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Polymer waveguide variable optical attenuator and its reliability

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Abstract

A variable optical attenuator (VOA) made of novel low-loss fluorinated polymers is demonstrated showing a low operating power of less than 30 mW, due to the superior thermo-optic effect of polymer material. Less than 1.0 dB of the device insertion loss is achieved by incorporating highly fluorinated polymers with a low absorption loss for 1550 nm. Device characteristics with a closed-loop feedback control circuit are investigated, exhibiting low wavelength and negligible temperature dependence for the practical attenuation application. By following the completed reliability test of the Telcordia GR1221, the reliability issue of the polymeric device is carefully addressed in order to confirm that the device has sufficient reliability for commercial applications.

Keywords: Integrated optics; Polymer waveguide; Variable optical attenuator; Thermo-optic effect

1. Introduction

Recently, the variable optical attenuator (VOA) has become an essential optical component especially for power equalization in a dense wavelength division multiplexing (DWDM) optical transmission system [1]. And, as a basic component of an optical transmission system, the application area is rapidly growing. There have been various approaches for fabricating the VOA, including opto-mechanical systems [2], micro-electromechanical systems (MEMS) [3,4], and planar lightwave circuits (PLC) [5–7]. In each approach, unique operating principles have been explored. Among them, an

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integrated-optic waveguide type VOA is preferred for WDM systems where a compact array type device is required. Further advantages of the waveguide devices have been emphasized when they are integrated with other devices such as optical switches and wavelength multiplexers [8–10].

A silica waveguide fabricated on a silicon substrate is the most popular way to fabricate the PLC device. Particularly when the waveguide length is relatively long, the silica waveguide has an advantage over the polymer due to its extremely low propagation loss. Compared to the silica, though the absorption loss is higher, the polymer waveguide has strong competitiveness when one needs to control the optical signal. Due to the high thermo-optic coefficient and the low thermal conductivity of the polymer, the efficiency of index modulation is more than 10 times higher than that of the silica. However, there has been widespread concern regarding the long-term stability of the polymeric waveguide device. Though there are some reports demonstrating the stability of polymer material [11], we must still address issues surrounding each optical device fabricated with a specific polymer material.

In this work, a polymeric VOA based on higher-order mode coupling in a planar waveguide is proposed. Through the optimization of the device structure and the fabrication procedure, we have optimized device performances such as insertion loss, polarization dependence, wavelength dependence, and the temporal response. Further improvement of the intrinsic characteristics of the device is achieved by employing an optical feedback scheme, which is openly used in a practical optical communication system. For a completely packaged VOA, the reliability issue of the polymeric device is thoroughly addressed in accordance with the Telcordia reliability test recommendation [12].

2. Design of the polymeric VOA

Optical polymer materials have been intensively investigated in order to meet with the requirements of high performance thermo-optic devices. The material properties required for optical devices are low absorption loss, controllable optical refractive index, low optical birefringence, and long-term environmental stability. Considerable efforts have been devoted to reduce the near-IR optical loss, which is introduced through the vibration absorption of C–H bond in the polymer chain. Replacing C–H bond with C–F bond, one can reduce the optical loss and increase thermal stability due to the heavy mass of fluorine and the higher strength of C–F bond. There have been various approaches used to synthesize low-loss optical polymers based on acrylates [13], polyimides [14], polyarylene ethers [15,16], and perfluorocyclobutane [17]. Among them, fluorinated UV-curable acrylates was most actively investigated due to convenient low temperature processing using UV curing. Therefore, our research focuses on the development of highly fluorinated UV-curable acrylate polymers, the ZPU series.

To investigate the propagation loss of the ZPU series polymer, the liquid immersion loss measurement technique was used [18]. A slab waveguide structure was prepared by coating two ZPU polymers successively, which had a refractive index of 1.464 and 1.450 for the core and lower-cladding layers, respectively. The optical loss as a function of propagation distance is shown in Fig. 1, in which the propagation losses are below 0.02, 0.05, and 0.31 dB/cm, for 830, 1310, and 1550 nm, respectively.

