Demonstration of Long-Term Thermal Stability of a Silicon-Organic Hybrid (SOH) Modulator at 85°C

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Abstract: We demonstrate highly stable silicon-organic hybrid (SOH) modulators fulfilling Telcordia standards for high-temperature storage. We show error-free 40 Gbit/s signaling with drive voltages of 1.65 V_{pp} using a device stored at 85°C for 2700 hours.

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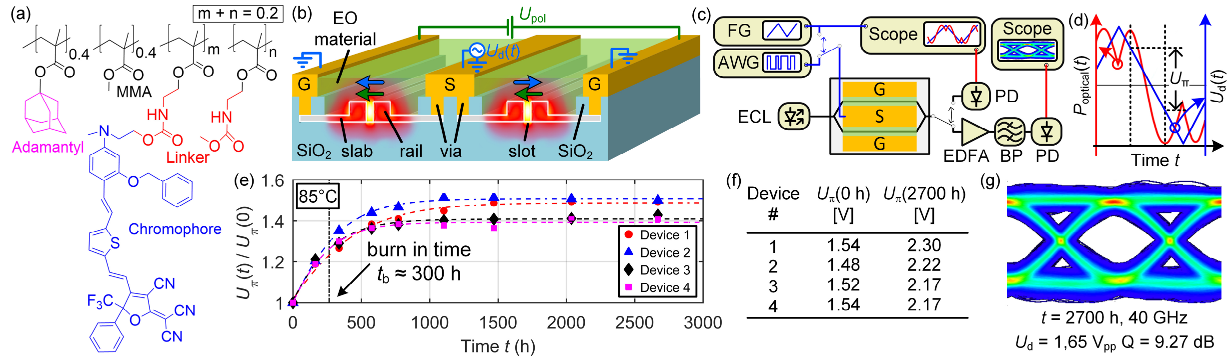
1. Introduction

Efficient electro-optic (EO) modulators are at the heart of optical transceivers used in a variety of networks from short-reach data-center communications to metro and long-haul links. A particularly attractive modulator concept relies on the silicon-organic hybrid (SOH) approach, which combines silicon photonic (SiP) waveguide structures with organic EO materials and thus merges the advanced SiP fabrication technology with the unrivalled EO coefficients of organic materials [1]. SOH modulators have shown outstanding performance in terms of modulation efficiency [1,2] and achievable data rates [3] proven, e.g., by recent demonstrations of 16QAM transmission at a symbol rate of 100 GBd [4]. However, one of the remaining challenges is the long-term stability of SOH devices at elevated temperatures, limited by thermally induced relaxation of the poled organic EO materials. In this paper, we report on the first demonstration of long-term stable SOH modulators, fulfilling Telcordia standards for high-temperature storage [5], requiring that the modulators retain 85 % of the EO activity when stored at 85 °C for more than 2000 h. This is achieved by employing a recently introduced side-chain EO polymer [6] with adamantyl side groups, which increase the glass transition temperature (T_g) to 172 °C. The viability of the device is demonstrated by generating error-free 40 Gbit/s on-off-keying (OOK) signals using a device which was stored at 85 °C for 2700 h.

2. Device fabrication and characterization

The SOH Mach-Zehnder modulator (MZM) concept is shown in Fig. 1(b). Each MZM arm comprises an SOH phase shifter consisting of a Si slot waveguide. The slot waveguide is formed by two parallel 240 nm-wide and 220 nm-high Si rails which are separated by a 190 nm wide slot filled with the EO material, see Fig. 1(a) for the chemical structure. Thin *n*-doped Si slabs connect the rails to a ground-signal-ground (GSG) transmission line. This geometry results in a large overlap of the radio frequency (RF) mode and the optical mode in the slot region, leading to highly efficient EO modulation. The waveguide structure is fabricated on standard silicon-on-insulator (SOI) wafers in a SiP foundry using 248 nm deep-UV lithography, while the EO material is deposited by an in-house post-processing step. An average acentric molecular orientation and thus an appreciable macroscopic EO activity is achieved by poling: We heat up the chip close to the glass transition temperature T_g of the EO material and apply a poling voltage U_{pol} across the floating ground electrodes of the MZM, which induces poling fields (green arrows) for aligning the dipolar molecules. Then the device is cooled down while U_{pol} is maintained. The MZM allows push-pull operation as a drive voltage $U_d(t)$ will induce electric fields (red arrows) that are parallel to the poling direction in one arm and antiparallel in the other arm. The experimental setup for measuring the π-voltage U_π is shown in Fig. 1(c). We optically feed the MZM with an external cavity laser (ECL) while we apply a triangular electrical waveform with a peak-to-peak amplitude $U_{d,pp} > U_\pi$ provided by a function generator (FG). The light is detected by a photo diode (PD) connected to an oscilloscope which also measures the drive voltage. U_π can thus be directly extracted as the drive voltage difference needed to switch the MZM from maximum to minimum transmission, see Fig. 1(d).

