A 100 Gbaud On-off-Keying Silicon-Polymer Hybrid Modulator Operating at up to 110°C

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***Abstract*— We demonstrate 100-Gbaud on-off-keying (OOK) transmission driven at a low voltage using an electro-optic (EO) polymer modulator combined with a silicon Mach-Zehnder interferometer waveguide. Various types of organic- and polymer-based modulators have been reported to perform efficient EO modulation and high-speed data transmission at over 100 Gbaud. However, there are critical concerns regarding the practical application of polymer devices in terms of environmental stability. In particular, long-term thermal storage and stability during operation require improvements before EO polymer modulators can be applied in practical systems. We have developed an EO polymer with enhanced thermophysical stability and used it to fabricate an efficient EO polymer modulator. In this study we extend our earlier work on high-speed EO polymer modulators by performing fiber-link 100-Gbaud OOK transmission at various operating temperatures. A thermal stability test revealed that the EO polymer modulator can survive high-temperature exposure up to 110°C. Error-free signal transmissions over a distance of 2.0 km was successfully demonstrated with a driving voltage of 1.9 V_{pp} and a bit error rate below the 7% overhead forward error correction threshold. The driving voltage, bandwidth, bit error rate, and fiber-link performance of the device are presented.**

***Index Terms*— Electro optic modulators, polymer, silicon, optical interconnections, on-off-keying.**

I. INTRODUCTION

THE exponential growth of interconnect bandwidth requirements for next-generation optical fiber links has driven an upgrade of Ethernet products to 200 Gigabit Ethernet (GbE) and 400 GbE. Ultra-fast electro-optic (EO) modulators are promising building blocks inside the device for high-speed and energy-efficient interconnects. While the latest technologies meet current demands, researchers in both academia and industry are beginning to shift their efforts towards implementing more advanced technology that operates with 0.8 and 1.6 Tbit/s links. Various types of EO modulators based on efficient optoelectronic platforms, such as silicon [1], indium phosphide [2], and lithium niobate [3], have been fabricated. These modulators are essential for achieving a low driving voltage, an expanded bandwidth, a small footprint, and CMOS-compatible integration. Among modulators made with various types of materials, EO polymers have demonstrated high-speed modulation at rates of more than 100-Gbaud and efficient electrical energy dissipation [4]. In particular, hybrid silicon waveguides coated with an EO polymer have been shown to compensate for the limited nonlinear optical efficiency of silicon by taking advantage of the second-order nonlinear optical properties of such polymers [5]. For integrated optical device manufacturing, the unique processability of EO polymers allows the development of new manufacturing processes and can increase yield.

There are three fundamental ways for scaling the interconnect bandwidth: i) increasing the symbol rate per lane; ii) parallel processing in multiple lanes; and iii) encoding of more bits per symbol. The simplest method is to increase the symbol rate to well beyond 100 Gbaud. Traveling-wave EO polymer modulators are promising for realizing such high-baud-rate operation. An electrical modulation bandwidth of >100 GHz has been theoretically predicted based on a minimized velocity mismatching between light and radio-frequency (RF) waves [6]. An EO response of >140 GHz using an EO polymer modulator has already been experimentally demonstrated [7]. These properties make EO polymer modulators attractive for simple signaling at rates of 100-Gbaud and beyond. To exceed 100-Gbit/s on-off-keying (OOK) and 200-Gbit/s 4-level pulse-amplitude modulation (PAM4) polymer-based modulators are being developed [5], [8], [9]. However, the reliability and environmental stability of such devices have not been fully clarified. Previous studies have indicated that the nonlinear optical molecules with large first-order hyperpolarizability are key for realizing efficient EO modulation. Therefore, research has mainly focused on using efficient EO molecules in the polymer host. The main problem is the loss of EO activity at elevated temperatures due to the thermal disordering of EO molecules in poled polymer films. The main standard for the reliability of optoelectronic devices