A schematic diagram of the proposed VOA structure is shown in Fig. 2. The multi-mode waveguide section in the middle of the device plays a key role in device operation. The heating electrode covers the multi-mode waveguide section with an angle of α to introduce an index change by the thermo-optic effect. The operating principle of the VOA is explained through the mode coupling and filtering process. The result of the two-dimensional beam propagation method (BPM) simulation for the case of no index perturbation is shown in Fig. 3(a). Adiabatic fundamental mode propagation is observed when the taper angle is less than 0.6°. On the contrary, when a voltage is applied across the heating electrode, the refractive index underneath the heater is lowered due to the thermo-optic (TO) effect of the polymer film. Through induced index perturbation, the light will experience a coupling to a higher order mode and a partial reflection by an an-

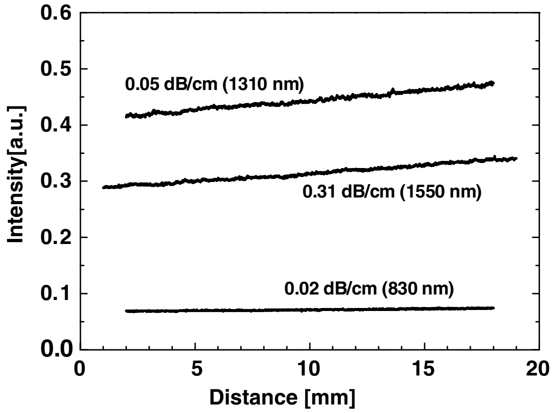

Fig. 1. Optical propagation losses measured by a liquid immersion technique from slab waveguides made of ZPU polymers.

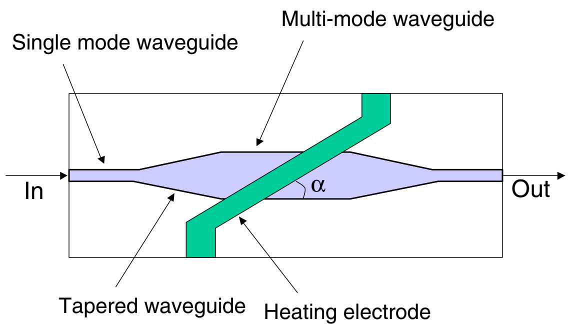

Fig. 2. Schematic diagram of the proposed polymeric thermo-optic variable optical attenuator, where a tapered optical waveguide and a tilted heating electrode are presented.

gle of 2α. Fig. 3(b) shows the higher order mode coupling and the radiation of the light when a temperature change of 42° is applied. These excited higher-order modes are filtered out as it propagates through the output taper section and the output single mode waveguide. The higher voltage introduces stronger perturbation to the guided mode and provides greater attenuation.

A single mode waveguide is designed to have a 7×7 μm^2 rectangular cross-section with a core-cladding index contrast of 0.34%. The upper cladding has a lower refractive index than the lower cladding in order to reduce upper cladding thickness and enhance heating efficiency at the core. Based on 3-D BPM analysis, it is confirmed that

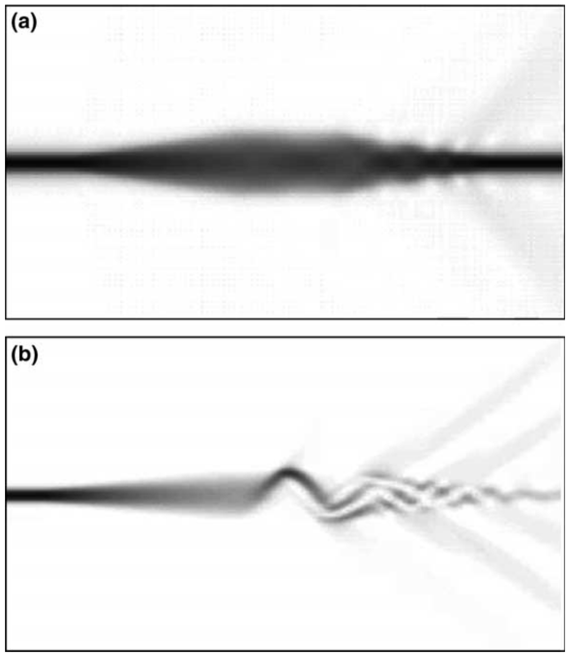

Fig. 3. Results of a BPM simulation: (a) without the thermo-optic index perturbation, and (b) with an index perturbation induced by a temperature change of 42 °C.

over 30-dB attenuation is obtainable for a temperature difference of 60 °C.

