Silicon-Polymer Hybrid Modulators with High-Temperature Resistance for Energy-Efficient Data Centers

Guo-Wei Lu
Computer Engineering Division, The University of Aizu
Aizu-Wakamatsu, Japan
Institute for Materials Chemistry and Engineering, Kyushu University
Fukuoka, Japan
gordon.guoweilu@gmail.com
https://orcid.org/0000-0002-0739-1556

Hiromu Sato
Institute of Materials Chemistry and Engineering, Kyushu University
Fukuoka, Japan
h_sato@cm.kyushu-u.ac.jp

Jiawei Mao
Institute of Materials Chemistry and Engineering, Kyushu University
Fukuoka, Japan
mao.jiawei.799@s.kyushu-u.ac.jp

Shiyoshi Yokoyama
Institute of Materials Chemistry and Engineering, Kyushu University
Fukuoka, Japan
s_yokoyama@cm.kyushu-u.ac.jp
https://orcid.org/0000-0002-0434-9950

***Abstract*—We demonstrate a high-speed silicon-polymer hybrid modulator with exceptional thermal stability. The modulator supports 200 Gbit/s data rates and maintains reliable operation up to 110 °C, making it a promising technology for energy-efficient data centers.**

Keywords—EO polymer, Silicon-polymer hybrid modulators, Thermal stability, Data centers

I. Introduction

The widespread adoption of cloud computing, coupled with the rise of content-heavy applications and the ever-increasing demand for storage space, has fueled the rapid growth of data centers. Unfortunately, this growth has come at a significant cost to the environment, as data centers alone are estimated to consume over 1% of global electricity. With the data center market expected to continue growing at a rate of at least 5% annually, optimizing data center operations has become critical. One essential aspect of data center operation is managing the temperature, as servers and other IT equipment generate heat that must be dissipated. Cooling systems are necessary to protect the sensitive components from overheating, but they can be expensive to operate. Research indicates that up to 40% of a data center's energy consumption is used for cooling. However, recent studies have shown that increasing the ambient temperature of data centers by just one degree Celsius can result in a 4% decrease in cooling system costs. This finding highlights the importance of improving the thermal stability of the installed components and devices to enhance the energy efficiency of data centers.

As one of the essential components in data centers, electro-optic (EO) modulators have been extensively studied on various material platforms, such as silicon, $LiNbO_3$, $BaTiO_3$, organic, III-V compounds and so on. With the increasing bandwidth and energy demands in data centers, the requirements of EO modulators are becoming more stringent in terms of performance metrics such as EO bandwidth, power consumption, thermal stability, extinction ratio, footprint, insertion loss.

Herein, we present and review our recently-demonstrated silicon-polymer hybrid (SPH) modulators, which incorporate EO polymer onto silicon photonic waveguides [1]. The SPH modulators possess high-temperature resistance with a bearable ambient temperature of up to 110 °C and thus can potentially help data centers reduce their cooling system costs while maintaining ultra-fast signaling ability with up to 200 Gb/s aggregate data rates. The remarkable performance of the fabricated SPH modulators is mainly attributed to the intrinsic high glass transition temperature (T_g=172 °C) and high EO figure of merit (n^3r_{33}=1021 pm V^{-1}) of the underlying side-chain EO polymer.

II. Silicon-Polymer Hybrid Modulators

A. Side-chain EO polymer

Compared with traditional inorganic materials such as Lithium niobate (LN), EO polymers possess a higher electro-optic (EO) coefficient, which can be as high as 300 pm/V. This is several times higher than the EO coefficient of LN, making EO polymer a promising material for high-performance EO modulators. A high EO coefficient in EO polymer modulators offers several advantages, including the ability to achieve the same modulation depth with a smaller applied voltage, in other words, lower the V_π. This, in turn, reduces the power consumption and device footprint, making EO polymer modulators more energy-efficient and compact. Additionally, a high EO coefficient enables faster modulation response times, making these modulators suitable for high-speed applications. In the fabricated SPH modulator, the active material is a side-chain EO polymer [2-3], in which electro-optic (EO) chromophores with high molecular are attached to a polymer backbone as side chains to provide Pockels effect. The molecular structure of the deployed side-chain EO polymer is illustrated in Fig. 1(a). With loading density of