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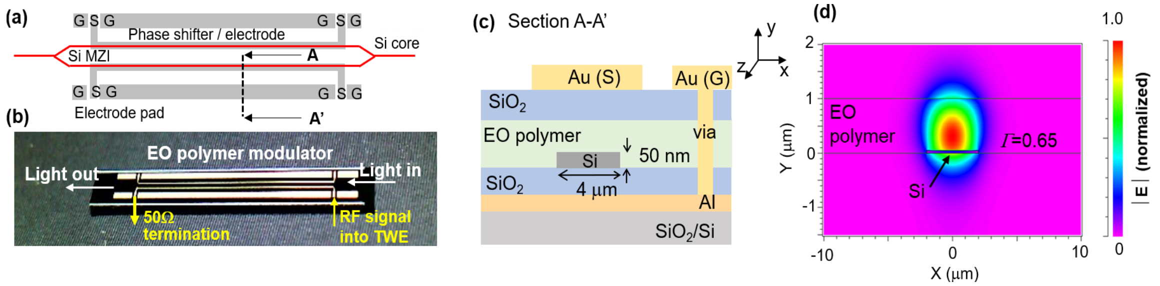

Fig. 1. EO polymer modulator. (a) Schematic structure of Mach-Zehnder interferometer (MZI) waveguide with two-arm 8-mm-long phase shifter. (b) Photograph of fabricated EO polymer modulator (TWE: traveling-wave electrode). (c) Cross section of waveguide and electrode, which consists of bottom Al electrode, silicon core, EO polymer and SiO$_2$ cladding, and top Au electrodes. (d) Calculated optical mode for waveguide (Γ: mode confinement factor).

is Telcordia GR-468-CORE The key parameters for thermal stability are resistance to high-temperature storages (85°C), high-temperature operation (85°C), damp heat (85°C, humidity 85%), and heat cycling (−40°C to +100°C). We have previously reported that EO polymers with thermo-physically enhanced properties are an alternative to commonly used EO materials. The fabricated EO polymer modulators have exhibited a high EO coefficient, high-speed modulation up to 120 Gbaud, a low driving voltage, and robustness of storage at high temperatures [8]. The modulators showed little performance degradation after storage at 105°C for longer than 2,000 h [10]. This is the best thermal stability, to the best of our knowledge, reported for polymer-based modulators. To further evaluate the device properties for commercial applications, fiber-link data transmission should be performed under harsh environmental conditions. This study extends our earlier work on high-speed EO polymer modulators by performing thermal stability tests for a fiber-link application over a distance of 2.0-km. The RF driving voltage, bandwidth, 100-Gbaud OOK, fiber-link, and bit-error rate were measured at temperatures of up to 100°C.

II. EXPERIMENT AND RESULTS

A. Structure of EO Polymer Modulator

Figures 1(a) and 1(b) respectively show a schematic diagram and a photograph of a fabricated EO polymer modulator. The modulator chip with a phase shifter length of 8.0 mm was produced by dicing. The cross section in Fig. 1(c) shows that the waveguide consists of a silicon core covered with an EO polymer (glass transition temperature $T_g = 182°C$). The spin-on SiO$_2$ layers were deposited between the EO polymer as cladding layers to protect the device during the modulation processes. The refractive indices of the EO polymer and SiO$_2$ cladding are 1.67 and 1.48, respectively, so that the optical mode is concentrated around the 50-nm-thick and 4.0-μm-wide silicon core, and most of the optical field overlaps the EO polymer along the optical path length. The calculated optical modal distribution for the transverse magnetic (TM) mode in the waveguide is shown in Fig. 1(d). A confinement factor of 65% was calculated to be necessary for efficient EO modulation. The confinement factor is the ratio of the optical power trapped within the EO polymer to the power for the entire waveguide. More details about the materials and fabrication can be found elsewhere [10], [11]. Single-mode optical fiber (SMF) pigtails were used to couple the laser light to the EO polymer waveguide. To avoid a large fiber-to-waveguide insertion loss, fiber pigtails with a high numerical aperture were used for power coupling. The insertion loss of the EO polymer modulator at a wavelength of 1,550 nm was around 6.1 dB, which is dominated by the material absorption loss of the EO polymer (~0.4 dB/mm) and the waveguide loss, and the total fiber-to-fiber insertion loss was 13 dB, consisting of 6.9 dB coupling loss and 6.1 dB on-chip loss (polymer absorption and waveguide scattering). The MZI modulator allows differential signaling operation when driving electronics are applied to the two arms of the phase shifters. After a final electrical poling of the EO polymer, a half-wave voltage (V_π) of 1.8 V was measured at a wavelength of 1,550 nm, which leads to $V_\pi \cdot L = 1.4$ V·cm as a π-voltage length product. For RF modulation in the GHz regime, the traveling-wave electrodes must effectively conduct the driving electrical signal to the modulator to avoid microwave loss. For this purpose, 3-μm-thick and 20-μm-wide electrodes were formed on the phase-shifter arms. The measured bandwidth was 70 GHz as discussed later.