3. Fabrication of the polymer VOA

The device was fabricated using facilities for 4-in. silicon wafer processing. The core material was the ZPU series with a refractive index of 1.464. The lower cladding and upper cladding had an index of 1.459 and 1.430, respectively. First, the lower cladding layer consisting of 20 μm thickness was spin-coated and cured by the UV exposure with an intensity of 12 mW/cm^2 for 1 min in an N_2 atmosphere. Post baking was performed on a 160 °C hotplate for 1 h. Using a silicon-containing photoresist, ATMR-29^{TM}, which has excellent selectivity for etching the polymer, the waveguide pattern was formed on the lower cladding layer through conventional photolithography. By using reactive ion etching (RIE) in oxygen, a waveguide pattern was grooved until the depth reached 7 μm.

The groove was then filled with the core material by spin coating, and then cured by UV exposure. Next, until only the rectangular core remained, the whole surface of the wafer was etched by RIE. Finally, the upper cladding layer was coated and cured by the same condition. The thickness of the upper cladding was 5 μm.

The heating electrode for attenuation was deposited by the e-beam evaporation of Cr and Au to obtain appropriate electrical resistance. The deposition rate was kept below 1 Å/s, in order to avoid cracks on the polymer surface due to the difference of thermal expansion between polymer and metal. The electrical resistance of the electrode was designed to be 120 Ω for 2.5 V of operation voltage; and the bonding pads measuring 3 μm in thickness were formed by Au electro-plating. After device fabrication, the wafer was diced into individual chips with rough end facets and the end facets were then polished to improve coupling efficiency and obtain an angle of 7° for the reduction of back reflection. For packaging the device, a metal case and a metalized fiber were used; the cover was then hermetically sealed with a solder in air without inert gas.

4. Intrinsic performance of the polymer VOA

The typical attenuation characteristics of a fabricated VOA for 1310 and 1550 nm are shown in Fig. 4. The length of the fabricated device was 1 cm and the insertion loss of the device without applied voltage was less than 1 and 0.7 dB for 1550 and 1300 nm, respectively. The propagation loss and the coupling loss measured by the cutback method were about 0.5 dB/cm and 0.15 dB/facet, respectively. The propagation loss measured by the cut-back method was higher than that of the slab waveguide measured using the immersion technique, which may have been caused by some material imperfection and side wall roughness. For the shorter wavelength, higher attenuation was obtained for the same applied voltage. The electrical power to obtain 30-dB attenuation was 29 and 24 mW for 1550 and 1300 nm, respectively.

The higher-order mode coupling occurring at the multimode region of the VOA may introduce a difference of device response depending on the light polarization and wavelength. Hence, as a function of input wavelengths, the insertion losses of the device were measured for the various attenuation levels as shown in Fig. 5(a). Initially, with no attenuation, the WDL was less than 0.2 dB. However, for 10- and 20-dB attenuation levels, the WDL in the C-band became 0.5 and 1 dB, respectively. The wavelength dependence of the device may have been caused by both the material absorption spectrum and the multimode interference effect. The current material we used for this device has an absorption increase for a wavelength over 1590 nm due to the incomplete fluorination in the polymer. The multi-mode interference is an inherent property of the device, which is presented from the device design based on the BPM. A feedback circuit, which will be explained later, is useful to reduce the WDL.