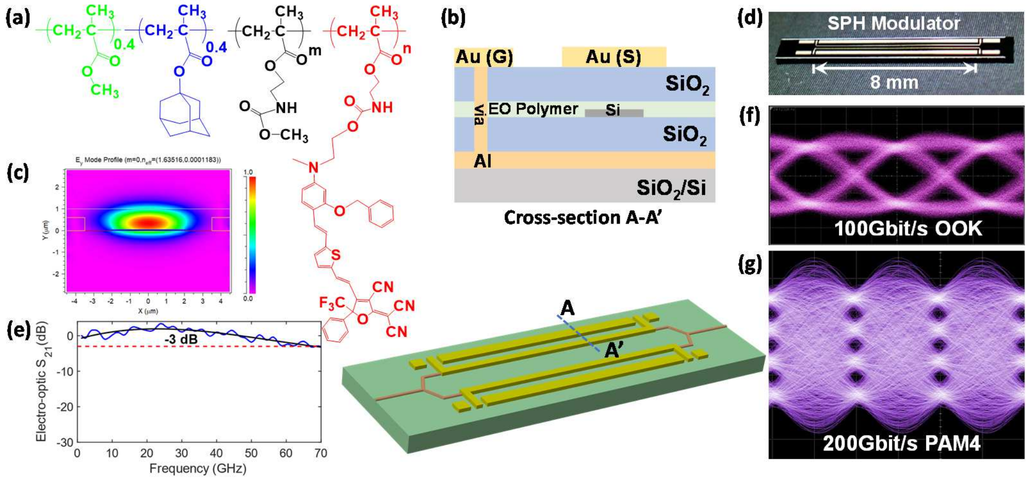

Fig. 1. (a) Molecular of the side-chain EO polymer. (b) Schematic diagram of the fabricated SPH modulator and the cross-section (A-A'). (c) Calculated optical field distribution in the cross-section. (d) Top-view photograph of a fabricated SPH modulator. Eye diagrams of (e) 100 Gbit/s OOK and (f) 200 Gbit/s PAM4.

chromophore at approximately 37 wt% and of admayntyl at approximately 34 wt%, the synthesized EO polymers attain a high glass transition temperature of 172 °C and a remarkable in-device EO figure of merit (n^3r_{33}) of 1021 pm V^{-1}.

B. Silicon-polymer hybrid EO modulators

Using the synthesized EO polymer, a hybrid silicon-polymer EO modulator is fabricated, consisting of a thin amorphous-silicon core, an EO polymer layer, SiO_2 cladding layers, and electrodes, as depicted in Fig. 1(b). In the fabricated EO modulator, a Mach-Zehnder interferometer (MZI) waveguide is patterned on the 40-nm-thick silicon layer, and a 1-µm-thick EO polymer layer is sandwiched between two SiO_2 cladding layers. To leverage the high Pockels effect of the underlying EO polymer, the guided light should be well confined between silicon and polymer layers. Given that the refractive indices of the EO polymer, SiO2, and silicon are 1.67, 1.45, and 3.48, respectively, with a 4-µm×40-nm silicon core, the calculated confinement factor, defined as the ratio of the optical power in the EO polymer to the total power, is around 73.8%. This high confinement factor indicates that a significant amount of the optical power is confined in the active region, which is essential for achieving high modulation efficiency in the EO modulator. Fig. 1(c) shows the calculated optical modal distribution of the TM mode.

On the top of the device, microwave electrodes with a length of 8 mm are deposited along the MZI arms. A top-view photograph of the fabricated modulator is shown in Fig. 1(d). Figure 1(e) illustrates the measured frequency response of the fabricated SPH modulator, which exhibits a broad 3-dB bandwidth of 68 GHz. In addition, a π-voltage-length product ($V_\pi \cdot L$) of 1.44 V·cm is measured with the fabricated SPH modulator.

C. High-speed Signalling with SPH modulators

The broad modulation bandwidth of the fabricated SPH modulator allows for high-speed signaling at rates up to 100 Gbaud. Experimental results show successful error-free operations at bit rates of 200 Gbit/s using four-level pulse amplitude modulation (PAM4) and 100 Gbit/s using on-off keying (OOK). Figure 1(f) and 1(g) depict the eye diagrams for 100 Gbaud OOK and PAM4, respectively.

D. High-temperature Reliability of SPH modulators

Building on the high-speed signaling enabled by the high EO coefficient of the deployed EO polymer, the high T_g of the EO polymers in the SPH modulator allows for high-temperature operations without failures, which is essential for improving energy efficiency in data centers by enabling higher ambient temperatures. To assess the high-temperature reliability of the fabricated SPH modulators, high-speed

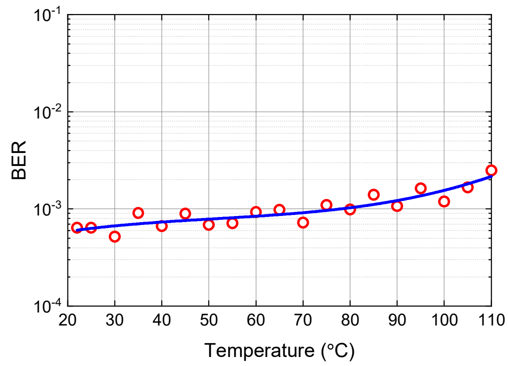

Fig. 2. Measured BER of 200 Gbit/s PAM4 versus operating ambient temperatures (22-110 °C).

