High-speed transmission and dispersion characteristics of an arrayed-waveguide grating

M.E. Vieira Segatto a,1, G.D. Maxwell b, R. Kashyap b,2, J.R. Taylor c,*

a Departamento de Engenharia Elétrica, Universidade Federal do Espírito Santo, Av. Fernando Ferrari, Vitória-ES, 29060-900, Brazil
b Corning Research Centre, Astra Park, Martlesham Heath, Ipswich IP5 3RE, UK
c Femtosecond Optics Group, The Blackett Laboratories, Imperial College, Prince Consort Road, London SW7 2BZ, UK

Received 31 January 2001; accepted 16 May 2001

Abstract

In this paper we investigate experimentally and theoretically the dispersion characteristics of arrayed-waveguide gratings (AWGs) and their influence in the performance of high-speed transmission systems. The dispersion of a 17 × 17 AWG was measured using the “phase-delay” technique. Results show that dispersion is not negligible within the 10 dB transmission bandwidth. The system performance was studied in terms of the eye-closure penalty in a 40 Gbit/s system. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Arrayed-waveguide gratings; High-speed optical transmission; Dispersion measurements

1. Introduction

The ever-increasing demand for bandwidth in optical communication networks has increased the interest for dense WDM (DWDM) technology. This demand requires high-performance multiplexers and demultiplexers with low crosstalk and small channel separation. In general, the demultiplexing process is more difficult to implement. Several kinds of filters such as Fabry–Perot (FP) etalons, thin film filters, fibre gratings, and arrayed waveguide gratings (AWGs) have been proposed and used. The use of FP filters and fibre gratings has been quite successful for small number of channels. Above 16 channels, the AWG [1–3] has several advantages due to its compactness, low crosstalk [4], ability of working as a multiplexer or demultiplexer [3], and flexibility in the number of channels [5]. In general, parameters linked to the amplitude response such as insertion loss, crosstalk and spectral structure and are analysed in detail for AWGs but little attention is paid to the phase response. Non-linearities in the phase cause dispersion and lead to degradation of the system performance [6]. It has been suggested in previous works [6] that the phase response of AWG is linear and only small changes occur in presence of loss. We show here that in presence of loss, the AWG dispersion is no longer negligible and can have variations of the order of 40 ps/nm in the 10 dB transmission bandwidth. In this paper we investigate experimentally and theoretically the dispersion characteristics of an AWG and their influence.

*Corresponding author. Fax: +44-171-594-7782.
E-mail address: jr.taylor@ic.ac.uk (J.R. Taylor).
1 Partially supported by CAPES/Brazil.
2 Now with Corvis Canada.
in the performance of high-speed transmission systems. The system performance is studied in terms of the eye-closure penalty (ECP) due to wavelength fluctuations of laser diodes. This paper is organized as follows: In Section 2 we briefly describe the AWG theory. Section 3 presents measurements of the dispersion characteristics of a 17 × 17 AWG, and Section 4 presents ECP in a 40 Gbit/s system. Conclusions are given in Section 5.

2. Theory

Fig. 1 shows the diagram of a $N \times N$ AWG. It is composed of $N$ input/output waveguides, two identical slab waveguides, and an array of uncoupled curved waveguides [1,2,7]. Since the demultiplexing and multiplexing operations are the same, except that the light propagation direction is reversed we will describe only the demultiplexing process. Multiplexed light is launched into one of the input waveguides. The light is diffracted in the input slab and coupled into the arrayed waveguide. Every arrayed waveguide is located on a circle whose centre is at the end of the centre input waveguide. The radius of the circle is the focal length $L_f$ of the slab. The diffracted light enters the arrayed waveguides with the same phase. The lengths of any two adjacent arrayed waveguides differs by $\Delta L$. Each light propagates individually in the waveguide, thus attaining a phase difference at the waveguide exit. This phase difference results in wavelength dependent wavefront tilting. The output slab focusses the light from the arrayed waveguide in the vicinity of the output waveguides. The position of the input and output waveguides, slab waveguides and arrayed waveguide are based on the Rowland circle construction [8,9]. The focal position depends on the wavelength because of the wavelength-dependent phase shift caused by the path difference in the arrayed waveguide.

