Thermal Behavior of Arrayed-Waveguide Grating Made of Silica/Polymer Hybrid Waveguide

Duk-Jun Kim, Jang-Uk Shin, Young-Tak Han, Sang-Ho Park, Yun-Jung Park, Hee-Kyung Sung, and Dong-Kun Kim

ABSTRACT—The thermal behavior of an arrayed-waveguide grating made of a silica/polymer hybrid waveguide was examined. We experimentally confirmed that the hybrid waveguide is effective to decrease the temperature and polarization dependence of the center wavelength owing to the negative thermo-optic coefficient of the refractive index and extremely low baking temperature of the polymer cladding. However, the detachment of the polymer cladding from the silica core, which took place either during a repeated heat cycle test or during long-term storage in atmosphere, was a serious problem for practical use.

Keywords—Athermalization, hybrid waveguide, AWG.

I. Introduction

A silica-based arrayed waveguide grating (AWG) exhibiting high reliability as well as excellent performance is a key component for dense wavelength division multiplexing telecommunication systems. However, the AWG must be operated together with a heater or Peltier cooler as the center wavelength (λ_0) has a temperature dependence of about 0.012 nm/℃, which increases the size and cost of the packaged module. On account of this, an athermal AWG whose spectral response is not influenced by temperature change is needed, especially for outdoor use.

Both the filling of a polymer resin into a triangular or crescent-shaped groove formed in the arrayed or slab waveguide region and the connection of the two divided slab waveguide parts with a copper plate are powerful methods for eliminating temperature dependence [1]-[3]. A special waveguide with the negative temperature coefficient of the refractive index also has the capability to athermalize λ_0 without modifying the conventional AWG structure [4]. This negative thermo-optic (TO) coefficient can be attained by heavily incorporating titania in the silica waveguide core or by partially surrounding the silica core with a polymer cladding [5], [6]. Considering that the titania incorporation requires much skill and experience, the silica/polymer hybrid waveguide will provide an easy way to demonstrate an athermal AWG.

Succeeding our previous work in [6], here we applied the hybrid waveguide to the fabrication of an AWG and present in more detail the experimental results relevant to athermalization, polarization, and reliability.

II. Experiment and Results

Figure 1 shows a schematic cross-section for the hybrid waveguide used in this work. The height and width of the silica core are equal to 6 μm, and the relative refractive index difference between the core and cladding is 0.75%, regardless of the cladding material, at the reference temperature of 20℃. As it departs from this temperature, the effective refractive index for the fundamental mode in the hybrid waveguide (n_c) varies along with the modification in the temperature dependence of λ_0, which is expressed by

$$d\lambda_0/dT = (dn_c/dT + n_c\alpha_s)\cdot(\lambda_0/n_c),$$

where α_s is the thermal expansion coefficient (TEC) of the Si substrate given as 2.63×10^{-6}/°C [4]. This λ_0 dependence was

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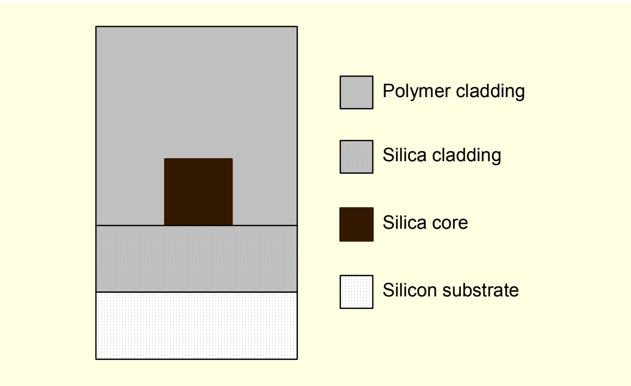

Fig. 1. Schematic cross-section for the silica/polymer hybrid waveguide.

calculated by varying the TO coefficient for the polymer cladding from 7.93×10^{-6}/℃ to that for the silica core or cladding, -250×10^{-6}/℃.

