Reducing the Thermal Dependence of Silica-Based Arrayed-Waveguide Grating Using Inorganic–Organic Hybrid Materials

Eun-Seok Kang, Woo-Soo Kim, Duk-Jun Kim, and Byeong-Soo Bae

Abstract—**This study demonstrates the application of a temperature-independent arrayed-waveguide grating (AWG) using a simple hybrid waveguide structure composed of silica core/inorganic–organic hybrid material overcladding layer. The thermooptic effect of the hybrid materials varies over a wide range of temperature and provides athermal characteristics in an AWG. The temperature dependence of the AWG was reduced through the precision control of the thermooptic coefficient of the hybrid materials ($\Delta\lambda = \sim 3$ pm/°C).**

Index Terms—**Arrayed-waveguide grating (AWG), athermal waveguide, integrated optics devices, sol-gel hybrid materials, thermooptic effect, wavelength-division multiplexing.**

I. Introduction

DUE TO its capability to increase the aggregate transmission capacity of a single-strand optical fiber, the arrayed-waveguide grating (AWG) multiplexer is considered a key component in the construction of a dense wavelength-division-multiplexing system [1]. However, an AWG made of silica is so sensitive to the ambient temperature that the output wavelength changes by as much as ~0.0125 nm/°C. Thus, this condition requires the use of temperature control units, such as heat or Peltier coolers.

To eliminate the undesirable temperature dependence of the AWG, the application of athermalization has been explored [2], [3]. Athermalization leaves the characteristics of the AWG device unaffected by ambient temperature variations. Among the various approaches, a hybrid waveguide structure (silica core and polymer overcladding), which can resist the thermooptic characteristics of the materials, is considered as the most attractive method of athermalization due to its simple fabrication process [4]. However, existing waveguide materials, such as silica and polymer, do not provide sufficient control of dn/dT over a wide range of temperature, resulting in a nonoptimized athermalization. Accordingly, the structure of the athermal AWG was modified in order to optimize its athermal characteristics. For example, multiovercladding layers, specifically the combination of dn/dT in the layers, were used to fabricate the athermal AWG structure [5]. The research findings revealed that new waveguide materials that have the ability to control dn/dT over a wide range of temperature variations are required for designing and producing a simple but effective athermal AWG structure.

Recently, an inorganic–organic hybrid material (HYBRIMER) derived from sol-gel and composed of silica and an organic component was discovered as a promising alternative material for an optical waveguide device.

In a previous study, we also presented the origin and wide controllability of dn/dT in a HYBRIMER through the variation of its structure [6], [7]. The previous study confirmed that the HYBRIMER is a highly flexible choice for the design and fabrication of thermooptic waveguide devices.

In this study, we demonstrate a silica-based athermal AWG with a simple waveguide structure, consisting of silica core and a HYBRIMER overcladding layer. The silica provides low optical loss, while the variation of dn/dT in the HYBRIMER provides the athermal characteristics to the AWG.

II. Fabrication

In the fabrication of an athermal AWG, the determination of the athermal condition should be considered first. The athermal condition in the waveguide can be expressed as follows:

$$\alpha_{\text{sub}} + \frac{1}{n_{\text{eff}}}\frac{dn_{\text{eff}}}{dT} = 0 \qquad (1)$$

where α_{sub} is the thermal expansion coefficient of substrate and n_{eff} is the effective refractive index of the waveguide. The athermal condition is satisfied when the suitable effective refractive index and dn_{eff}/dT are determined, thus compensating the thermal expansion term of substrate. Moreover, it is possible to fabricate an athermal waveguide by modifying the overcladding layer, since the overcladding layer affects both the effective refractive index and the dn_{eff}/dT of the guided mode [5].

To determine the composition of the HYBRIMER material required for satisfying the athermal condition of the AWG, the output central wavelength dependence on temperature was simulated. As shown in Fig. 1, the dn/dT of the overcladding layer is set as the only variable while the other parameters are fixed. Fig. 2 also shows that, in most cases, the central wavelength executes a U-shape variation as a function of temperature, indicating a derivation from athermality at high temperatures. This derivation is caused by the confinement of the guided mode, which increases at higher temperatures

Manuscript received May 17, 2004; revised July 16, 2004. This work was supported by the Sol-Gel Innovation Project (SOLIP) founded by the Ministry of Commerce, Industry, and Energy (MOCIE) in Korea.