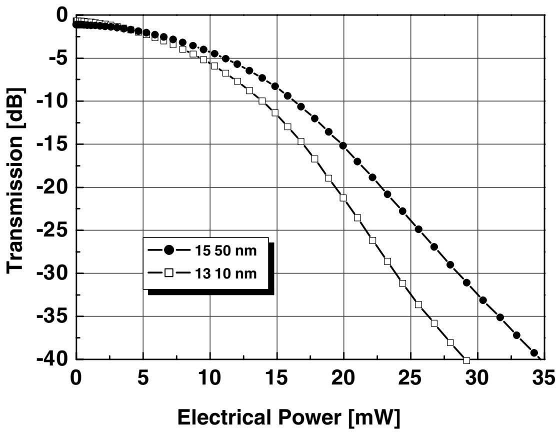

Fig. 4. Typical attenuation characteristics of the fabricated VOA measured for 1300 and 1550 nm wavelengths, where the insertion loss increases gradually depending on the applied voltage.

To measure the polarization-dependent loss (PDL) characteristics of the device, a polarization-scrambled light was coupled into the device and the insertion loss fluctuation was then monitored. PDL is defined by the difference of the maximum and the minimum insertion losses for all the polarization states. For the various attenuation levels, the measured PDL of the VOA is shown in Fig. 5(b). The PDL for the 0-dB attenuation, which was caused by material birefringence and

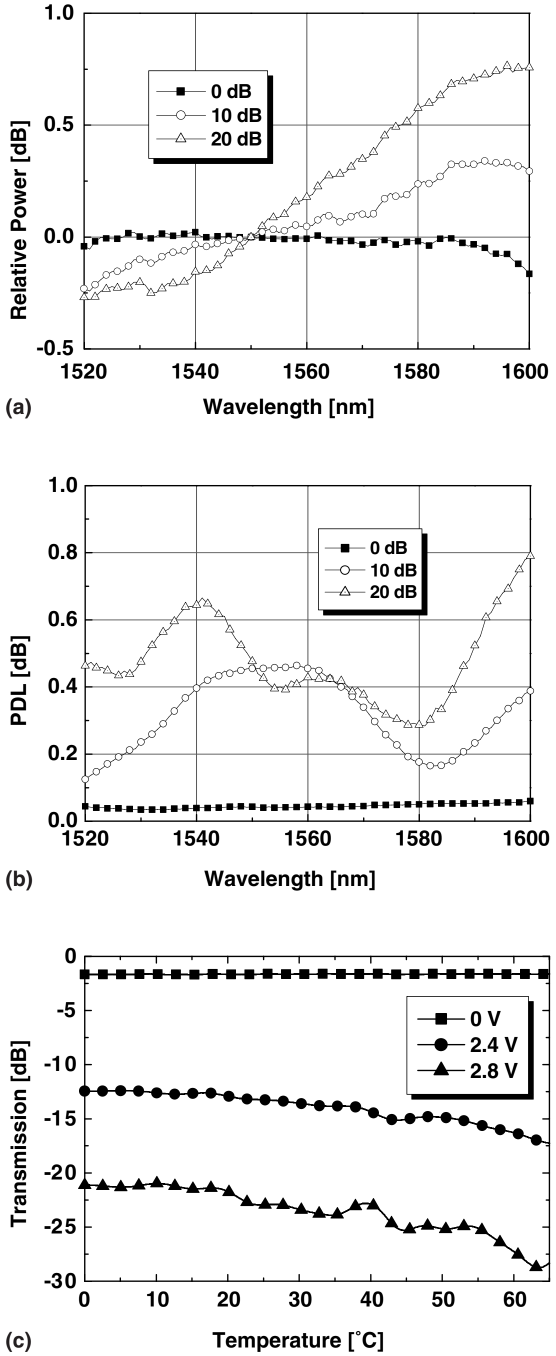

Fig. 5. Intrinsic transmission characteristics of the VOA: (a) insertion loss as a function of wavelength, (b) polarization-dependent loss measured as a function of wavelength, and (c) temperature dependence of the device for various attenuation levels.

the device structure, was less than 0.1 dB. The PDL also increased similar to the WDL according to higher attenuation level. For 10- and 20-dB attenuation in the C-band, the PDL was typically about 0.5 and 1 dB, respectively.