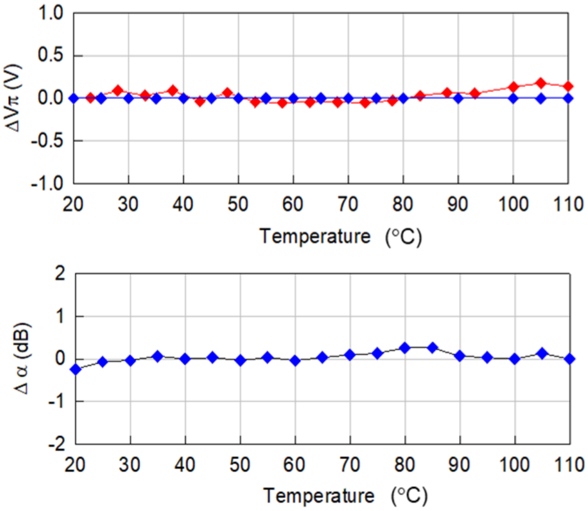

Fig. 2. Thermal properties of EO polymer modulator. (a) Change in V_π (ΔV_π) at 10 kHz (blue) and 10 GHz (red) and (b) change in insertion loss ($\Delta\alpha$) at temperatures of 20 to 110°C.

B. Properties of EO Polymer Modulator

Figures 2(a) and 2(b) show the temperature dependence of V_π for 10 kHz and 10 GHz signals and insertion loss, respectively, for temperatures up to 110°C. Compared to the V_π value measured at a frequency close to DC, that obtained with RF driving is more important for evaluating