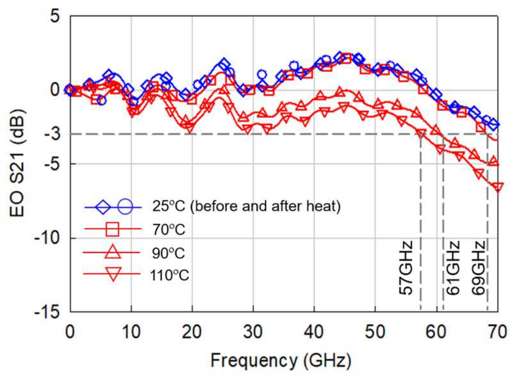

Fig. 3. Measured Frequency response (S21) of SPH modulator at temperatures up to 110 °C.

operating performance of the SPH is investigated while varying the ambient temperature from 25 °C to 110 °C. The measured bit-error rates (BERs) of the synthesized 200 Gbit/s PAM4 are measured. As shown in Fig. 2, when the temperature is elevated to 110 °C, a slight increase in BER within one order of magnitude is observed, demonstrating the excellent thermal reliability of the SPH modulator at high temperatures. To further investigate the EO activities of the SPH modulator at elevated ambient temperatures, we measured the frequency response of the device at several temperatures [4]. As shown in Fig. 3, when the ambient temperature is increased to 70 °C, the modulation bandwidth slightly decreases to 61 GHz. When the temperature is increased up to 110°C, the bandwidth decreases to 57 GHz because of a partial disorder in the chromophore alignment. This results in a reduction of the electro-optic (EO) activities. However, it is important to note that the frequency response, as indicated by the S21 curve, is restored once the device is cooled back down to room temperature.

III. CONCLUSION

We have successfully fabricated and demonstrated a SPH modulator capable of supporting data rates up to 200 Gbit/s, while maintaining excellent thermal reliability at high ambient temperatures up to 110 °C. This is attributed to the utilization of a side-chain EO polymer with exceptional properties, including a high glass transition temperature (172 °C) and EO figure of merit (1021 $pm \cdot V^{-1}$). The work represents a significant advancement in the development of high-speed and thermally reliable interconnects for energy-efficient data centers.

ACKNOWLEDGMENT

We acknowledge the funding support of JSPS KAHENHI (22H01490) and NICT Project (02101).

REFERENCES

[1] Guo-Wei Lu, Jianxun Hong, Feng Qiu, Andrew M. Spring, Tsubasa Kashino, Juro Oshima, Masa-aki Ozawa, Hideyuki Nawata & Shiyoshi Yokoyama, "High-temperature-resistant silicon-polymer hybrid modulator operating at up to 200 Gbit s^{-1} for energy-efficient datacenters and harsh environment applications," *Nature Communications* **11**, 4224, 2020.

[2] Hiroki Miura, Feng Qiu, Andrew M. Spring, Tsubasa Kashino, Takamasa Kikuchi, Masaaki Ozawa, Hideyuki Nawata, Keisuke Odoi, and Shiyoshi Yokoyama, "High thermal stability 40 GHz electro-optic polymer modulators," *Opt. Express* **25**, 28643-28649, 2017.

[3] Hiromu Sato, Hiroki Miura, Feng Qiu, Andrew M. Spring, Tsubasa Kashino, Takamasa Kikuchi, Masaaki Ozawa, Hideyuki Nawata, Keisuke Odoi, and Shiyoshi Yokoyama, "Low driving voltage Mach-Zehnder interference modulator constructed from an electro-optic polymer on ultra-thin silicon with a broadband operation," *Opt. Express* **25**, 768-775, 2017.

[4] Hiromu Sato, Jiawei Mao, Alisa Bannaron, Takuro Kamiya, Guo-Wei Lu, Shiyoshi Yokoyama, "A 100 Gbaud on-off-keying silicon-polymer hyrbid modulator operating at up to 110°C," *IEEE Photonics Technology Letters* **33**, pp. 1507-1510, 2021.