As known from the calculation results in Fig. 2, a temperature region exists in which the λ_0 change is considerably small relative to that for the original silica waveguide owing to the negative TO coefficient, although it does not fully cover the entire temperature range in consideration, and its location and width are strongly dependent on the magnitude of the negative coefficient. Besides, the temperature-dependent behavior of λ_0 is not any more linear in the hybrid waveguide differing from the silica waveguide. Figure 2 also shows that the more negative TO coefficient gives rise to mode cut-off at a higher temperature, which is inevitable due to the difference in the sign of the coefficient between the silica core and polymer cladding.

We have searched for a low loss polymer material suitable for the cladding purpose and found a UV-curable fluoracrylate polymer solution (ZPU13-RI; Zen Photonics Co., Ltd., Daejeon, Korea). The refractive index of the polymer film is adjustable to a value between 1.43 and 1.45 at a wavelength of 1550 nm by appropriately mixing the two corresponding polymer solutions; the propagation loss for the film is not more than 0.4 dB/cm. From the refractive index measurement carried out at various temperatures, it was known that the TO coefficient is not constant even at the same mixing ratio but ranges in value from -1.6×10^{-4}/℃ to -2.3×10^{-4}/℃ depending on the fabrication history of the films. According to the Prod' homme theory [7], accounting the origin of the negative TO coefficient of dielectric materials, the refractive index of organic polymer is governed by the specific volume rather than the electronic polarizability because of its large TEC. The UV-curing and subsequent post-baking of the polymer solutions spin-coated on the Si substrate will produce a residual strain in the resultant polymer film, and the magnitude and vertical distribution of the strain will be affected by the curing and baking condition as well as by the film thickness. These may cause the variance in the measured TO coefficient. For the AWG made of the hybrid waveguide, it is expected that the strain effect on λ_0 is considerable and complicated as the residual strain or stress concentrates near the rectangular silica core.

The thermal stress that originates from the TEC mismatch between the waveguide film and Si substrate is one of the main factors to determine the polarization dependence of λ_0, and it is possible to roughly estimate the thermally induced birefringence of the film with R to be the radius of the curvature for the substrate since the sign and magnitude of the curvature reflect the elongated or compressed state of the film. The curvature measurement was carried out for the AWG specimen made of the hybrid waveguide with a varying temperature, and the curvature data expressed as the reciprocal of R, together with those for another AWG specimen made of the conventional silica waveguide and a Si substrate containing

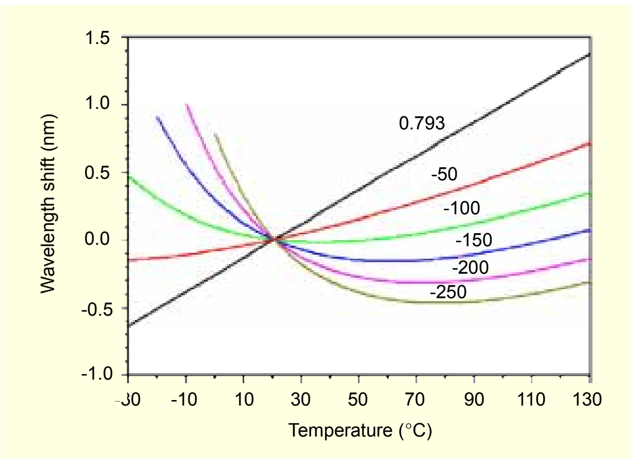

Fig. 2. Effect of the TO coefficient of refractive index ($\times10^{-6}$/°C) in the polymer cladding on the temperature dependence of λ_0.