For sake of simplicity, we will consider the AWG working as a demultiplexer and input light in the central input. The multiplex operation can be easily explained by reverting the propagation direction. The electrical field at an output located at angle $\theta$ from the central arrayed waveguide (see inset in Fig. 1) is given by [10]

$$E = \sum_{j=0}^{n-1} f_j^2 \exp[i2\pi j n_c (\Delta L + d \theta)/\lambda + j \pi \Delta L],$$

where $n$ is the number of arrayed waveguides, $i = \sqrt{-1}$, $n_{\text{eff}}$, the effective refractive index of the arrayed waveguide, $d$, the arrayed waveguide pitch, $\theta$, the angle between the central arrayed waveguide and the output waveguide, $\lambda$, the wavelength dependent loss, $\lambda$, the wavelength, and $f_j$, the field coupling coefficient (considering identical input and output slabs). As the device response is a sum of $n$ weighted delays, Eq. (1) can be compared to the response of finite impulse response (FIR) digital filters [6,11]. The phase response depends mainly on two factors: the wavelength dependent

![Fig. 1. Schematic configuration of the AWG. $L_f$: focal length, $d$: arrayed waveguide pitch, $\theta$: the angle between the central arrayed waveguide and the output waveguide, $\Delta L$: spacing between output waveguides, $n$: number of arrayed waveguides.](image-url)
loss, and the coupling coefficients. Linear phase response is obtained only in lossless devices [6] with symmetric, in relation to the central arrayed-waveguide, coupling coefficients as shown in Appendix A.

3. Dispersion characteristics

Non-linearities in the phase response cause dispersion and lead to degradation of the system performance. In this section, we present the measured dispersion of a $17 \times 17$ AWG using the “phase-delay” technique commonly used to characterize fibre gratings [12]. The results are compared with those obtained theoretically by Eq. (1). Section 3.1 shortly describes the “phase-delay” technique, and the results are presented in Section 3.2.

3.1. Experimental setup

The dispersion in the AWG is measured based on phase-delay technique [12,13] as shown in Fig. 2. Light from a tunable laser with resolution of 1 pm is modulated by a Mach-Zehnder modulator at a frequency $f$ and launched into the input port of the AWG. The amplitude and phase of the transmitted signal is compared with the input modulated signal in a vector voltmeter. A computer is used to control the tunable laser, wavemeter, and vector voltmeter.

With the right choice of the modulation frequency, e.g., $f = 277.777778$ MHz, one degree of phase change is equivalent to a group delay $\tau$ of 10 ps. As the wavelength ($\lambda$) of the laser is tuned, the group delay is measured. The dispersion is then obtained by taking the numerical derivative of $\tau$.

3.2. The measured dispersion

In this section we present an experimental characterization of an AWG based on the phase-shift technique described above. The device under test was a $17 \times 17$ AWG designed and made at BT Research Labs. – Ipswich, using SiO$_2$-on-Si planar waveguide technology. Fig. 3 shows in detail the measured amplitude and group delay characteristics for the pair of central input–central output ports. It demonstrates that the group delay varies with the wavelength and the device presents positive and negative dispersion across the transmission bandwidth. The figure also shows the theoretical values to the amplitude and group delay obtained from Eq. (1). The field coupling coefficients were chosen in such way that the amplitude responses in the 10 dB bandwidth are the same for both, the measured and computed responses. For all results, a Gaussian profile is used for $f_j$ with values varying from 1 to 0.2, using a similar procedure.

![Fig. 2. The “phase-delay” experimental setup used to measure the amplitude and phase characteristics of the AWG.](image-url)
previously reported in Ref. [10]. The measured amplitude and group delay shows good agreement with theory. For this study we have ignored the variation of $f_j$ with wavelength, it would explain the small difference between the measured and computed amplitude response on the short wavelength side.

The dispersion is obtained directly from the derivative of the group delay. Fig. 4 shows the dispersion characteristic for the central input–output. The computation of the dispersion was limited to the 10 dB transmission bandwidth of each channel (pair input–output). Results show that the dispersion varies from $-20$ to $+20$ ps/nm inside the 10 dB transmission bandwidth.

4. High-speed transmission

In this section, the effects of the AWG dispersion on the system performance are theoretically studied in terms of the ECP in a 40 Gbit/s system. Fig. 5 shows the setup used in the simulations. Light from a DFB laser is externally modulated in an electro-absorption modulator by 40 Gbit/s, $2^7$-1 NRZ-PRBS pulses. The output of the external modulator is connected to the AWG input port. The output signal is then analysed on an oscilloscope.
In general, simulation software for optical communication uses Gaussian filters as a model for the AWG. Those filters have constant phase, and do not take into account the AWG dispersion. Here, we will analyse two different models for the AWG: the Gaussian-like AWG (Model 1), and a model (Model 2) based on Eq. (1) where the phase response is also taken into account.