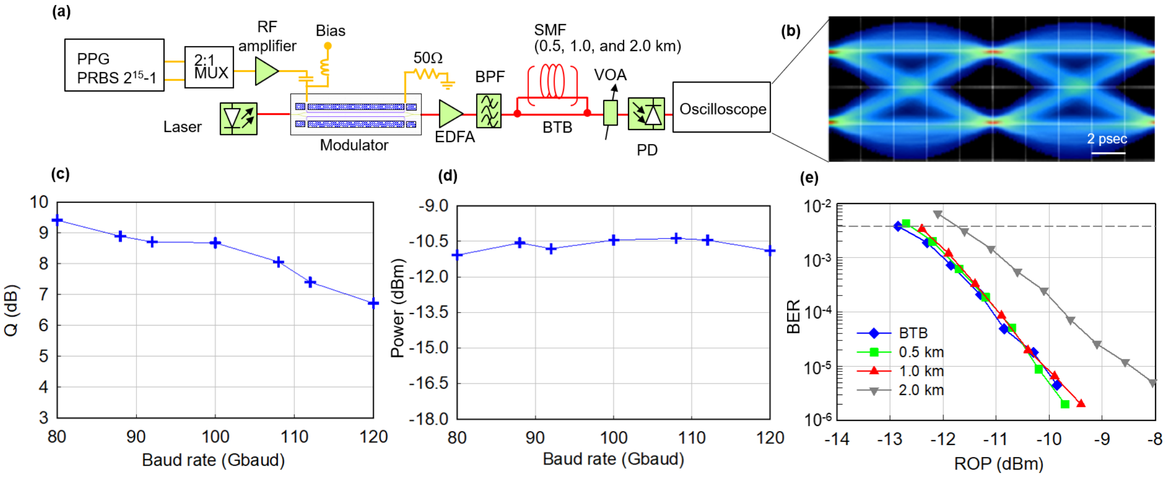

Fig. 3. High-seed operation of EO polymer modulator. (a) Setup for OOK transmission up to 120-Gbaud. A programmable pulse generator (PPG) and a 2:1 multiplexer (MUX) are used to apply an electrical signal to the EO polymer modulator. The light from a laser at a wavelength of 1,550 nm is coupled to the waveguide, and the output light is conducted to a photodetector (PD) after being amplified using an EDFA and passing through a band-pass filter (BPF). For fiber-link transmission, SMFs are connected. Eye patterns were measured using a digital communication analyzer or a real-time digital storage oscilloscope. (b) Measured eye pattern at 100-Gbaud OOK. (c) Q factor at various baud rates. (d) Measured electric power of OOK signals at various baud rates. (e) BER curves for 100-Gbaud OOK over various distances. Hashed line is BER threshold of 3.8×10^{-3}.

the modulator performance at high speed. To evaluate the RF V_π, we performed an optical spectral analysis using a Bessel function transform [12] to conduct the value of 1.9 V, which was almost identical to the V_π of 1.8 V with 10 kHz signal. In this thermal stability test, the EO polymer modulator was placed on a thermoelectric cooler (TEC), which controlled the temperature of the modulator to be between 20°C and 110°C. The V_π at 10 kHz and insertion loss were almost constant within this wide temperature range, implying that the microscopic morphology of the EO polymer and other waveguide components did not change at temperatures below 110°C. Therefore, de-poling (molecular disordering) was suppressed, resulting in excellent thermal stability of the EO activity. The RF V_π remained around up to 80°C and increased at higher temperatures. Compared to material stability of the EO polymer, RF response, including the effect of microwave loss and impedance match, becomes sensitive to higher temperatures. The RF V_π recovered to near its original value when the temperature returned to room temperature. Disordering of the EO polymer occurs at $<\sim$40°C below T_g. The upper thermal limit of our EO polymer modulator is thus around 140°C.

C. High-Speed Operation

To assess modulation performance, we applied an electrical signal to the EO polymer modulator and verified OOK signaling. The experimental setup is shown in Fig. 3(a). With a peak-to-peak driving voltage 1.9 V_{pp}, we varied the electrical signals for a transmission rate of 80 Gbaud to 120 Gbaud. In Fig. 3 (b), typical modulation result, in the form of measured eye pattern at 100 Gbaud is shown. The eye patterns were evaluated by measuring the Q factor and are shown as a function of the baud rate in Fig. 3(c). The Q factor decreased with increasing baud rate but did not abruptly drop up to 120 Gbaud. Figure 3(d) shows the change in the electrical power of OOK signals, which is almost constant for a range of 80 to 120 Gbaud, indicating a flat frequency response in the high frequency regime.

To further investigate the performance of the modulator, a bit error rate (BER) analysis was carried out at 100 Gbaud with offline post-processing that included timing recovery, feed-forward equalization, and error counting. For back-to-back (BTB) transmission, a BER of 3.9×10^{-6} was measured, which is below the BER threshold of the 7% overhead hard-decision forward error correction threshold (HD-FEC).

BER sensitivity curves for 100-Gbaud OOK transmission were analyzed for optical fiber links (0.5-, 1.0-, and 2.0-km SMFs), which are likely to be used in intra-data center applications. To determine the receiver sensitivity, the BER for various received optical power (ROP) levels was analyzed. In the analysis, the 7% HD-FEC threshold was used as a reference. Figure 3(e) shows the dependence of the BER on the ROP for fiber links for which successful post-FEC transmission was expected. The 100-Gbaud OOK transmission varied with a very small penalty (<0.5 dB) over a 1.0-km distance compared to the BTB result. We obtained a BER value lower than 10^{-5} and a sensitivity as low as −12.4 dBm. As expected, the transmission performance degrades after a distance of 2.0 km due to the limited fiber chromatic dispersion at a wavelength of 1,550 nm. Nevertheless, we achieved error-free transmission over 2.0 km with a receiver sensitivity of −11.7 dBm.

