Application of Nano-Technology in Planar Silica Waveguides to Enhance the Performance of AWG's and Other Standard Devices

Anthony Ticknor, Ming Yan, Brian McGinnis, Liang Zhao, and Hao Xu

NeoPhotonics Corporation
2911 Zanker Rd., San Jose, CA 95134
tticknor@neophotonics.com

ABSTRACT

Silica waveguide planar lightwave circuits (PLCs) are generally not regarded as a platform well suited for implementing nano-technology optics due to comparatively low index contrast, feature sizes substantially larger than the optical wavelength, and processing that intentionally suppresses high-spatial-frequency structures in order to minimize random scattering losses. Furthermore, the material sets available for standard PLC processes do not yet include the range in index of refraction commonly associated with nano-optical structures. Nonetheless, the performance of top-of-the-line PLC circuits is only achieved is only achieved using tools and processes providing control of the optical circuits at a nanometer-scale. These achievements do not come by accident, but are the results of judicious application of nanotechnology, although by a rather oblique course.

Keywords: optical path length, optical metrology, phase error, arrayed waveguide grating

1 INTRODUCTION

The consideration of nanotechnology optics typically engenders visions of small-volume devices with densely-packed structures having high refractive-index contrast, quintessentially such things as photonic crystals, 'holey' fibers and the like. Much less likely would one think of planar lightwave circuit (PLC) devices such as arrayed waveguide gratings (AWGs) with hundreds of low refractive-index contrast waveguides meandering across many square mm or square cm of device surface. However, in order to meet the commercial specifications for premium-grade components, it is necessary to control the optical paths of these waveguides with relative precision of a few nanometers. The achievement of this level of precision requires some uncommonly sophisticated capabilities, most notably: 1) The relative modal index of the waveguides must be repeatable to within about 1 part in 10^6; 2) There must be metrology capable of determining optical path lengths with nanometer accuracy; and 3) There must be means for adjusting the design of individual path lengths at nanometer-scale accuracy.

Reproducibility of the effective index is not a subject of this paper and will not be discussed here other than to assert that we have that capability. The design and metrology issues however are directly nanometer-scale technology issues and that is what will be described here.

2 PERFORMANCE IMPACT

The archetypical PLC waveguide filter is the AWG, which interferes the optical signal from dozens or hundreds of optical paths to disperse several closely-spaced wavelengths into individually terminated waveguides.

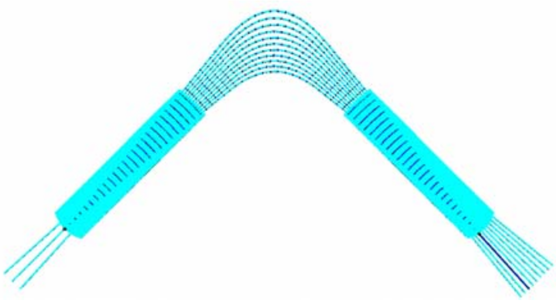

Figure 1: Typical AWG configuration

In fiber-optic networks, optical efficiency of the components is placed among the highest-importance specifications. Since there is not yet any practically integrable means to efficiently match waveguides with significantly different numerical apertures, AWG waveguides must have similar refractive-index contrast to the fibers that they connect, which is relatively low in practical networks. This constrains the index contrast of AWG waveguides to be in the range of about 0.5% to 1.5%, about 1/100th the index contrast of typical photonic-bandgap devices. This leads to typical AWG devices having optical circuits that are several cm along the optical path by a few cm laterally. AWG filters are used to distinguish telecommunications wavelength channels typically separated by about 0.025% or 0.05% of the optical carrier frequency. To achieve sufficient dispersion at the selected numerical aperture, the optical path-length difference (OPD) between adjacent arms is commonly between 50μ and 100μ. Since there are no recursive optical paths in the

AWG, it is capable of providing very-low dispersion, meaning that the transit time for an optical signal passing through the device does not change much as the wavelength of the optical signal changes. Since AWG's are capable of providing exceptional filtering performance, many applications specify that they do provide that level of performance. Along with all the other performance specifications, out-of-band power needs to be rejected to levels below –50dB and the magnitude of the dispersion needs to be less than 10 picoseconds/nanometer. Analysis of the AWG function reveals that in order to meet these specifications for manufacturing a population of parts, the path-length difference between each of the AWG arms must achieve the targeted value to within about λ/300, or about 5nm optical path, which is about 3nm waveguide length.