Temperature dependence of the polymer device should be clarified since the large thermo-optic effect of polymer material makes it hard to avoid temperature dependence. Without applied voltage, the change of loss was less than 0.2 dB during the −30–85 °C temperature cycling test. With an applied voltage, significant temperature dependence was observed as shown in Fig. 5(c). For 2.4 V fixed applied voltage, the attenuation level varied from 10 to 15 dB for temperatures ranging from 0 to 65 °C. The larger variation was observed for the higher attenuation level. Such large temperature dependence may be caused by the variation of the thermo-optic coefficient of the polymer at an elevated temperature. Moreover, the resistivity change of the metal electrode may be another reason for temperature dependence. However, the temperature dependence of the intrinsic VOA device could be reduced by incorporating an optical feedback circuit as explained in the following.

To measure the time response of the device, a rectangular control signal was applied as shown in Fig. 6(a). When the signal is adjusted to give an attenuation of 8 dB, the response time from 0 to 8 dB was about 7 ms. In addition to this fast response time, a slow response of the VOA was also measured as shown in Fig. 6(b). When the input voltage changes through a step function, the output optical signal follows the control signal and changes abruptly to another level. However, the optical signal experiences slight initial overshoot before it reaches a final stabilized level. Such a slow drift occurring in a few tens of seconds may be caused by the visco-elastic property of the polymer material. The slow drift of the attenuation level could also be improved by the optical feedback.

5. VOA performance with an optical feedback

In a practical optical communication system that includes a VOA, monitoring of the attenuated optical power and closed loop feedback control

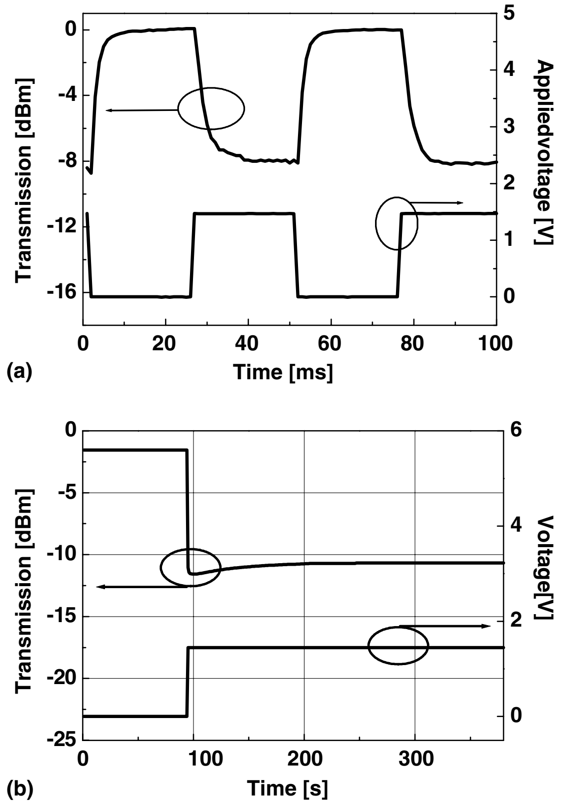

Fig. 6. Time response of the VOA: (a) with a fast control signal, and (b) with a DC signal applied for a longer time in order to observe a slow drift of the attenuation level.