E.-S. Kang, W.-S. Kim, and B.-S. Bae are with the Laboratory of Optical Materials and Coating (LOMC), Department of Materials Science and Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 305-701, Korea (e-mail: sstony@kaist.ac.kr; ysmet@kaist.ac.kr; bsbae@kaist.ac.kr).

D.-J. Kim is with the Optical Interconnection Module Team, Electronics and Telecommunication Research Institute (ETRI), Daejeon 305-350, Korea (e-mail: djkim@etri.re.kr).

Digital Object Identifier 10.1109/LPT.2004.836348

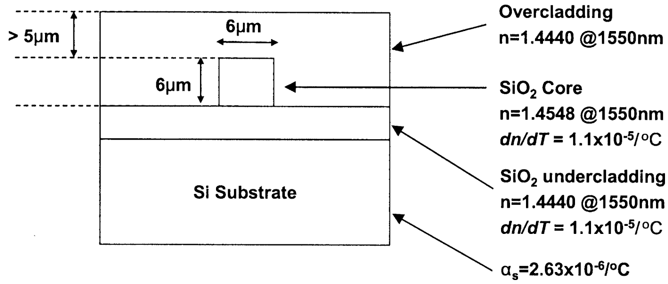

Fig. 1. Cross section design of the silica-based athermal AWG.

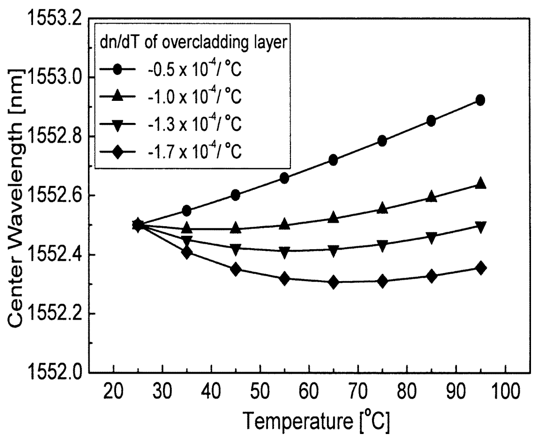

Fig. 2. Change of the center wavelength in AWG as a function of ambient temperature and dn/dT of overcladding layer.

and triggers a refractive index change for both the core and the overcladding layers. Consequently, the HYBRIMER overcladding layer decreases the modification of the dn_{eff}/dT. In addition, temperature dependence is known to be dramatically suppressed when the dn/dT of the overcladding layer is between $-1.0 \times 10^{-4}/°\mathrm{C}$ and $-1.3 \times 10^{-4}/°\mathrm{C}$. Therefore, we determined the optical properties of overcladding layer ($n = 1.4440, dn/dT = -1.0 \sim -1.3 \times 10^{-4}/°\mathrm{C}$ at 1550 nm) for a silica-based AWG. The dn/dT of an optical polymer is generally more negative than this calculated value. Consequently, an athermal AWG with a multiovercladding layer structure is required when a polymer serves as overcladding layer in silica-based AWG. Furthermore, it is difficult to simultaneously modify both the refractive index and dn/dT of an optical polymer. On the other hand, the refractive index and dn/dT of HYBRIMER can be varied over a wide range of temperature [7]. Thus, this study confirms that we can fabricate an athermal AWG with a simple structure and a HYBRIMER overcladding layer, in order to control its athermal characteristics.

To develop a HYBRIMER that satisfies the athermal condition, a coating solution was prepared by combining three precursors [methacryloxypropyltrimethoxysilane (MPTMS)/perfluoroalkylsilane (PFAS)/zirconium n-propoxide (ZPO)] through the conventional sol-gel process. Applying the flame hydrolysis deposition process on a silicon substrate, the prepared solution was spin-coated at 1000 rpm for 30 s onto a 1×8 silica-based AWG, which consisted of a silica core and a silica undercladding layer. The coated AWG was heat-treated at 150 °C for 5 h, and then scanning electron and optical microscopy confirmed the presence of a thick ($\sim$12 μm) and homogeneous HYBRIMER overcladding layer.

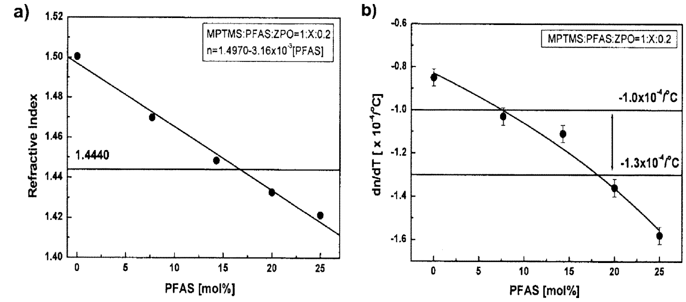

Fig. 3. Variation of (a) refractive index and (b) dn/dT of HYBRIMER (MPTMS/PFAS/ZPO) as a function of the concentration of PFAS.