D. Thermal Stability Test With High-Speed Operation

The electrical modulation bandwidth of the EO polymer modulator was characterized using a vector network analyzer from 1 to 70 GHz. As shown in Fig. 4, the measured frequency response of the EO S21 parameter shows a 3-dB bandwidth of about 70 GHz, indicating the OOK signaling capability at rates above 100 Gbaud. Fabrication of the traveling-wave electrodes is critical to increase the bandwidth of the EO polymer modulator. The bandwidth was larger than that obtained in our previous study [11]. We improved the Au deposition process for better RF transmission by using chemical plating. Given that for an EO polymer modulator the dielectric loss

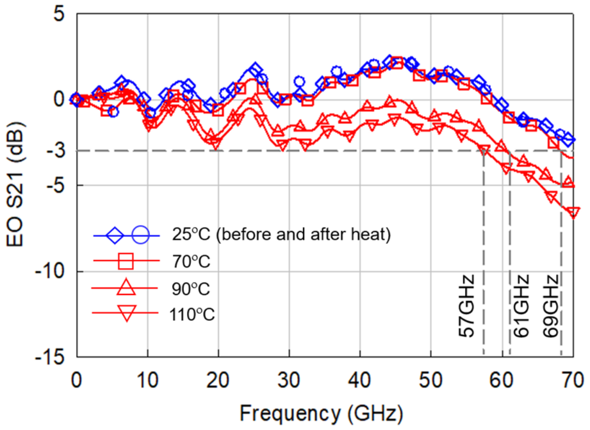

Fig. 4. EO frequency response (EO S21) for EO polymer modular measure at temperatures up to 110°C.

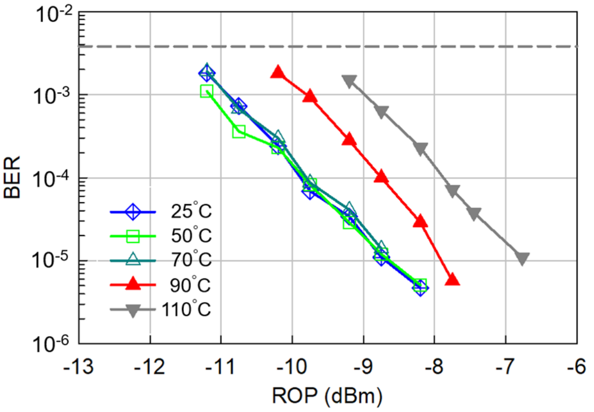

Fig. 5. BER for 100 Gbit/s OOK transmission at ambient temperatures of 20°C to 110°C. Hashed line is BER of 3.8×10^{-3}.

and velocity mismatch are rather frequency-insensitive above 100 GHz a further increase in the bandwidth can be expected by improving the design and fabrication of the traveling wave electrode.

The temperature dependence of V_π (DC) shown in Fig. 2(a) suggests that the EO coefficient for the modulator is independent of temperature up to 110°C. A comparison of the EO S21 curves at various temperatures is shown in Fig. 4. The bandwidth remained at around 67 GHz and only slightly changed up to 70°C. The frequency response degraded gradually when the temperature was increased further. When the modulator was heated to 90°C and 110°C, the 3-dB bandwidth was reduced to 61 GHz and 57 GHz, respectively. The measured temperature dependence of the bandwidth can be attributed to the temperature sensitivity of the RF V_π. Nevertheless, the bandwidth is determined by the temperature dependence of the dielectric loss, velocity mismatch, and electrical resistance. It should be noted that the EO S21 curve is completely recovered when the temperature is decreased to 25°C.

To further demonstrate the high-temperature performance of the EO polymer modulator, instead of measuring static device properties such as V_π and insertion loss, the BER was monitored at elevated temperatures to determine the dynamic properties. Fig. 5 shows the BER versus ROP at 100-Gbaud OOK after a 2-km distance at various temperatures. Between 25 and 70°C, the transmission accuracy degrades with a very small penalty of <0.2 dB, which is identical to the thermal bandwidth properties shown in Fig. 4, showing constant values within the same temperature range. When the temperature was increased, we observed a 1.5-dB power penalty at 90°C and an extra 0.8-dB penalty at 110°C. These penalties can be explained by degradation of the modulation bandwidth from 70 to 57 GHz at the corresponding temperatures. However, even at high temperatures (>110°C), the EO polymer modulator achieved error-free transmission with a BER that was sufficiently lower than the 7% HD-FEC threshold.

