Temperature-Insensitive Reflective Arrayed-Waveguide Grating Multiplexers

L. Grave de Peralta, A. A. Bernussi, V. Gorbounov, and H. Temkin

***Abstract*—We present a new approach to temperature compensation of silica-based arrayed-waveguide grating multiplexers. An external mirror rotating with temperature at a constant rate, in combination with a reflective multiplexer, is used to compensate for the temperature-induced change of the refractive index, and the resulting wavelength shift of individual channels, making the device athermal. A wavelength-temperature slope of less than 3.2×10^{-4} nm/°C was obtained in the temperature range 5 °C–70 °C, without noticeable degradation in the device performance.**

***Index Terms*—Dielectric materials, mirrors, temperature, waveguide arrays, wavelength-division multiplexing.**

I. Introduction

The suppression of the temperature sensitivity of arrayed-waveguide grating (AWG) (de)multiplexers has been a subject of considerable interest in the last few years [1]–[6]. This interest is driven primarily by closer channel spacing of systems based on dense wavelength-division multiplexing and the need for improved wavelength precision relative to the ITU standard grid [7]. In silica-based AWGs, the channel peak wavelength shifts as a result of the temperature dependence of the refractive index of the waveguide. A common approach to eliminate the wavelength shift is to use an external heater or thermoelectric cooler maintaining the device at a constant temperature. However, this requires provision of electric power to an otherwise passive device, incorporation of temperature sensing and controlling elements, resulting in a complex package. Alternative solutions to produce temperature-insensitive AWGs have, thus, continued to be proposed [1]–[4]. Among them, introduction of grooves placed at the center of the grating waveguides and filled with a material having an opposite refractive index temperature dependence than the glass waveguide, have been described [1], [2]. However, in this approach, grooves must be fabricated with high precision in order to avoid additional contributions to phase errors that degrade performance of AWGs. Another approach is to use the thermal expansion of a metal plate to displace the input coupler [4]. This method, however, requires cutting the device in two parts, polishing all the surfaces, and precise realignment of the parts into a functional device.

In this letter, we describe a new method of compensating the temperature dependence of silica-based AWGs. We show that the use of a combination of a reflective AWG (R-AWG) [8]–[11] with an external mirror compensates for the temperature-induced wavelength dependence, resulting in athermal operation. This is achieved by preparing a composite mirror, using differential thermal expansion of a metal rod and a silicon base, which rotates with temperature at a constant rate. The R-AWG operates with the composite mirror without any appreciable degradation in performance. We applied this method to produce athermal R-AWGs with the channel center wavelength dependence, in the temperature range 5 °C–70 °C, of less than 3.5×10^{-4} nm/°C.

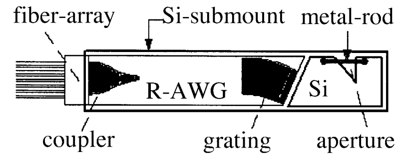

Fig. 1. Schematic arrangement used to obtain athermal operation of R-AWG. The mirror was fabricated in 800-μm-thick Si wafer. It was approximately 20 mm long and 16 mm wide. The triangular aperture was 5 mm wide at the top. The brass rod had a cross section of 1 mm^2 and was 10 mm long.

II. R-AWG and the External Mirror Fabrication

R-AWGs used in this work were obtained by folding the grating of the device. Details of the device structure and its performance are described elsewhere [10], [11]. Briefly, R-AWGs were fabricated in a conventional silicon integrated circuit foundry using doped and undoped SiO_2 layers deposited on wafers of silicon. The relative refractive index difference between the core and the cladding materials of the waveguide was $\Delta = 0.68\%$. The waveguides were 5 μm thick and were etched to produce 5-μm-wide cores. The grating and input–output regions were separated by a slab waveguide with the radius of 5 cm. High reflectivity of the reflecting surface folding the grating was assured by deposition of a Cr–Au layer. R-AWGs with Gaussian response were designed for 40-channel operation with the channel-to-channel separation of 100 GHz. The average insertion losses of -2.5 dB, loss nonuniformity of -0.6 dB, crosstalk of -30 dB, and polarization-dependent wavelength shift of 0.012 nm were obtained. In the experiments discussed here, the Cr–Au layer was removed from the reflecting surface and an external mirror was used instead as a reflector.

In order to compensate the temperature-induced wavelength shift of silica waveguides, we combined an R-AWG with a composite external mirror, as shown schematically in Fig. 1. The external mirror was positioned ~ 5 μm away from the reflecting surface terminating the grating. The rotation of a composite

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mirror is achieved through the use of materials with different linear thermal expansion coefficients. The body of the mirror was machined in a Si wafer. A metal rod attached across a triangular-shape aperture fabricated in the wafer is used to tilt the reflecting surface of the mirror. The reflecting surface was formed by diamond polishing. The linear expansion coefficient of the brass is about six times larger than that of silicon. Consequently, when the temperature is increased (decreased) the metal rod elongates (contracts), tilting the mirror. The back part of the mirror assembly (away from the reflecting surface) is fixed to a Si submount supporting the R-AWG, while the reflecting part is able to tilt freely. In the schematic configuration of Fig. 1, the angular rotation of the mirror with temperature is designed to compensate for the shift of the R-AWG channel center wavelength. Rotation of the external mirror introduces an additional path length difference between consecutive waveguides in the grating of the R-AWG. This results in a linear shift of the center channel wavelength that is proportional to the angular position of the external mirror. By adjusting the placement of the metal across the aperture in the Si base the temperature-induced rotation rate of the mirror can be precisely controlled.