III. Characteristics

Refractive index measurements were carried out for the films, using the prism coupling method. The prism coupler, equipped with an autocontrolled hot stage, was used to measure dn/dT. The flexible heater, which was thin enough not to affect the optical coupling between the prism and the film, was used to elevate the sample temperature. A film-type thermocouple was attached to the sample's surface and the refractive index was measured over the temperature range of 30 °C–100 °C. Previous publications can provide more details about this measurement technique [6].

Fig. 3(a) and (b) shows the variation of the refractive index and the variation of dn/dT as a function of concentration of PFAS at an MPTMS : ZPO ratio of 1 : 0.2, respectively. It is observed that both indicators gradually decrease as the PFAS concentration increases. According to the Lorentz–Lorenz relation, the variation in the refractive index is related to changes in density and polarization. Consequently, the refractive index decreases with PFAS content due to the fluorine group in the PFAS, which has low polarization.

In previous studies, the variation of dn/dT in HYBRIMER was investigated, and was found to decrease with organic content [7]. Thus, the decrease in dn/dT can be explained in terms of the desired organic content, since PFAS has a long organic chain in comparison to other precursors. Finally, it can be seen in Fig. 3 that the athermal HYBRIMER overcladding layer is achieved when the PFAS content is set at 16.7 mol% ($n = 1.4440$, $dn/dT = -1.25 \times 10^{-4}/°\mathrm{C}$ at 1550 nm).

Prior to the observation of the temperature dependence of AWG, the wavelength-demultiplexing characteristics of AWG were measured using the fiber coupling method. As designed, the wavelength difference between neighboring channels, specifically the channel spacing, was set at 1.6 nm, indicating that the resultant AWG fulfilled its basic function. To investigate the temperature dependence of the device, the AWG was placed in a constant temperature chamber, and then the shift of peak position was observed at the center output channel as a function of temperature ($10\ °\mathrm{C} \sim 90\ °\mathrm{C}$). Fig. 4 shows the change in wavelength spectrum depending on temperature. As shown in the figure, the insertion loss is $\sim$9 dB over the measurement temperature. In a previous study, the AWG using the silica overcladding layer showed an insertion loss of $6 \sim 7$ dB [8]. Generally, the application of the HYBRIMER through a sol-gel process leads to a high absorption loss at 1550 nm, caused by the remaining hydroxyl group. As a result, the insertion loss

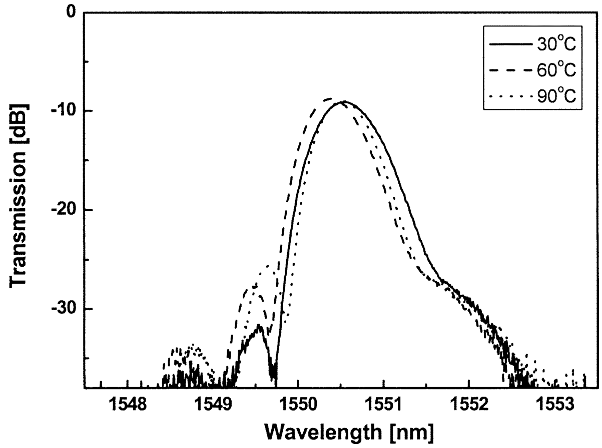

Fig. 4. Change of wavelength spectrum in the AWG using HYBRIMER (MPTMS /PFAS /ZPO) overcladding layer as a function of temperature.

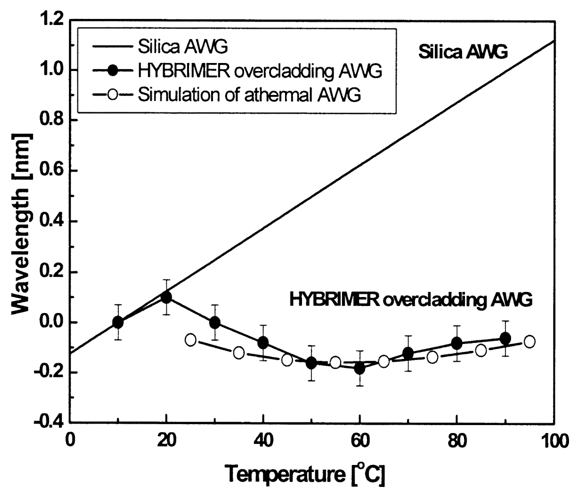

Fig. 5. Variation of the central wavelength in an AWG device as a function of temperature.

