High-Speed, Low Drive-Voltage Silicon-Organic Hybrid Modulator Based on a Binary-Chromophore Electro-Optic Material

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Abstract—We report on the hybrid integration of silicon-on-insulator slot waveguides with organic electro-optic materials. We investigate and compare a polymer composite, a dendron-based material, and a binary-chromophore organic glass (BCOG). A record-high in-device electro-optic coefficient of 230 pm/V is found for the BCOG approach resulting in silicon-organic hybrid Mach-Zehnder modulators that feature low $U_\pi L$ -products of down to 0.52 Vmm and support data rates of up to 40 Gbit/s.

Index Terms—Electro-optic modulators, nonlinear optical devices, photonic integrated circuits.

I. INTRODUCTION

SILICON electro-optic modulators are key building blocks of highly integrated photonic circuits and particularly important for future high-performance optical interconnects. Due to the absence of linear electro-optic (EO) effects in bulk sil-

icon, current modulators mostly rely on the plasma-effect, using either free-carrier depletion [1] or injection [2] in diode or metal-oxide-semiconductor-(MOS-)structures [3]. However, trade-offs have to be made when aiming at fast devices that feature low drive voltage and small footprint simultaneously. In particular, carrier-injection devices feature voltage-length products as small as $U_\pi L = 0.36$ Vmm, but free-carrier lifetime limits modulation speed to few Gbit/s if no pre-emphasis of the drive signal is used [2]. In contrast, carrier-depletion modulators support symbol rates of up to 50 GBd [4], but typical voltage-length products are beyond 10 Vmm [5], [6] and thus much larger than those of injection-type devices. Drive voltage and device footprint can be strongly reduced by using resonant structures [5], [7]. However, resonant devices feature limited optical bandwidth and their resonance wavelength is particularly prone to temperature fluctuations

Silicon-organic hybrid (SOH) integration pursues a fundamentally different approach [8], [9]. Here, light is guided in a silicon waveguide core and nonlinear optical effects of second order are realized by exploiting evanescent interaction of the guided light mode with an organic electro-optic cladding material [10]–[12]. Specifically tailored organic materials with strong linear EO effect (Pockels effect) enable small voltage-length products and high modulation bandwidth simultaneously [10], [13]–[15]. So far, the most commonly used cladding materials for SOH integration are polymers doped by EO chromophore molecules [11], [16]. While these guest-host materials have shown EO coefficient as high as 118 pm/V in bulk material [17], values measured in SOH devices were much smaller, ranging from 20 to 60 pm/V [11], [16], [12], [18]–[20]. This has significantly limited the performance of SOH electro-optic modulators up to now.

In this paper we demonstrate that in-device EO coefficient can be significantly increased by using a binary electro-optic material system consisting of shape-engineered spherical dendritic and rod-shaped dipolar chromophores. This material system clearly outperforms conventional guest-host and neat dendritic materials. We demonstrate a record-high in-device EO coefficient of $r_{33} = 230$ pm/V, which results in a low modulator voltage-length product of $U_\pi L = 0.52$ Vmm. In addition we show that these modulators support data rates of up to 40 Gbit/s.

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Fig. 1. SOH MZM. (a) Schematic of the MZM. The device consists of two slot waveguide phase modulators, driven in push-pull operation by a single coplanar ground-signal-ground (GSG) transmission line. Multimode interference couplers (MMI) are used as power splitters and combiners. Logarithmically tapered low-loss strip-to-slot mode converters are used for coupling access strip waveguides to slot waveguides [23]. (b) Cross-section of the MZM. The organic material is poled by applying a poling voltage U_{poling} across the floating ground electrodes of the modulator. Dark blue arrows denote the orientation of the chromophores after poling. The red arrows indicate the orientation of the RF modulation field of the GSG transmission line, which is parallel to the chromophore orientation in the left phase shifter and anti-parallel in the phase shifter on the right-hand side, thereby resulting in push-pull operation of the device. (c) Cross-sectional view and simulated optical mode of one phase modulator. The light is strongly confined to the slot region due to electric-field discontinuities at the slot sidewalls. (d) Simulated RF mode field of the slot waveguide. The two rails of the silicon slot waveguide are electrically connected to metal electrodes by 60 nm-high n-doped (As, $7 \times 10^{17} \text{ cm}^{-3}$) silicon slabs. The modulation voltage drops across the narrow slot resulting in a high modulation field that has a strong overlap with the optical mode.