III. Principle of Temperature Compensation

In an R-AWG with an external mirror, the optical path-length difference between consecutive grating waveguides is expressed as $n_c\Delta L + n_g\Delta L_g$, where $n_c\Delta L$ is the optical path-length difference designed into the grating of the R-AWG, and $n_g\Delta L_g$ is the additional contribution to the optical path length due to light propagating through the medium filling the gap between the reflecting surface terminating the grating and the external mirror. The center wavelength (λ_c) and the corresponding condition for the athermal operation of an R-AWG with an external mirror are given by the following expressions, respectively [12]:

$$\lambda_c = 2\frac{n_c\Delta L + n_g\Delta L_g}{m} \tag{1}$$

$$\frac{\partial(n_c)}{\partial T}\Delta L + \left[\frac{\partial(n_g)}{\partial T}\Delta L_g(T) + \frac{\partial(\Delta L_g)}{\partial T}n_g(T)\right] = 0 \tag{2}$$

where m is the diffraction order. It can be immediately verified from (1) that the center wavelength changes linearly with the additional path length difference ΔL_g.

In the vacuum, and approximately in air, the athermal condition (2) can be rewritten in terms of the angle (θ) between the external mirror and the reflecting surface of the R-AWG

$$\frac{\partial\theta}{\partial T} \approx -\frac{1}{n_g}\frac{\partial(n_c)}{\partial T}\frac{\Delta L}{\frac{\partial(\Delta L_g)}{\partial\theta}} \tag{3}$$

where $(\partial\theta)/(\partial T)$ is the temperature sensitivity of the angular position of the external mirror and $(\partial(\Delta L_g))/(\partial\theta)$ corresponds to the additional constant path length difference contribution added to the grating waveguides when an angle θ between the external mirror and the R-AWG is introduced. The R-AWGs used here have $(\partial(\Delta L_g))/(\partial\theta) \sim 1.22$ μm/degree.

Equations (1)–(3) are strictly valid for a constant separation (d_{wg}) between consecutive waveguides at the surface terminating the grating. All R-AWGs used in this work rely on this design. In addition, all the waveguides of the grating terminate perpendicular to the reflecting surface. Nonconstant values of d_{wg} would result in phase errors, producing additional loss and increased channel bandwidth penalties [11].

If the gap between the R-AWG and the external mirror is filled up with index-matching material, its refractive index temperature dependence should be taken into account in order to compensate the thermal sensitivity of the device. A detailed evaluation of (2) shows that it is possible to use an external mirror with angular-temperature dependence given by (3) as a starting point in order to produce athermal R-AWGs.

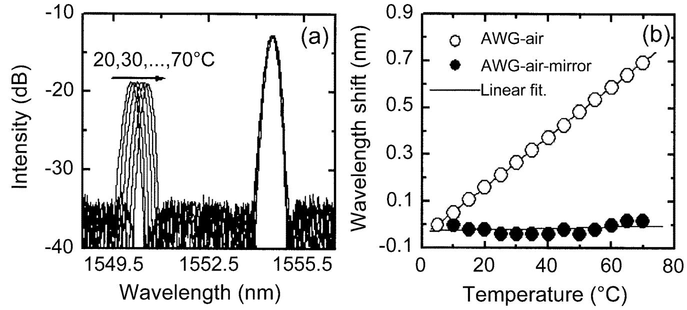

Fig. 2. (a) Transmission spectra from a single channel of an R-AWG at different temperatures with air-filled gap between the external mirror and the reflecting surface terminating the grating. (b) Wavelength shift as a function of temperature for the transmission peaks corresponding to reflections at interfaces R-AWG-air (o) and R-AWG-air-external mirror (•).