3 METROLOGY

Optical low coherence interferometers have been reported to successfully measure the phase and amplitude information of AWG's.[1-3] We have constructed and employed such an interferometer in a fiber Mach-Zehnder (MZ) configuration similar as shown in Figure 1. Light from a 1.5mm broadband LED with a coherence length less than the OPD of adjacent grating waveguides was coupled into two optical fibers, one to the device under test (DUT), the other to a reference path with length adjustment. Once re-combined, the interferometer generated a series of interferograms, each interferogram associated with a single waveguide in the AWG, by delaying the optical path in the reference arm. The low coherence length of the LED enabled the separation of the interferograms for each grating waveguide and the relative phase and amplitude distributions between interferograms were used to derive the deviations from ideal. A 1.3 mm laser diode (LD) was used as the clock signal for accurately measuring the optical path length difference in MZ interferometer. The zero crossings of the high coherence interference signal were used to trigger the sampling of the LED's interferogram as the reference path length is scanned. Therefore, the interval between the adjacent fringes was half of the LD wavelength. Sampling of the LED interferogram occurs at a frequency slightly greater than the Nyquist frequency.

To obtain the required resolution, an improved low coherence optical fiber MZ interferometer was built and used to measure the phase error and amplitude distribution of AWGs. This information was used to verify and improve our AWG performance. Oversampling was used in conjunction with a Hilbert transformation technique. To improve the achievable resolution of the instrument. The new interferometric system is able to resolve phase errors less than λ/500. The improved configuration also allows windowing technique to be used to reduce overlap noise that can occur when characterizing AWGs with grating order that do not provide an adjacent OPD exceeding the coherence length of the broadband source. Group delay (GD) and chromatic dispersion (CD) were derived from the phase error measurements and compared with directly measured results from a commercial CD measurement instrument. The correlation between the phase error, GD, and CD was evaluated, and phase error was used as the criterion for improving the CD for the narrow channel spacing AWG.

4 RESULTS AND ANALYSIS

The method described has been established to work very well for the measurement of our AWG products. The phase and amplitude distributions for low grating order, as well as narrow channel spacing AWG's, as extreme cases have also been accurately measured. Phase errors of less than λ/500 can be resolved with this technique.

4.1 Phase error and amplitude

As described, accurate phase error and amplitude information allows verification of device design, monitoring of device processing, and targeting of phase compensation. The measured amplitude and phase error result of an exemplary 100GHz Gaussian AWG (G-AWG), and 50GHz passband flattened AWG (PF-AWG) are shown in Figure 3(a) and 3(b), respectively.

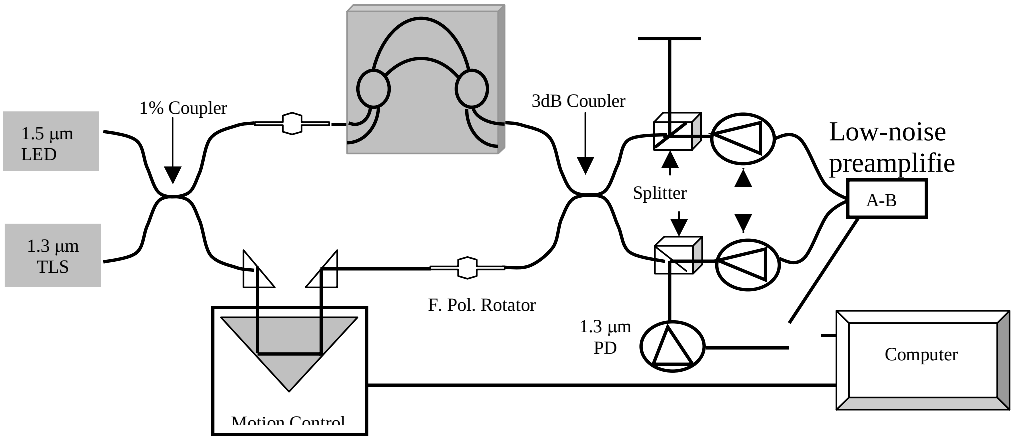

Figure 2. Schematic of Optical Low-Coherence Interfereometer

By decomposing the phase error into slow-varying and fast-varying components, we can identify random material and process defects (fast-varying) from slow-varying design or within wafer variations that can reduce AWG performance. Fast-varying components contribute to an increase in the noise floor, while slow-varying components contribute to passband shape and adjacent channel isolation in AWG's used in demultiplexing applications.