II. SILICON-ORGANIC HYBRID MODULATOR

Our experiments are based on single-drive SOH Mach-Zehnder modulators (MZM), see Fig. 1(a) for an illustration of the device structure. The MZM comprises two SOH phase modulators that are driven in push-pull mode by a single coplanar transmission line in ground-signal-ground configuration (GSG). Each of the phase modulators consists of a slot waveguide (slot width 160 nm, rail width 210 nm), which is covered by an organic EO material, Fig. 1(b). The fundamental optical quasi-TE mode field of the waveguide is strongly confined to the slot region due to field discontinuities at the slot sidewalls [21], Fig. 1(c). At the same time, the copper strips of the transmission line are electrically connected to the rails of the

phase modulators by 900 nm-high tungsten vias and 60 nm-thick n-doped (As, $7 \times 10^{17} \text{ cm}^{-3}$) silicon slabs. A voltage applied to the transmission line drops across the narrow slot, resulting in a high modulation field that strongly overlaps with the optical quasi-TE mode, see Fig. 1(d).

The waveguide structures were fabricated by 193 nm deep-UV lithography on an 8" silicon-on-insulator wafer with 220 nm device layer thickness and 2 μm -thick buried oxide as described in [22]. The fabrication of the silicon photonic integrated circuit (PIC) was carried out using a combination of CMOS-based technology and deposition of the electro-optic cladding in a post-processing step. The transmission line is composed of tungsten vias, an oxide buffer layer, and copper electrodes [22]. After fabrication the oxide cladding is locally removed in the slot waveguide regions by a combination of dry and wet etching to open the slots for applying the EO organic material. The EO organic material is then deposited from a solution by spin-coating and fill the opened oxide regions and the slots of the slot waveguides. Deposition of the electro-optic material can hence be completely decoupled from CMOS processing.

Directly after the deposition, the organic material does not feature any macroscopic EO effect due to the random orientation of the chromophore molecules. For inducing macroscopic EO activity the material needs to be poled. This is achieved by heating the sample to the glass-transition temperature T_g of the organic material while applying a dc poling voltage U_{poling} between the floating ground electrodes. The resulting poling field in the slot aligns the dipolar chromophores in the slot as indicated by the dark blue arrows in Fig. 1(b) [13]. While holding the poling voltage, the chip is cooled back to room temperature, thereby conserving the acentric order of the chromophores. The RF modulation field of the GSG transmission line, indicated by red arrows in Fig. 1(b), is parallel to the chromophore orientation in the left phase shifter and anti-parallel in the phase shifter on the right-hand side. This results in push-pull operation of the device.

In the following, we investigate two SOH MZM of different lengths: A 1 mm-long modulator that is terminated by a 50 Ω load, and a 250 μm -long modulator without termination ("lumped"). Grating couplers are used for fiber-chip coupling [24]. The fiber-to-fiber loss of a 1 mm-long MZM is 16.5 dB, dominated by fiber-chip coupling losses of the non-optimized grating couplers. The on-chip loss of the MZM amounts to approximately 6 dB for maximum transmission of the modulator, which can be decomposed into losses of passive components, material absorption loss of the organic cladding, free-carrier absorption within the doped silicon waveguides, and scattering loss due to sidewall roughness of the slot waveguide. Passive components, such as MMI and strip-to-slot mode converters contribute only 0.5 dB to the total loss. Material absorption of the organic cladding amounts to 0.2 dB/cm in the C-band and can be neglected. Free-carrier absorption and scattering loss hence remain the dominant effects. For the free-carrier absorption, we estimate a contribution of approximately 1.3 dB/cm, taking into account that only around 50% of the guided light actually interacts with the doped silicon structure, in which the donor doping concentration amounts to $7 \times 10^{17} \text{ cm}^{-3}$ [25]. The

remaining propagation losses of 4 dB/mm are attributed to scattering due to fabrication imperfections that occur during etching of the waveguides and during opening of the back-end oxide. We expect that scattering losses can be significantly reduced by optimization of the process parameters. For 300 nm CMOS technology, recent developments [26] indicate that the propagation loss of slot waveguides can be below 1 dB/mm. Similarly, for 200 nm technology, propagation losses below 0.7 dB/mm have been reported using larger slots of 190 nm width [27], and these figures can be further reduced by deploying asymmetric slot geometries, where losses of 0.2 dB/mm have been demonstrated [28]. We believe that an optimization of the fabrication process and a reduction of the device length will enable next-generation SOH MZM that feature an insertion loss of 1 to 2 dB.