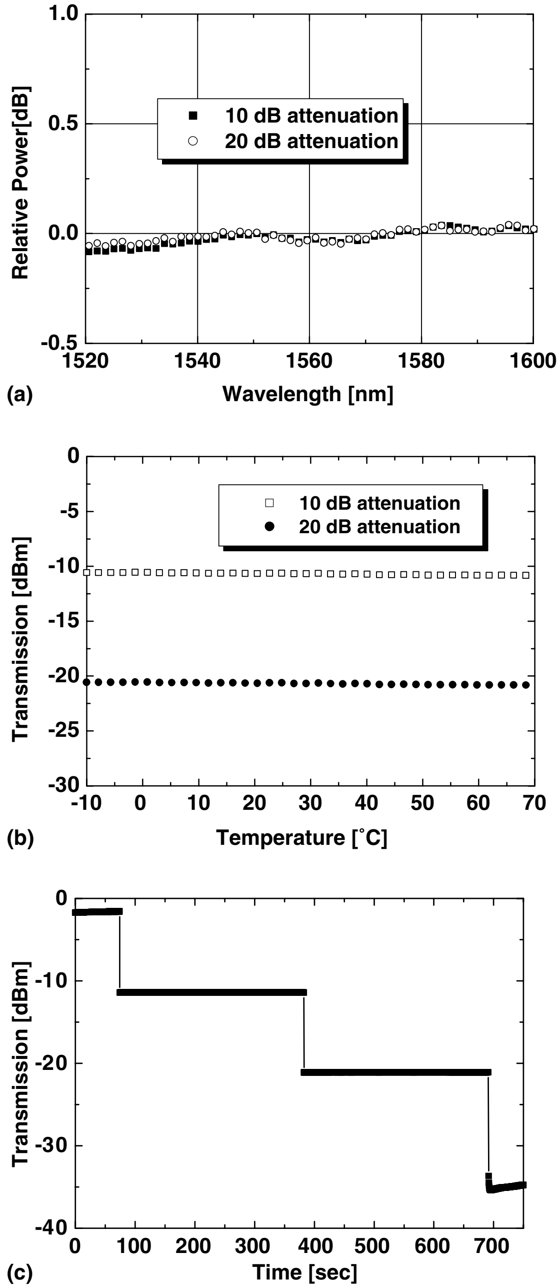

Fig. 7. Modified VOA characteristics by the optical feedback which demonstrates: (a) improved wavelength dependence, (b) temperature dependence of the feedback controlled output power, and (c) suppressed slow drift in the DC response.

are often implemented in order to provide an accurate and reproducible attenuated optical power level. Hence, the performance of a VOA should be reconsidered when a feedback circuit is included. The feedback circuit consists of a fiber tap coupler with a tapping ratio of 5% or 10% and a photodiode for tapped power monitoring. An analog electrical circuit is used to generate an applied voltage to the VOA based on the input voltage and the feedback signal. If the monitored power level deviates from the reference power, the circuit generates an error signal; the applied voltage is then adjusted to reduce the error.

Though the polymer VOA has wavelength and temperature dependence as an inherent property, these problems could be overcome by introducing a feedback scheme. The improved performance of the feedback controlled VOA are summarized in Fig. 7. A wavelength dependence of only 0.15 dB was observed in the measured data shown in Fig. 7(a), which showed great improvement compared to the intrinsic VOA performance shown in Fig. 5(a). The temperature dependence of the device became almost negligible as shown in Fig. 7(b), which was a serious problem of the original VOA as shown in Fig. 5(c). The slow drift in the time response of Fig. 6(b) was not observed in the optical feedback controlled VOA as shown in Fig. 7(c).

6. Reliability

According to the Telcordia reliability assurance requirements for passive optical components GR-1221-core, optical components should pass a series of tests to show mechanical integrity and endurance [12]. In the case of a polymeric device, mechanical integrity is relatively easy to prove because the solid-state polymer components do not have any moving parts. Following the standard procedures described in the GR-1221-core, we performed a mechanical shock test, a variable frequency vibration test, and a thermal shock test. For each test, 11 VOA samples were prepared as the minimum number of samples for statistical analysis. The change of insertion loss was negligible so that the polymer device passed all tests of mechanical integrity.

The temperature cycling test was performed based on the procedures stated in the MIL-STD-883, method 1010 of the Telcordia requirements. The temperature of the oven was cycled from −40 to 85 °C in 7 h and 20 min. The insertion loss change of the VOA was monitored as shown in Fig. 8. The fluctuation of the loss variation was less than 0.3 dB. Fig. 9(a) shows the variation of insertion loss measured from 11 VOA samples for more than 700 cycles which is longer than the Telcordia requirement of 500 cycles. A successful test result was obtained with a loss change less than ±0.2 dB.