III. CONCLUSION

We demonstrated the thermal stability of an EO polymer modulator for high-speed transmission for 100-Gbaud OOK at temperatures up to 110°C. This is best thermal stability achieved for a polymer modulator. Error-free transmission was achieved over a 2.0-km fiber-link under a threshold of 7% HD-FEC at this high temperature. Because of the high thermophysical durability of the EO polymer ($T_g > 180$°C), no significant changes were observed in the insertion loss or V_π. Importantly, the bandwidth and BER characteristics fully recovered to their original values after high-temperature testing. We hope that our results will stimulate further development of EO polymer modulators for use as efficient optical interconnects for large-bandwidth requirement and severe-environment applications such as data centers, 5G wireless networks, and autonomous driving.

REFERENCES

[1] G. T. Reed, G. Mashanovich, F. Y. Gardes, and D. J. Thomson, "Silicon optical modulators," *Nature Photon.*, vol. 4, pp. 518–526, Jul. 2010.

[2] Y. Ogiso *et al.*, "Over 67 GHz bandwidth and 1.5 V $V\pi$ InP-based optical IQ modulator with n-i-p-n heterostructure," *J. Lightw. Technol.*, vol. 35, no. 8, pp. 1450–1455, Apr. 15, 2017.

[3] M. He *et al.*, "High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gbit s^{-1} and beyond," *Nature Photon.*, vol. 13, pp. 359–364, Mar. 2019.

[4] P. Groumas *et al.*, "Multi-100 GbE and 400 GbE interfaces for intra-data center networks based on arrayed transceivers with serial 100 Gb/s operation," *J. Lightw. Techn.*, vol. 33, no. 4, pp. 943–954, Feb. 15, 2017.

[5] S. Wolf *et al.*, "Silicon-organic hybrid (SOH) Mach–Zehnder modulators for 100 Gbit/s on-off keying," *Sci. Rep.*, vol. 8, no. 1, Dec. 2018, Art. no. 25981.

[6] X. Zhang, B. Lee, C.-Y. Lin, A. X. Wang, A. Hosseini, and R. T. Chen, "Highly linear broadband optical modulator based on electro-optic polymer," *IEEE Photon. J.*, vol. 4, no. 6, pp. 2214–2228, Dec. 2012.

[7] M. Lee *et al.*, "Broadband modulation of light by using an electro-optic polymer," *Science*, vol. 298, no. 5597, pp. 1401–1403, Nov. 2002.

[8] G.-W. Lu *et al.*, "High-temperature-resistant silicon-polymer hybrid modulator operating at up to 200 Gbit s^{-1} for energy-efficient datacentres and harsh-environment applications," *Nature Commun.*, vol. 11, no. 1, p. 4224, Dec. 2020.

[9] C. Kieninger *et al.*, "Silicon-organic hybrid (SOH) Mach–Zhender modulators for 100 GBd PAM4 signaling with sub-1 dB phase-shifter loss," *Opt. Exp.*, vol. 28, no. 17, pp. 24693–24707, 2020.

[10] H. Miura *et al.*, "High thermal stability 40 GHz electro-optic polymer modulators," *Opt. Exp.*, vol. 25, no. 23, pp. 28643–28649, 2017.

[11] H. Sato *et al.*, "Low driving voltage Mach–Zehnder interference modulator constructed from an electro-optic polymer on ultra-thin silicon with a broadband operation," *Opt. Exp.*, vol. 25, no. 2, pp. 768–775, 2017.

[12] Y. Shi, L. Yan, and A. E. Willner, "High-speed electrooptic modulator characterization using optical spectrum analysis," *J. Lightw. Technol.*, vol. 21, no. 10, pp. 2358–2367, Oct. 1, 2003.