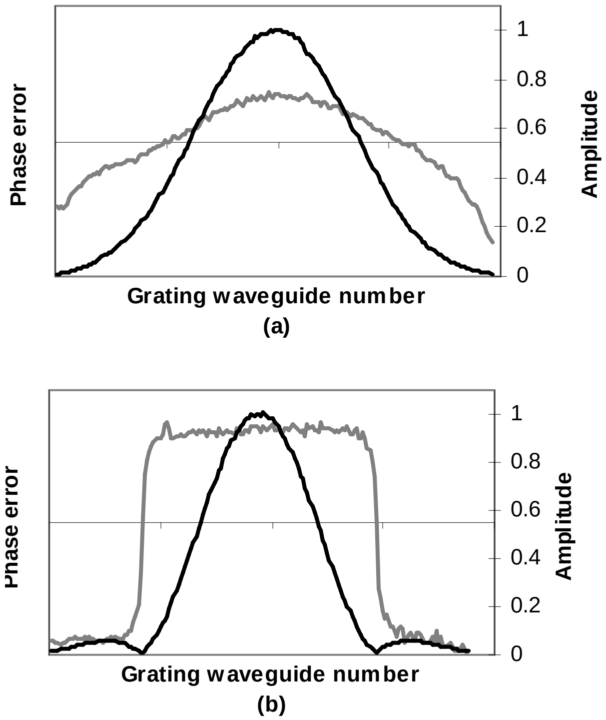

Figure 3 Relative amplitude (black) and phase (gray) errors of Gaussian (a) and passband-flattened (b) AWGs

4.2 GD and CD derivation from the Phase and amplitude data

Chromatic dispersion (CD) is an important issue for high bit rate transmission systems. Generally, an AWG is a finite impulse response (FIR) filter, which exhibits minimum dispersion properties. Deviation from this ideal arises from phase errors generated by the process variations and were found to contribute significantly to the group delay (GD) and CD for the narrow channel spacing components such as 50GHz and 25GHz AWG's. The low coherence interferometer described proves to be a useful tool to measure and improve the GD and CD performance. The GD and CD were directly calculated from the amplitudes and phase profile of its measurement result. The transfer function, H, of an AWG filter can be expressed as

$$H(\sigma) = \Sigma\, h_k(\sigma) = \Sigma\, A_k(\sigma)*\exp(-j2\pi\sigma\Delta_k(\sigma)-j\phi_k) \qquad (1)$$

where $A_k(\sigma)$ and ϕ_k are the amplitude and phase of the light propagating through the kth arrayed waveguide. $\Delta_k(\sigma)$ is the optical path length of the kth grating waveguide. The GD depends on the transfer function according to

$$GD = -d\Phi/d\omega \qquad (2)$$

where ω is the optical frequency and Φ is the phase of the transfer function, which is related to the real and imaginary parts of H according to

$$\tan(\Phi) = Im(H)/Re(H). \qquad (3)$$

Chromatic dispersion (CD) is related to group delay according to

$$CD = -d(GD)/d\lambda. \qquad (4)$$

The phase and amplitude of a 50GHz PF-AWG was measured and its GD and CD were derived. The calculated GD and CD were compared with the result from the commercial CD tester using the Modulation Phase Shift Method. As shown in Figure 4, the two measurements show good agreement and the reduced noise in this technique is apparent. Figure 4 also shows that finite impulse response (FIR) AWGs have much less chromatic dispersion than infinite impulse response (IIR) filters, such as dielectric thin film filters and fiber Bragg gratings.

4.3 Correlation of slow phase error to the GD slope and CD

As discussed above, the phase error was separated into the slow-varying and the fast-components. The fast-varying phase error usually corresponded to the fabrication defects. The slow-varying phase error usually represented the design and process error both of which affect the device optical performance. We found that slow-varying phase error was the dominant factor in determining the chromatic dispersion within passband. This was consistent with the conclusion of Yamada, et al.[3] Reduced slow-varying phase error components resulted in lower group delay slope. As a consequence, the chromatic dispersion performance is improved. Further studies showed that the average of the slow-varying phase error correlated well with the CD at the passband center.