IV. Experimental Results and Discussion

Transmission spectra of a single output channel of an R-AWG with the external mirror are displayed in Fig. 2 as a function of temperature. The experiment used the arrangement illustrated in Fig. 1. The data of Fig. 2 were obtained with air-filled gap, ~ 10 μm wide, between the Si-mirror and the R-AWG. This was done intentionally in order to be able to monitor simultaneously the output spectra corresponding to the reflections arising from the R-AWG-air and air-Si-mirror interfaces. The R-AWG transmission spectra of Fig. 2(a), thus, consisted of two peaks. The short wavelength peak was due to reflection at the R-AWG-air interface. The long wavelength peak was due to reflection from the external mirror. In this experiment, the external mirror was positioned at an angle ($\sim$0.04°) relative to the surface of the grating in order to avoid overlap between the two peaks. The reflecting surface of the external Si mirror was not metallized resulting in a reflection loss of -7.9 dB. The intrinsic loss of the R-AWG used in this experiment was -3.1 dB. An additional loss of 1 dB was introduced in attaching the fiber array to the device [13]. The gap distance between the device and the external mirror contributes an additional $\sim$0.3 dB in loss. The peak originating at the R-AWG-air interface shifted systematically toward longer wavelength with a slope of 1.06×10^{-2} nm/°C, as plotted in Fig. 2(b). This corresponds to the wavelength shift due to the temperature dependence of the index of refraction of the R-AWG, as expected from the known temperature dependence of the refractive index of silica glass [3], [12]. In contrast, the peak corresponding to the reflection from the external mirror is essentially insensitive to changes in the temperature. A

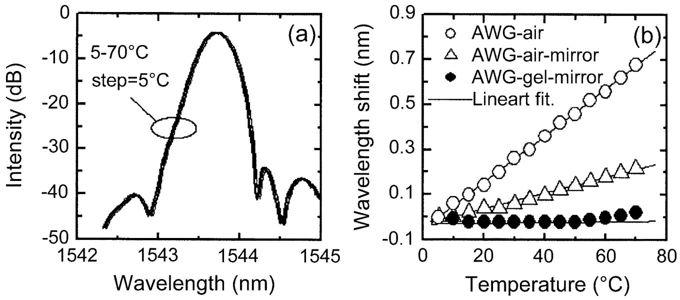

Fig. 3. (a) Temperature dependence of the transmission spectra of a single channel of an R-AWG with index-matching gel between the device and the external mirror. (b) Peak wavelength shift as a function of temperature corresponding to reflections at interfaces R-AWG-air (o), R-AWG-air-external mirror (△), before application of index-matching gel, and R-AWG index-matching gel-external mirror (•).

wavelength slope as low as 3.2×10^{-4} nm/°C was determined for the transmission peak originating at the external mirror, as shown in Fig. 2(b). This is almost two orders of magnitude lower than the slope shown by conventional silica-based AWGs. In the temperature range 5 °C–70 °C, a peak loss change of less than 0.2 dB was observed for the transmission peak corresponding to the external mirror. Similar results were obtained for other output channels of the same device. The results shown in Fig. 2 demonstrate that temperature-insensitive R-AWGs can be successfully prepared using a composite external mirror that rotates at a constant rate with the temperature. This is achieved without any appreciable degradation in the device performance.

For practical applications, the reflectivity of the external mirror was increased by the deposition of a Cr–Au film. In addition, the reflection at the R-AWG-air interface must be suppressed. For this purpose, we used an index-matching material. Its index changes with temperature at a rate of -3.5×10^{-4} /°C. Since the index-matching material has a negative temperature dependence, the rate of the external mirror rotation should be reduced accordingly. This was done by adjusting the metal rod position across the mirror aperture (see Fig. 1). Finally, the external mirror was positioned $\sim 5\ \mu$m away from the device. This reduces the gap related losses to less than 0.1 dB.

The resulting transmission spectra are shown in Fig. 3(a) as a function of temperature, for a single output channel. The gap was filled with index-matching material. The presence of the index-matching material suppressed reflection from the R-AWG-air interface and only the peak arising at the R-AWG-mirror interface is seen in Fig. 3(a). In the temperature range of 5 °C–70 °C, the transmission spectra are essentially identical and the transmission peak changes by less than 0.2 dB. The peak wavelength shift is plotted as a function of temperature in Fig. 3(b). We include, for comparison, the wavelength shift of the peak response corresponding to reflections at the R-AWG-air, as shown in Fig. 2(b). The position of the metal rod across the aperture was adjusted to obtain a slope of $\sim 3.5 \times 10^{-3}$ nm/°C in the transmission peak originating at the external mirror, before application of index-matching material. This rate, together with the temperature dependence of the index-matching material itself, resulted in a peak wavelength slope as low as 2.23×10^{-4} nm/°C, as shown in Fig. 3(b). This demonstrates that athermal operation of R-AWGs can be obtained with index-matching material between the device and the external mirror.

V. Conclusion

We have demonstrated athermal operation of a silica-based 40-channel multiplexer obtained by combining an R-AWG with a composite external mirror. The mirror was fabricated of materials with different linear thermal expansion coefficients. Preparation and characteristics of a mirror using a Si base and a brass expansion rod is described in some detail. We show that the mirror rotates with temperature at a constant rate. With the use of an external mirror, the temperature sensitivity of silica-based R-AWGs was reduced from 1.06×10^{-2} nm/°C to less than 3.2×10^{-4} nm/°C, in the temperature range of 5 °C–70 °C. There was no significant degradation in the device performance. The proposed approach can be implemented without any modification to the device design or the fabrication process.

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