The poling-induced average acentric orientation of the EO molecules represents an energetically unfavorable state leading to a thermally induced reorientation and resulting in an increase of U_π. For a systematic investigation of this process we pole four nominally identical 1.5 mm-long SOH MZMs and store them in an oven at a temperature of 85 °C in accordance with pertinent Telcordia standards [5]. The modulators were removed from the oven from time to time to monitor the increase in U_π. The results are summarized in Fig. 1(e), where U_π normalized to its respective initial value is plotted as a function of time. All devices show qualitatively the same trend: After an initial burn-in of approximately 300 h, the devices retain over 85 % of their modulation efficiency, fulfilling Telcordia standards for high-temperature storage. As indicated by the dashed lines, the data show fairly good agreement with an adapted Debye model [7] of the form $U_\pi(t)/U_\pi(0) = 1/(a + b\exp(-t/\tau))$, where t is the time and $a = 0.7$, $b = 0.3$ and $\tau = 250$ h are typical fitting parameters. The increase in U_π may be attributed to the release of stress in



Device #	U_π(0 h) [V]	U_π(2700 h) [V]
1	1.54	2.30
2	1.48	2.22
3	1.52	2.17
4	1.54	2.17

Fig.1. SOH-modulator concept and characterization. **(a)** Chemical structure of the employed side-chain EO polymer containing an adamantyl group, which increases T_g to 172 °C. **(b)** SOH MZM cross section. Each arm comprises a Si slot waveguide clad by the EO material. For poling, we apply a voltage U_{pol} across the floating ground electrodes at elevated temperature. This aligns the dipoles of the EO material (green arrows). We remove U_{pol} after cooling down which freezes this alignment. A drive signal $U_d(t)$ leads to electric fields (blue arrows) that are parallel (antiparallel) to the poling orientation in the left (right) arm, hence enabling push-pull operation. **(c)** Setup for U_π characterization and data transmission. A low-speed function generator (FG) or a high-speed arbitrary waveform generator (AWG) is used to drive the MZM. We couple light from an external cavity laser (ECL) to the MZM via grating couplers. The slowly modulated light is detected by a photo diode (PD) for measuring U_π. For high-speed operation, the modulated light is amplified and detected by a PD for generating the eye diagram. **(d)** U_π measurement. **(e)** Normalized U_π as a function of time for four 1.5 mm long SOH devices stored at 85 °C. After an initial increase during the first hundreds of hours, U_π reaches a stable value. **(f)** Absolute U_π measurements at $t = 0$, 2700 h. **(g)** Eye diagram for OOK signaling at 40 Gbit/s with a device stored at 85 °C for 2700 h. After post-equalization, the Q factor amounts to 9.27 dB, indicating error-free transmission.

the EO polymer induced during the cooling step of the poling process. This effect can generate free volume (voids) in the EO material, which facilitates the reorientation of the molecules. The stable value of U_π after its initial increase can be attributed to the large difference between T_g and the storing temperature of 85 °C, at which the molecular mobility of the polymer chain is negligible. To the best of our knowledge, this is the first demonstration of long-term thermal stability of SOH MZM. The absolute values for U_π at 0 h and 2700 h are summarized in Fig. 1(f), indicating consistent performance. Note that the devices with a length of $L = 1.5$ mm exhibit an average modulation efficiency $U_\pi L$ of only 3.3 Vmm after 2700 h at 85 °C. This is roughly 4 times more efficient than other stable organic EO modulators [8,9]. Given the vast potential of theory-guided material optimization, we expect that even more efficient long-term stable SOH devices with $U_\pi L$ products well below 1 Vmm will come into reach.

3. Data transmission

The viability of these MZM for high-speed modulation is demonstrated in a data transmission experiment, see Fig. 1(c) for the experimental setup. We apply a pseudo-random bit sequence of length 2^{15}-1, obtained from an arbitrary waveform generator (AWG) to an MZM aged for 2700 h at 85 °C. The optical carrier provided by an external cavity laser is coupled to and from the device using grating couplers. The fiber-to-fiber loss amounts to 16 dB and is compensated by amplifying the modulated light with an EDFA. A band pass filter (BP) is used to suppress noise before detecting the light in a photo diode connected to a real-time oscilloscope. We apply a post equalizer on the detected data and obtain the eye diagram in Fig. 1(g) for a data rate of 40 Gbit/s and a peak-to-peak drive voltage of 1.65 V$_{pp}$. The measured Q-factor amounts to 9.27 dB, which suggests error-free transmission.

4. Summary

We have shown that SOH MZM employing an EO material with a large T_g fulfill Telcordia standards for high temperature storage. The devices outperform competing organic-based modulators [8,9] in terms of modulation efficiency and show great potential for further improvement. In addition, we proved the high-speed performance of SOH modulators even after high temperature storage by generating error-free 40 Gbit/s OOK signals. We believe that these results pave the way towards industrial applications of SOH devices.

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