III. ORGANIC ELECTRO-OPTIC MATERIALS AND POLING

A widely used EO material class for SOH integration are chromophore-polymer guest-host materials. The concentration of the EO active chromophores in these materials is typically limited to 25 wt.% to prevent detrimental head-to-tail orientation of the dipolar molecules and partial crystallization of the material. The efficient activation of the second-order nonlinearity in SOH devices remained an unsolved problem and reported in-device EO coefficient of these materials were a factor 2 to 5 below the corresponding values of bulk organic materials [11], [12], [16]–[20]. This phenomenon is usually explained by incomplete poling.

It has recently been shown that in-device EO coefficient of up to $r_{33} = 180$ pm/V can be achieved by using so-called monolithic EO materials, that do not require a polymer matrix to prevent detrimental dipole-dipole interaction and that have a molecular structure that is engineered for enhanced poling efficiency [15], [17]. Here we expand on these findings by investigating two different material systems: A neat material that consists of the multi-chromophore dendritic molecule PSLD41 [29], and a mixture of the chromophores YLD124 and PSLD41 (25:75 wt.%), also referred to as binary chromophore organic glass (BCOG) [30]. These materials are compared to a conventional guest-host material consisting of YLD124 (25 wt.%) in a PMMA matrix [17]. The chemical structures of the involved chromophores are depicted in Fig. 2. The chromophore YLD124, Fig. 2(a), is a simple rod-shaped EO molecule that only consists of a donor and an acceptor group, linked by a ring-locked π -conjugated bridge. The dendritic chromophore PSLD41, Fig. 2(b), consists of a central connecting motif to which three EO substructures are attached (marked in green). This results in a spherical shape of the molecule, which is known to lead to an improved poling efficiency as compared to oblate and prolate structures [29], [31]. In addition, perfluorinated containing side-groups (marked in blue) are attached to the EO substructures. These site-isolation groups effectively reduce the dipole-dipole interaction of neighboring molecules [31]. This way, PSLD41 can be used as a neat material without the need of an isolating polymer matrix.

Fig. 2. Chemical structures of the individual chromophores. The EO cores of the chromophores are drawn in red. (a) The chromophore YLD124 consists only of a donor group, of an acceptor group, and of a π -conjugated bridge. (b) PSLD41 is a dendritic configuration that combines three EO substructures, marked in green. Each EO substructure comprises one electro-optic core with functional sidegroups (blue) that lead to a defined three-dimensional dendron structure with spherical shape. The site-isolation groups (blue) decrease intermolecular interaction and thereby reduce head-to-tail orientation of neighboring molecules, while the spherical shape results in an enhancement of poling efficiency [32].

Of special interest is the investigation of the BCOG composed of 25 wt.% YLD124 and 75 wt.% PSLD41. It has been shown that the EO activity of a BCOG is greater than the sum of its individual components [30]. Formation of a stable YLD124/PSLD41-complex during poling was offered as an explanation for this remarkable phenomenon [30].

For comparison, the three materials are applied to nominally identical chips by spin-coating from an 8% solution dissolved in 1,1,2-trichloroethane. After deposition, the materials are poled for push-pull operation of the MZM by applying a poling voltage between the floating ground electrodes of the modulator, as depicted in Fig. 1(b). After poling, the π -voltage U_π of the modulator is derived from the voltage-dependent transmission characteristics, see Fig. 3. For better comparison of the EO coefficients the π -voltage is measured at a dc bias > 5 V, since free charges in the cladding lead to partial field screening at small dc fields. However, this effect is slow and does not impair the modulation efficiency of our device for frequencies > 1 kHz, i.e., the π -voltage is found to be independent of the bias voltage at frequencies > 1 kHz.