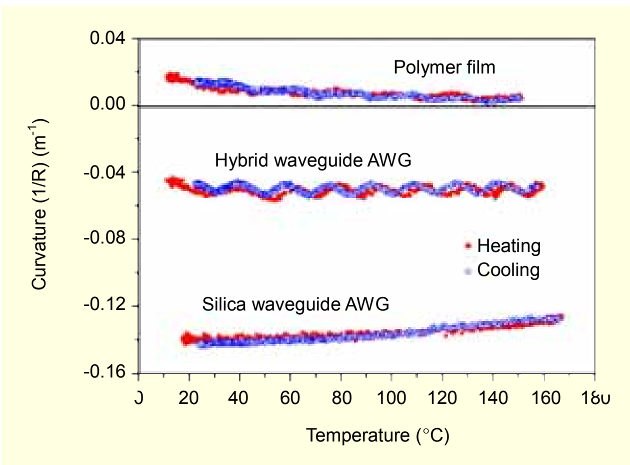

Fig. 3. Effect of the hybrid waveguide on the thermal stress of AWG.

only the polymer film, were given in Fig. 3 as a function of temperature. This polymer film is equivalent to the polymer cladding for the hybrid waveguide in thickness as well as in UV-curing and post-baking condition, and the thickness of the Si substrates was 1 mm regardless of the film or waveguide type. As known from Fig. 3, the positive curvature for the polymer film specimen is much smaller than the negative curvature for the two AWG specimens. The positive and minute curvature for the polymer film is due to its TEC value (300~ 400×10^{-6}/°C) being larger than that of the Si substrate and the post-baking temperature (160°C) being much lower than the consolidation temperature of the silica film (>1150°C). Figure 3 also shows that the curvature for the hybrid waveguide is about three times smaller than that for the silica waveguide. Besides, the curvature approaches zero with an increasing temperature for both the silica waveguide and the polymer film owing to the stress relaxation, but it is nearly constant for the hybrid waveguide in spite of the slight fluctuation during heating and cooling. This curvature fluctuation is thought to be a result of the competition between stress relaxation and accumulation, which stems from the fact that the silica waveguide core and cladding with the smallest TEC value intervenes between the polymer cladding and Si substrate. On the other hand, the smaller curvature for the hybrid waveguide may be understood from the scenario that the thermal stress formed during the high-temperature consolidation for the silica core layer is fairly released during the reactive ion etching process for the silica core, and the subsequent post-baking for the polymer cladding rarely contributes to the re-accumulation of the residual stress related with the thermally induced birefringence. AWG spectral data illustrating this was presented in our previous report [6].

A series of steps of the fabrication process for the hybrid waveguide was conducted to form a 1×8 AWG with the channel spacing of 200 GHz. As known from the AWG spectra in Fig. 4, as the temperature goes up above 15°C, the peak power as well as the line width of the main lobe gradually decreases with the appearance of the shoulder at the lateral side of the lobe. Meanwhile, the AWG loses its wavelength-filtering capability while producing a drastic decrease in optical power as it goes down below 0°C. By plotting the wavelength corresponding to the peak power, it can be known that the temperature dependence of the peak wavelength approximates a linear decrease with the rate of –0.006 nm/°C, contrary to the expectation based on Fig. 2. This linear dependence may be understood from the fact that the polymer cladding does not freely expand or contract according to a TEC value corresponding to the supposed TO coefficient until it detaches from the silica core. Namely, from the viewpoint of n_c, it is desirable to acknowledge that the effective TO coefficient for

