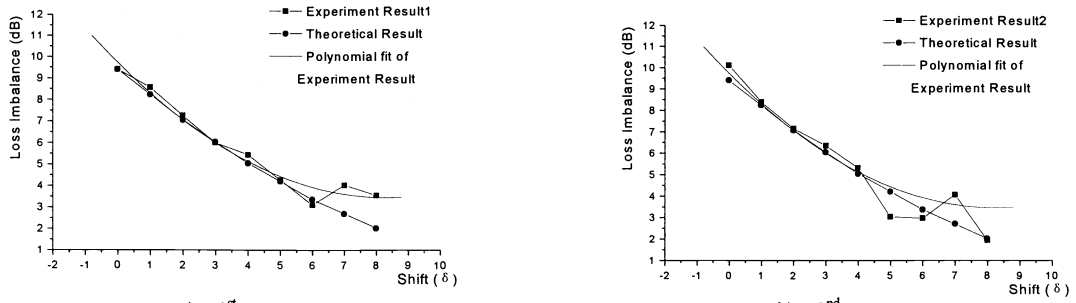
The property of the 16x16 AWG that we used in our experiment is as following: Maximum Insertion Loss≤10dB, and loss-imbalance≤7.55dB. Thus we deduce α_0=2.45dB and β=0.08394 respectively.

Our experiment result is shown in Table 2 and Fig 10.

Table2. Experiment results

1st measure	δ	0	1	2	3	4	5	6	7	8
	Loss-imbalance(dB)	9.4	8.55	7.25	6	5.43	3.54	4.26	3.1	4.01
2nd measure	δ	0	1	2	3	4	5	6	7	8
	Loss-imbalance(dB)	10.1	8.38	7.14	6.34	5.31	3.03	2.95	4.05	1.93

We find from Equation (5) that the relationship between the loss-imbalance and shift δ is a quadratic equation. So we use a quadratic function to fit the experiment result, as shown in Fig 10. Also we draw the theoretical result in the same plot with loss-imbalance parameter α_0=2.45dB and β=0.08394 of our experiment AWG. We find that our experiment fits with our theory quite well. But when δ becomes bigger (δ =5,6,7,8), the experiment error caused by measurement becomes more evident. The reason is that even the measure error is the same (e.g. 0.5dB) , it will have more effect on smaller values (2-3dB) than bigger values (9-10dB). But from Fig 10, we can still say that our experiment is very successful.



a)、1st measure　　b)、2nd measure

Fig.10. Experiment result

V. Conclusion

We have analyzed how to equalize the loss-imbalance in AWG-based OADM. We theoretically analyzed loss-imbalance equalization in two basic configurations: loopback path configuration and foldback path configuration. We deduced the loss-imbalance equation of each euqlization configuration and the loss-imbalance limit together with many significative conclusions. Finally we successfully valid our theory result with experiment Our research on loss-imbalance equalization of AWG-based OADM has significative importance in WDM systems.

VI. Acknowledgment

The author would acknowledge the support of National Nature Science Foundation (NSF).

VII. References

1、Osamu Ishida, et al, Loss-Imbalance equalization in Arrayed-Waveguide-Grating (AWG) Multiplexer Cascades, Journal of Lightwave Technology, Vol.13, No.6, June 1995, pp1155-1163

2、Hiroshi Takahashi, Kazuhiro Oda, et al, Transmission Characteristics of Arrayed Waveguide NxN Wavelength Multiplexer, Journal of Lightwave Technology, Vol13, No.3, Mar 1995, pp447-454

3、Michael C. Parker, et al, A novel active holographic arrayed-waveguide grating for WDM subsystems, OFC'2000 Technical Digest, WE6, pp77-79

4、M.K.Smit, New Focusing and Dispersive Planar Component Based on an Optical Phased Array, Electronics Letters, Mar. 1988, Vol.24, No.7, pp385-386

5、C.Dragone, An NxN Optical Multiplexer Using a Planar Arrangement of Two Star Couplers, IEEE Photon. Tech. Lett., VOL.3, NO. 9, Sept. 1991, pp812-814