A damp heat test was also performed on 11 VOA samples. To pass the test, the change of insertion loss must be less than 0.5 dB after 2000 h of storage in an 85 °C oven with 85% relative humidity (RH) for uncontrolled environment application. The data measured during the damp heat test are shown in Fig. 9(b). Less than ±0.2 dB of loss fluctuation was observed for the entire

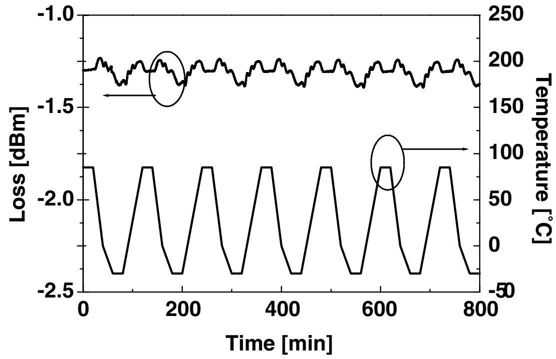

Fig. 8. Insertion loss fluctuation during the temperature cycling test from −40 to 85 °C with no applied voltage.

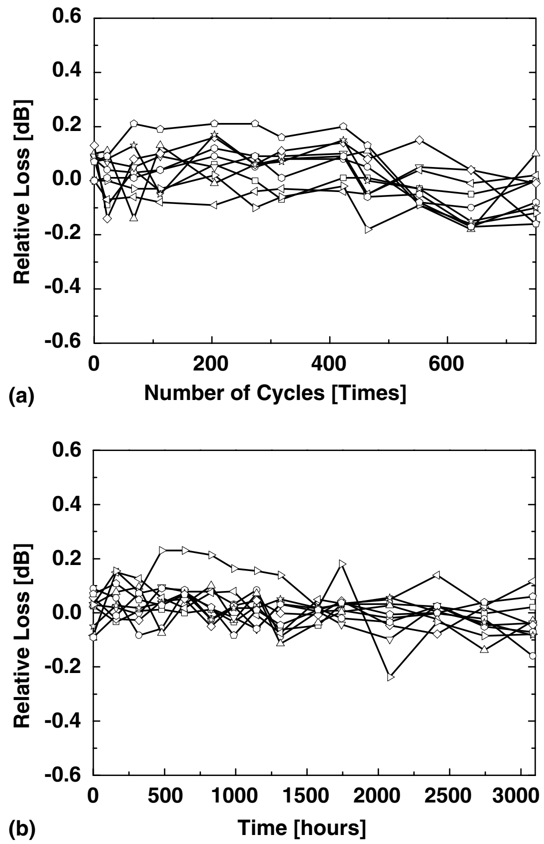

Fig. 9. Insertion loss variation of the hermetically sealed VOA: (a) in the temperature cycling test from −40 to 85 °C, and (b) in the damp heat test stored at 85 °C, 85% RH.

test period. Before the damp heat test, as an accelerated endurance test, we also performed a conventional pressure cooker test (PCT) at 120 °C, 2 atm with 100% RH, which is about 100 times more effective than the 85 °C, 85% RH environment. The device also passed the PCT test over 30 h which leads us to believe it could withstand a 3000 h at 85 °C, 85% RH environment test. There were no adhesion problems between the interfaces of the polymer-silicon and the polymer-heater during the tests. In addition to these passive loss measurements, the attenuation characteristics were checked after each reliability test. There were no significant effects on the VOA performance by any of the reliability tests.

7. Conclusion

Based on a novel low-loss fluorinated acrylate polymer material, we have designed and fabricated an integrated-optic VOA. The insertion loss of the device was as low as 0.8 dB, and the electrical power consumption for a 30 dB attenuation level was less than 30 mW. From the intrinsic VOA device, a WDL of 1 dB and a PDL of 1 dB were observed when 20-dB attenuation was applied. The device showed a variation of device performance depending on the environment temperature. By incorporating an optical feedback circuit which is inevitable in a practical optical transmission system, improvement of the intrinsic VOA performance was demonstrated. The WDL and temperature dependent loss was reduced to 0.15 and 0.3 dB, respectively. A complete reliability test was accomplished by following the procedures recommended by Telcordia Co. The insertion loss change of the device was less than ±0.2 dB throughout all the tests, which shows that the polymeric optical devices possess sufficient reliability for commercial optical communication systems.

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