Evaluation of the phase error in Si-wire arrayed-waveguide gratings fabricated by ArF-immersion photolithography

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Abstract: The phase errors in 100-GHz spacing, 8-ch, Si-wire arrayed-waveguide gratings (AWG) fabricated by ArF-immersion photolithography were measured by the frequency-domain interference method. To our knowledge, this is the first time phase error measurements in a Si-wire AWG have been performed. By comparing the reconstructed transmission spectrum to the directly measured spectrum, the accuracy of this phase error measurement was confirmed. The average phase error in the AWGs on 6 chips was 0.27π radian, and this value is equivalent to a fluctuation in the effective refractive index of 1.1 × 10⁻⁴.

Keywords: phase error measurement, si-wire arrayed-waveguide grating

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References

1 Introduction

Recently, many studies have been devoted to silicon photonics in efforts to miniaturize optical devices and to integrate these devices with electronic devices on the same chip. Si-wire waveguides have very small bend radius; therefore, the device size of a Si-wire arrayed-waveguide grating (AWG) is much smaller than one consisting of silica waveguides [1, 2]. However, the crosstalk and the deviations of the center wavelengths of Si-wire AWGs are very large because of the fluctuation in the effective refractive index of the waveguide, which is caused by the non-uniform core thickness and the roughness of the sidewalls of the waveguides. To improve the performance of Si-wire AWGs, an evaluation of the fluctuation of the effective refractive index is essential. An evaluation of the phase errors in coupled resonator optical waveguides using the transfer matrix method has been reported [3]. On the other hand, the phase error in each light path in an AWG and the power distribution to each waveguide can be measured using the frequency-domain interference method [4, 5, 6, 7], which is very useful for characterizing an AWG.

In this paper, we measured, for the first time, the phase errors in 100-GHz spacing, 8-ch, Si-wire AWGs using the frequency-domain interference method.

2 Theory of phase error measurement

The experimental setup for the frequency-domain interference method is shown in Fig. 1. It consists of a main interferometer section and a sub interferometer section. The former section acquires the interferogram between the light path through the AWG under test and another path; the latter is used to obtain an accurate frequency marker signal.

![Fig. 1. Schematic of the system used to measure the phase errors.](image-url)

References

In the main interferometer, the interferogram is derived from

$$I(k) = 1 + |H(k)|^2 + 2 \text{Re}[H(k) \exp(jkL)].$$  \hspace{1cm} (1)

In Eq. (1), $k$ is the wavenumber, $L$ is the path difference between the arms of the main interferometer, and $H(k)$ is the transfer function of the AWG, which is derived from

$$H(k) = \sum_{m=0}^{N-1} A_m(k) e^{-j\phi_m(k)} e^{-jmnk\Delta L}$$  \hspace{1cm} (2)

In Eq. (2), $N$ is the number of waveguides in the arrayed-waveguide, $A_m$ and $\phi_m$ are the amplitude coefficient and phase error of the $m$-th waveguide, respectively, $n$ is the effective refractive index of the waveguide, and $\Delta L$ is the path difference in the AWG. $H(k)$ is separated from the other terms by Fourier transformation of Eq. (1). There are $N$ peaks corresponding to each waveguide in the arrayed-waveguide. The $m$-th peak is obtained from

$$h_m(x) = \int_{-\infty}^{\infty} A_m(k) e^{-j\phi_m(k)} e^{-jk(x+mn\Delta L)} \, dk$$  \hspace{1cm} (3)

$A_m(k) \exp(-j\phi_m(k)) \exp(-jmnk\Delta L)$ is obtained from the inverse Fourier transform of Eq. (3). The argument is given by

$$\theta_m(k) = -\phi_m(k) - nmk\Delta L$$  \hspace{1cm} (4)

When $k$ is the center wavenumber ($= k_0$), the argument $\theta(k_0)$ is equal to the phase error derived from

$$\theta_m(k_0) = -\phi_m(k_0) - 2\pi m M = -\phi_m(k_0)$$  \hspace{1cm} (5)

because the path difference $\Delta L$ is given by

$$\Delta L = \frac{M}{n} \frac{2\pi}{k_0}$$  \hspace{1cm} (6)

where $M$ is the diffraction order. From Eq. (5), the phase error of each waveguide in the arrayed-waveguide can be obtained.

3 Design and fabrication of AWG

Fig. 2 shows the chip layout on the 300-mm SOI wafer, from which six chips were selected for measurements. A microscope photograph of the test AWG is shown in Fig. 3. AWGs were fabricated using an ArF-immersion photolithography process. The size of the test AWGs is $460 \, \mu m \times 1300 \, \mu m$. The core thickness is $0.22 \, \mu m$ and the core widths of the straight sections in the arrayed-waveguide widen to $0.80 \, \mu m$ through tapered waveguides. Other parameters of the test AWGs are shown in Table I. $\Delta \nu$ is the channel spacing in the TE polarization, $N_{\text{ch}}$ is the number of output channels, $N_a$ is the number of arrayed waveguides, FSR is the free spectral range, $\Delta L$ is the difference between the lengths of adjacent waveguides, and $L_{\text{ave}}$ is the average length of the waveguides. The simulated transmission characteristics of the test AWG are shown in Fig. 4. The crosstalk is $-60 \, \text{dB}$ and the peak wavelength of output channel 5 is $1549.6 \, \text{nm}$.
Fig. 2. Chip layout on the SOI wafer.

Fig. 3. Microscope photograph of the test AWG.

Table 1. Parameters of the test AWG

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$\Delta v$ [GHz]</td>
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</tr>
<tr>
<td>$N_{ch}$</td>
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</tr>
<tr>
<td>$N_a$</td>
<td>24</td>
</tr>
<tr>
<td>FSR [GHz]</td>
<td>800</td>
</tr>
<tr>
<td>$\Delta L$ [$\mu$m]</td>
<td>99.35</td>
</tr>
<tr>
<td>$L_{ave}$ [$\mu$m]</td>
<td>1865.7</td>
</tr>
</tbody>
</table>

Fig. 4. Simulated transmission characteristics of the test AWG.
4 Experimental results

The measured relative phase and the amplitude for each light path of AWG #4, which was located on chip #4, are shown in Fig. 5. The reconstructed transmission spectrum of the AWG from the phases and the amplitude distribution is shown in Fig. 6. The reconstructed spectrum is very similar to the spectrum measured directly by an optical spectrum analyzer. The results indicate that our frequency-domain interference measurement is sufficiently accurate to evaluate Si-wire AWGs.

![Fig. 5. Amplitude distribution and the relative phase of each path in AWG #4.](image1)

Fig. 6. Reconstructed transmission spectrum and the directly measured spectrum.

Fig. 7 shows the standard deviation of the phase errors of the test AWGs for the six chips shown in Fig. 2. The average standard deviation is \(0.27 \pi\) radian, and this is equivalent to a fluctuation in the effective refractive index of \(1.1 \times 10^{-4}\). The average shift in wavelength from the designed peak wavelength and the standard deviation were 1.26 nm and 1.40 nm, respectively.
5 Conclusion

The phase errors in 100-GHz spacing, 8-ch, Si-wire AWGs fabricated by ArF-immersion photolithography were measured using the frequency-domain interference method. The average standard deviation of the phase errors in six chips on a 300-mm SOI wafer was $0.27\pi$ radian which corresponds to a fluctuation in the effective refractive index of $1.1 \times 10^{-4}$.

![Fig. 7. Standard deviation of phase errors in each chips.](image-url)