Highly Reliable Organic Polymer Optical Modulators

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Abstract: We demonstrate a >100 Gbaud transmission using a thermo-physically enhanced EO polymer modulator. The error-free signal over a distance of 2.0 km was successfully demonstrated under high-temperature exposure at up to 110°C.

1. Introduction

Recent progress of highly efficient and high-speed electro-optic (EO) modulator technology has received intensive research attentions in microwave photonics and fiber-optic networks. Among modulator made with various types of materials, the EO organic polymers have been used to demonstrate high-speed modulation over 100 Gbaud signaling and efficient electrical energy dissipation. Highlights of EO polymer modulators can be seen due to their large EO coefficient (r_{33}>100 pm/V), low dielectric constant and loss, and excellent compatibility with other materials and silicon based photonic devices. In particular, hybrid silicon waveguide covered with the EO polymer demonstrated to compensate for the limited nonlinear optical efficiency of silicon by taking advantage of efficient second-order nonlinear optical polymers. For integrated optical device manufacturing, the unique processability of EO polymers allows the development of new manufacturing processes and can increase yield. So that polymer modulator might be a cost-effective 100G serial solution.

There are three fundamental ways for scaling interconnect bandwidth: i) enhancement of the symbol rate per lane; ii) parallel processing in multiple lanes; and iii) encoding of more bits per symbol. In those comparisons, increasing the available symbol rate to well beyond 100 Gbaud is simplest. To date, an electrical modulation bandwidth of >100 GHz has been predicted in the theoretical calculation based on the minimized velocity mismatching between light and radio-frequency (RF) waves [1]. An EO response of >140 GHz using an EO polymer modulator has been experimentally demonstrated [2]. Such a high frequency response property makes EO polymer modulator promising devices for simple 100 Gbaud signaling and beyond. To exceed the 100-Gbit/s on-off-keying (OOK) and 200-Gbit/s 4-level pulse-amplitude modulation (PAM4) generated by polymer modulators are being developed [3]. However, the reliability and environmental stability of polymer devices are not fully understood. Previous studies have indicated that the nonlinear organic 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. Telcordia GR-468-CORE, which summarizes the reliability assurance for optoelectronic devices, can be refereed. 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).

Clearly using the EO polymer with enhanced thermo-physical resistance is a simple solution to pass thermal stability test. We have previously reported that EO polymers having the glass transmission temperature (T_g) of over 180°C are an alternative to commonly used organic EO materials. The EO polymer modulators have shown inherent advantages, such as high EO coefficient, high-speed modulation up to 120 Gbaud, low drive voltage, and high thermal storage [4]. The modulator showed little change of the device activity after the thermal storage at 105°C for longer than 2,000 hours. This is the best thermal stability, to the best of our knowledge, reported for polymer-based modulators. To further evaluate device properties regarding the commercial applications, fiber-link data transmission should be characterized by assuming harsh environmental conditions. This study extends our earlier work on the fabricated high-speed EO polymer modulators by performing a thermal stability test for the fiber-link application over a distance of 2.0-km. At operation temperatures of up to 110°C, the measurements of the RF drive voltage, bandwidth, 100-Gbaud OOK, fiber-link, and bit-error rate are conducted and presented. The photostability issue of the device will be also discussed in the later section.

2. High-speed EO polymer modulator

Figures 1(a) and 1(b) respectively show photographs of a fabricated EO polymer modular and an assembled component. The modulator is prepared by using a silicon Mach-Zehnder interferometer waveguide, EO polymer, SiO_2 cladding, and electrodes. The fabrication of the modulator chip is completed on a 100-mm silicon wafer after conventional lithography and spin-on techniques using a polymer solution. For RF modulation in the GHz

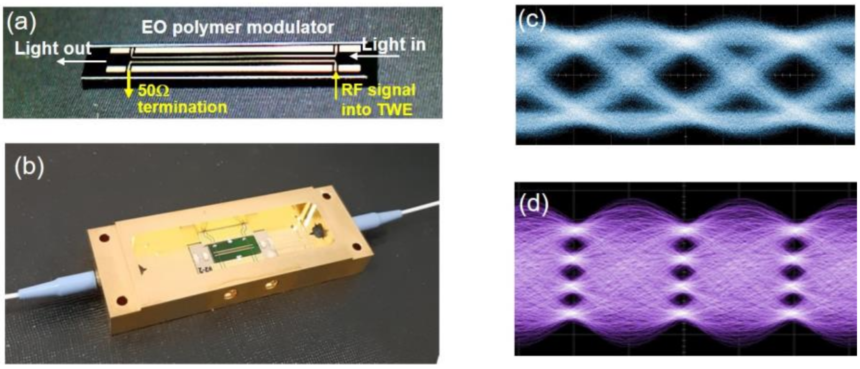

Fig. 1. EO polymer modular and high-speed operations. (**a**) Photograph of fabricated EO polymer modulator chip. (b) Assembled component inside the package. (c) Measured eye pattern at 120-Gbaud OOK. (d) Measured pattern at 100-Gbaud PAM4..