4.4 Improving the CD by phase error compensation

The chromatic dispersion of AWG's was shown to be effectively improved by reducing the slow-varying phase error. By using the low coherence interferometer to perform phase error measurements, the subsequent analysis of slow-varying phase error can be used to improve CD performance, especially in narrow channel spacing devices such as a 25GHz AWG. We found compensation of the measured phase error a powerful technique to reduce CD by either adjustment of physical path length during device design. By making slight adjustments to the angle of a waveguide, we are able to statistically leverage very small length adjustments below the resolution of the design grid, achieving axial length changes of only a few nanometers with lateral design shifts on a 0.1μ grid. Modification of effective index was also investigated as a post-process technique to verify improvements in the CD performance of one of our 25GHz PF-AWG, though this is not considered a practical manufacturing technique. Index adjustments were accomplished by UV laser trimming [4] taking advantage of the UV photosensitivity of doped-silica glasses. A portion of individual waveguide was photosensitized to induce an effective index change to compensate the phase error in that waveguide using

$$\delta n * L(k) = \Delta(k) \tag{5}$$

where δn is effective index change by UV laser irradiation and L(k) is the physical length of grating waveguide k that is exposed, D(k) is the corresponding phase error measured by low coherence interferometer. A single aperture mask with physical length L(k) for corresponding grating waveguide k could be used for reducing the total exposure time of UV laser.

The measured phase error and the CD after phase error compensation for the previously shown 25 GHz PF-AWG was reduced to within +20 ps/nm in the 10 GHz passband.

5 CONCLUSIONS

Application of nanometer-scale design and metrology is shown to be critical to the performance of AWGs, a class of devices not commonly associated with nanotechnology. Manufacturing of premium-grade AWG components is employing metrology, design, and relative control of the path lengths of hundreds of waveguides on each device to a level of 5 nanometers or below in order to ship to present-day commercial specifications, and applications are coming that will push those resolutions even smaller

REFERENCES

[1]. K. Takada, H. Yamada, and Y. Inoue, “Optical low coherence method for characterizing silica-based arrayed-waveguide grating multiplexes”, J. of Lightwave Technology, Vol. 14, No. 7, pp1677-1689, July 1996

[2]. H. Yamada, H. Sanjoh, M. Kohtoku, K. Takada, and K. Okamoto, “Measurement of phase and amplitude error distributions in arrayed-waveguide grating multi/demultiplexers based on dispersive waveguide”, J. of Lightwave Technology, Vol. 18, No. 9, pp1309-1320, September 2000

[3]. H. Yamada, K. Okamoto, A. Kaneko, and A. Sugita, “Dispersion resulting from phase and amplitude errors in arrayed-waveguide grating multiplexers-demultiplexers”, Optics Letters, Vol.25, No.8, pp569-571, April 15, 2000

[4]. K. Takada , Y. Inoue, H. Yamada, and M. Horiguchi, “Measurement of phase error distributions in silica-based arrayed-waveguide grating multiplexers by using Fourier transform spectroscopy”, Electronics Letters, Vol. 30, No.20, pp1671-1672, September 29, 1994

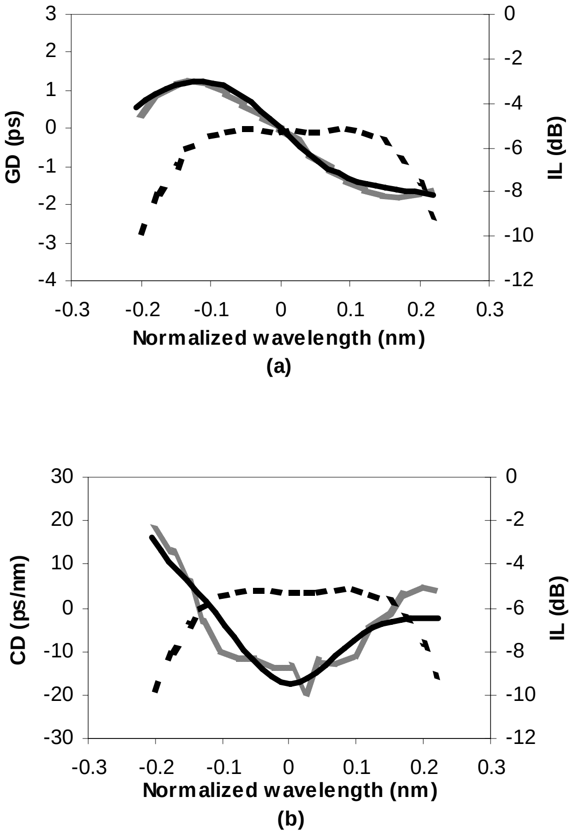

Figure 4 (a) Group delay, (b) Chromatic dispersion, dotted lines are the IL curves, the gray lines show the results from the commercial CD tester, and the black lines show the results from the low coherent interferometer.