of the HYBRIMER overcladding AWG becomes larger. In the case of a polymer overcladding AWG, the insertion loss and the bandwidth vary according to the temperature because the refractive index difference of silica–polymer rises with increasing temperature, due to the different signals of dn/dT to each other. Similarly, the bandwidth of the HYBRIMER overcladding AWG changes with temperature. However, the variation of insertion loss with temperature can be reduced to less than 0.5 dB over the measured temperature range. The polarization-dependent wavelength shift, splitting between transverse-electric and transverse-magnetic modes, can be decreased from 0.15 (silica overcladding) to ~0.05 nm, through the introduction of the HYBRIMER overcladding. This means that the polarization dependence can be eliminated by optimizing the waveguide parameters.

Fig. 5 shows the athermal characteristics of both a silica AWG and a HYBRIMER overcladding AWG. As shown in the figure, the HYBRIMER overcladding AWG exhibits a reduced wavelength variation depending on temperature ($\Delta\lambda = 0.28$ nm over the range of measurement, that is $\Delta\lambda =\sim 3$ pm/°C), in contrast with a silica AWG, which exhibited a change of 0.0125 nm/°C. This result is comparable to the athermal characteristics of an AWG using a multiovercladding layer. In addition, Fig. 4 shows that the measured athermal characteristic is similar to the simulated result. As expected, this indicates that the HYBRIMER overcladding layer affects the temperature dependence of AWG.

In summary, the results of the study demonstrated that a HYBRIMER overcladding AWG with a simple structure, which was fabricated by means of dn/dT modification and refractive index in the HYBRIMER overcladding layer, effectively reduced thermal dependence.

IV. Conclusion

In this study, we have demonstrated a silica-based AWG that can reduce thermal dependence. The silica-based AWG was made of a HYBRIMER overcladding layer using the sol-gel process. The appropriate HYBRIMER that exhibits both specific refractive index and dn/dT can be easily obtained by manipulating its composition. Even though the HYBRIMER overcladding AWG had a simple structure (silica core/HYBRIMER overcladding), it showed good performance with $\Delta\lambda =\sim 3$ pm/°C over the temperature range of 10 °C ~ 90 °C. Thus, this new method using HYBRIMER materials offers a simple and easy way to fabricate an athermal AWG, and other athermal devices.

References

[1] S. V. Kartalopoulos, *Introduction to DWDM Technology*: SPIE Optical Engineering Press, 2000.

[2] Y. Inoue, A. Kaneko, F. Hanawa, H. Takahashi, K. Hattori, and S. Sumida, "Athermal silica-based arrayed-waveguide grating multiplexer," *Electron. Lett.*, vol. 33, no. 23, pp. 1945–1946, 1997.

[3] A. Kaneko, S. Kamei, Y. Inoue, H. Takahashi, and A. Sugita, "Athermal silica-based arrayed-waveguide grating (AWG) multi/demultiplexer with new low loss groove design," *Electron. Lett.*, vol. 36, no. 4, pp. 318–319, 2000.

[4] Y. Kokubun, N. Funato, and M. Takizawa, "Athermal waveguide for temperature-independent lightwave devices," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 1297–1300, Nov. 1993.

[5] Y. Kokubun, S. Yoneda, and S. Matsuura, "Temperature-independent optical filter at 1.55 μm wavelength using a silica-based athermal waveguide," *Electron. Lett.*, vol. 34, no. 4, pp. 367–369, 1998.

[6] E. S. Kang, T. H. Lee, and B. S. Bae, "Measurement of thermo-optic coefficients in sol-gel derived inorganic-organic hybrid material films," *Appl. Phys. Lett.*, vol. 81, no. 8, pp. 1438–1440, 2002.

[7] E. S. Kang, J. U. Park, and B. S. Bae, "Effect of organic modifiers on the thermo-optic characteristics of inorganic-organic hybrid material films," *J. Mater. Res.*, vol. 18, no. 8, pp. 1889–1894, 2003.

[8] D. Kim, Y. Han, J. Shin, S. Park, Y. Park, H. Sung, S. Lee, Y. Lee, and D. Kim, "Suppression of temperature and polarization dependence by polymer overcladding in silica-based AWG multiplexer," in *Optical Fiber Communication (OFC 2003)*, vol. 1, 2003, Paper MF50, pp. 61–62.