regime, a traveling-wave electrode must conduct the derive electric signal to the modulator to avoid microwave loss. For this purpose, designed-thick Au electrodes are patterned on the phase shifter arms. More details about the materials and fabrication of the modulator chip can be found elsewhere [5]. The fabricated EO polymer modulator is operated at a wavelength of 1,550 nm. The electrical modulation bandwidth of the modulator chip was measured to be about 70 GHz as the EO S21 parameter, supporting the OOK signaling capability over 100 Gbaud. The assembled component has the limited bandwidth properties because the metal-wiring and bonding to the electrodes causes the additional RF loss. The RF connectors used in this preliminary device can be also improved for higher frequency signaling. To assess modulator performance for high-data-rate operations, we applied electrical signals of 120-Gbaud OOK and 100-Gbaud PAMM4. In Figs 1(c) and (d), typical modulation results, in the form of measured eye patterns are shown. In these high-speed experiments, we used the modulator chip. The peak-to-peak voltage swings were 2.0 V_{pp} for OOK and 1.3 V_{pp} for PAM4. The high-speed signals can be evaluated by extracting the quality (Q) factors from measured eye patterns. The Q factors were 4.7 for 120 Gbaud OOK signal and 3.7 for 100 Gbaud PAM4 signal.

3. Thermal stability test with high-speed fiber link

Generally, the EO (Pockel's effect) polymer modulator is completed by applying the DC voltage across the EO polymer waveguide to induce molecular dipole alignment at the temperature of around polymer's glass transition temperature (T_g). The EO polymer used in this study has T_g of 182°C [6]. High poling temperature is preferred to obtain thermally stable EO polymer modulators. Disordering of the EO polymer occurs at <~40°C below T_g. Thus, the upper thermal limit of our EO polymer modulator is much higher than the Telcordia defined thermal test temperature (85°C). To demonstrate the high-temperature performance of the EO polymer modulator, instead of measuring static device properties such as V_π and insertion loss, BER was monitored at elevated temperatures to determine the dynamic properties. Figure 2 shows the BER vs ROP at 100-Gbaud OOK after 2-km distance at various temperatures. The sensitivity curve of BER for 100 Gbaud transmission after 2.0-km SMF is likely to be used in intra-data center applications. The SMF was connected after the EO polymer modulator. The BER sensitivity is quite stable from 20°C to 70°C, and slightly become worse with a

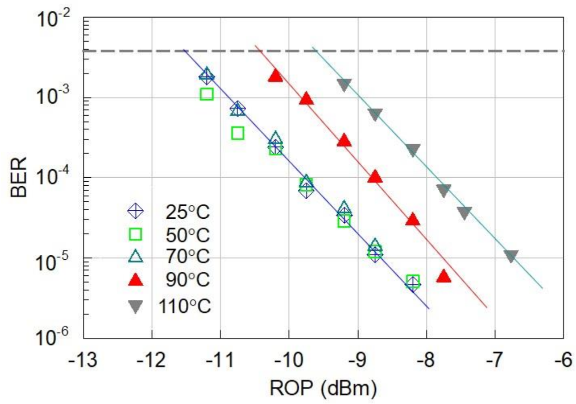

Fig. 2. BER for 100-Gbaud OOK transmission at temperatures of 25°C to 110°C. Hash line is BER of 3.8×10^{-3}.

1.5 dB power penalty at around 90°C. At temperature 110°C, we observed an extra 0.8 dB penalty. However, even in a high temperature environment (>110°C), EO polymer modulator achieved error-free transmission with a BER that was successfully lower than the 7% HD-FEC threshold. One obvious feature is that the BER sensitivity is completely recovered when the temperature is decreased to 25°C [7].

4. Discussion

As presented in our previous work, the thermal stability of the EO polymer is guaranteed even after long-term thermal exposure in accordance with Telcordia GR-468-CORE regarding high-temperature storage testing (85°C). The V_π for the modulator showed no change during a period of over 2,000 hours [6]. By further increasing the T_g of the EO polymer (194°C), we were able to push the temperature setpoint to 105 °C to test the EO properties. This temperature is much higher than the industry standard specified by Telcordia GR-468-CORE. In addition to testing the modulators related to static thermal properties, the high-T_g EO polymer allows the generation of OOK signals without failure in a wide temperature range. It was found that for 100-Gbaud OOK, the BER did not abruptly degrade at temperatures of up to 110°C, with error-free transmission was achieved over 2.0-km fiber-link with a ROP value of higher than -9 dBm. Optical power handling is another important parameter for assessing the reliability of an EO polymer modulator. A previous study predicted that the typical power damage threshold for the polymer was in the GW/cm^2 range and that the damage was generally due to the impurities or absorption centers in the materials [8]. Photo-oxidation is the main reason for degradation. The optical power handling capability of the EO polymer modulator required to withstand exposure to a high-power laser is approximately 1~2 MW/cm^2. The encapsulation of the device in an oxygen-free atmosphere is the simplest way to suppress photo-degradation. Packaging the modulator chip in a metal hermetic device is excellent to quickly demonstrate the photo stability test. Our assembled component showed little change of V_π during irradiation of the laser (1,550 nm, 10 dBm) for longer than 500 h at the storage temperature of 85°C. More details of optical power handling are under investigation.

4. Conclusion

We demonstrated the EO polymer modulator for high-speed transmission at >100-Gbaud OOK. The thermal stability test was carried out for the fiber-link transmission at various temperatures. We didn't find significant degradation of the signal generation at up to 110°C. This is best thermal stability achieved for a polymer modulator. Error-free transmission was achieved over 2.0-km fiber-link under a threshold of 7% HD-FEC at this high temperature. The bandwidth and BER characteristics fully recovered to their original values after high-temperature testing. To reach further reliability of the EO polymer devices, encapsulation in an oxygen-free atmosphere should be more effective. Device reliability tests regarding more details of photo stability and humidity stability issues are under investigation.

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