Fig. 6 shows the eye diagram for the AWG output. The parameters used in both models are the same of those used in Fig. 3. The Gaussian filter is obtained by fitting a Gaussian curve to the amplitude response of the AWG. In Fig. 6(a), the DFB laser wavelength is chosen to match the maximum transmission wavelength of the AWG. 

The output for Model 2 shows a slight asymmetry due to the AWG dispersion. Fig. 6(a) shows the same system but the laser wavelength presents a mismatch of 0.2 nm from the maximum in the AWG. The eye closes for both models. For the first model, the eye closure is due only to the amplitude response behaviour and for the second model the amplitude and phase are responsible. A comparison between the two models shows the influence of the dispersion.

Fig. 7 shows the ECP as function of the wavelength mismatch for Model 1 and Model 2. The penalty is computed by taking the eye diagram in Fig. 6(a) as the reference signal. The ECP for Model 1 is governed by the amplitude response of the AWG and it is about 1.4 dB for a wavelength mismatch of 0.2 nm. For Model 2, the ECP is 3.8 dB at the same point. The graph shows clearly the influence of the dispersion in the system performance.

5. Conclusions

We have investigated experimentally and theoretically the dispersion characteristics of AWGs

\footnote{In all simulations in this section, the central input–central output pair of the AWG was used.}
and their influence in the performance of high-speed transmission systems. The dispersion of a 17 × 17 AWG was measured using the “phase-delay” technique. The results show good agreement with theory and dispersion varies from −20 to +20 ps/nm inside the transmission bandwidth. Two factors in Eq. (1) determine the dispersion in the AWG: the coupling coefficients \( f_j \) and the loss in the arrayed-waveguides (\( a \)). Random phase changes due to errors in the fabrication process, small differences in the input and output slabs and losses in the slab waveguides cause asymmetry (in relation to the central arrayed-waveguide) in the coupling coefficients leading to non-linearities in the phase response and dispersion in the AWG (see Appendix A). The losses in the arrayed-waveguides have an effect similar to an exponential apodization in the coupling coefficients. The system performance was studied in terms of the ECP in a 40 Gbit/s system. Two different models were used to the AWG. In the first model, only the amplitude response of the AWG was taken into account and in the second model, the phase response was also included. The ECP was computed for both models as function of the wavelength mismatch between the maximum transmission wavelength of the AWG and optical carrier. Comparison between the results for both models show that the ECP is 2.3 dB worse for 0.2 nm of mismatch when the AWG dispersion is taken into account. The results of this investigation provide clear understanding of the dispersion behaviour of AWGs and its importance for high-speed transmission systems.

Appendix A. Phase linearity in arrayed-waveguide gratings

Eq. (1) can be rewritten in the frequency domain as

\[
E = \sum_{j=0}^{n-1} k_j \exp[iS(j\omega)],
\]

where \( \omega = 2\pi c/\lambda \),

\[
S = \frac{n_d\alpha}{c}(\Delta L + d\theta),
\]

and

\[
k_j = f_j^2 \exp[j\alpha \Delta L].
\]

The AWG has zero dispersion if the group delay is constant, i.e. the phase \( \Theta(\omega) \) varies linearly with the frequency

\[
\Theta(\omega) = \tau \omega.
\]

From Eqs. (A.1) and (A.4)

\[
\Theta(\omega) = \tau \omega = \tan^{-1} \left[ \frac{\sum_{j=0}^{n-1} k_j \sin(j\omega)}{\sum_{j=0}^{n-1} k_j \cos(j\omega)} \right]
\]

or

\[
\tan(\tau \omega) = \frac{\sum_{j=0}^{n-1} k_j \sin(j\omega)}{\sum_{j=0}^{n-1} k_j \cos(j\omega)} = \frac{\sin(\tau \omega)}{\cos(\tau \omega)}
\]

and

\[
\sum_{j=0}^{n-1} k_j \sin(\tau \omega - j\omega) = 0.
\]

The solution for Eq. (A.7) can be shown to be [11]

\[
\tau = \frac{(n-1)S}{2},
\]

\[
k_j = k_{(n-1-j)} \quad \text{for} \quad 0 \leq j \leq n - 1.
\]

Therefore, in order to obtain a dispersionless AWG, the coefficients \( k_j \) must be symmetrical about the central arrayed-waveguide.

References