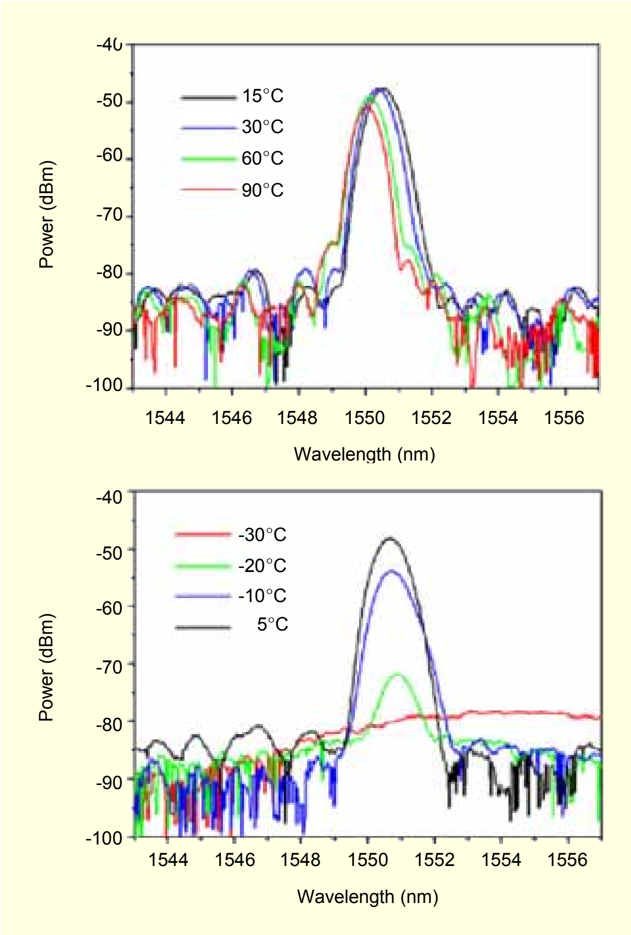

Fig. 4. Temperature dependence of the wavelength spectrum for the 1×8 AWG made of the hybrid waveguide.

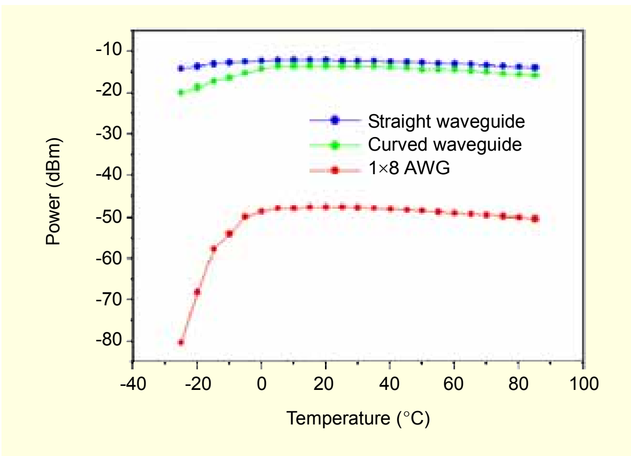

Fig. 5. Temperature dependence for the peak power of the 1×8 AWG and the transmitted power of the straight/curved waveguides.

the polymer cladding also has a temperature dependence connected with the residual strain.

Figure 5 shows a comparison of the peak power with the transmitted power for the straight and curved waveguides simultaneously formed on the same substrate. This optical power result clearly shows that the slight decrease of the peak power at the high temperature region is mainly caused by the mode field mismatch between the pigtailed single mode fiber and the input/output waveguide, while the weakened confinement of light between the silica core and the polymer cladding results in the drastic decrease of the peak power at the low temperature region. On the other hand, the detachment of the polymer cladding occurred on the 1×8 AWG specimen after a repeated heat cycle test or during the long term storage in atmosphere. Also, it was experimentally proved that such a detachment producing a severe deterioration in the AWG spectrum is accelerated in high humidity.

III. Conclusion

The hybrid waveguide in which the silica over-cladding is replaced with the polymer over-cladding is attractive because of its simplicity in fabrication and effectiveness in suppressing the temperature and/or polarization dependence of λ_0, but has an inherent drawback that the confinement of light between the silica core and the polymer cladding is temperature-dependent, which is detrimental to the athermalization of the insertion loss and crosstalk characteristics. It seems that the restriction of the hybrid waveguide in the arrayed-waveguide region can cope with the confinement problem. However, prior to this, a technique basically preventing the detachment of the polymer cladding is required for practical use.

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