The EO coefficient r_{33} can be obtained from the measured π -voltage U_π of the push-pull MZM by using the relation [10], [33]

$$U_\pi = \frac{w_{\text{slot}} \lambda_c}{2L r_{33} \Gamma n_{\text{slot}}^3}. \quad (1)$$

Fig. 3. Voltage-dependent transmission of 1 mm-long SOH MZM coated with different organic materials. The respective poling field E_{poling} , measured π -voltages U_{π} , and derived EO coefficient r_{33} are specific in the respective figures (a) YLD124/PMMA cladding. (b) PSLD41 cladding. (c) YLD124/PSLD41 cladding. The smallest U_{π} is found for the BCOG YLD124/PSLD41. The π -voltage is measured at a dc bias > 5 V to remove the effect of free charges in the cladding, that lead to partial field screening at small dc fields

The quantity w_{slot} denotes the measured slot width, λ_c is the wavelength of the optical carrier, L is the modulator length, n_{slot} is the refractive index of the organic material in the slot, and Γ is the field interaction factor that is linked to the fraction of the optical power that interacts with the modulation field [10], [33]

$$\Gamma = \frac{n_{\text{slot}}}{Z_0} \frac{\int_{A_{\text{slot}}} |\mathcal{E}_x|^2 dA}{2\mathcal{P}(\omega_c)}. \quad (2)$$

Here $\mathcal{E}_x$ is the x -component of the electric field of the optical mode, $\mathcal{P}$ is the power of the optical mode field Z_0 is the free-space wave impedance, and A_{slot} is the cross-sectional area of the silicon slot. For the device geometry used in our experiments, the calculated field interaction factors of the three investigated materials differ by less than 2% and amount to $\Gamma \approx 0.2$.

IV. RESULTS OF THE POLING EXPERIMENTS

For each of the investigated materials, we perform poling experiments at various poling field E_{poling} . The resulting EO coefficient r_{33} are depicted in Fig. 4.

A. Guest-Host System

First, the guest-host material YLD124/PMMA is investigated. The highest observed EO coefficient is 30 pm/V and was achieved by applying a poling field of 150 V/μm. The

Fig. 4. Measured poling efficiency r_{33}/E_{poling} for three different organic cladding materials: PMMA doped with 25 wt.% YLD124 (guest-host system, red), the neat dendritic chromophore PSLD41 (blue), and PSLD41 doped by 25 wt.% YLD124 (binary chromophore organic glass, black). The solid lines represent linear fit in the limit of low poling fields. The slope of these lines is used as a measure for poling efficiency. For the YLD124/PMMA mixture, only data points at low poling field ($E_{\text{poling}} < 150$ V/μm) were considered for the fit

corresponding voltage-dependent transmission of a 1 mm-long device is depicted in Fig. 3(a). The π -voltage is $U_{\pi} = 4$ V. When applying higher poling field the measured EO coefficient decreases, see Fig. 4. This is attributed to an increase of material conductivity during poling at high field strength. For low poling fields a linear relation between poling field and EO coefficient is expected [29], whereas for poling field beyond 200 V/μm, dielectric breakdown occurs. By linear regression of the data points obtained for low poling field $E_{\text{poling}} < 150$ V/μm (red line in Fig. 4) we determine a poling efficiency r_{33}/E_{poling} of $0.23 \text{ nm}^2/\text{V}^2$. The measured in-device EO coefficient and the measured poling efficiency are far lower than values reported in parallel-plate poled bulk reference samples, where maximum electro-optic coefficient of $r_{33, \text{max}} = 118$ pm/V and poling efficiency of $r_{33}/E_{\text{poling}} = 1.27 \text{ nm}^2/\text{V}^2$ were achieved [17]. These findings are thus in good agreement with findings in other publications where poling of similar guest-host materials in SOH devices was found to be inefficient [11], [12], [16], [18]–[20].

B. Multi-Chromophore Dendritic Molecules

Next, we analyze a sample coated with neat PSLD41 [29]. We find a slightly higher poling efficiency r_{33}/E_{poling} of $0.26 \text{ nm}^2/\text{V}^2$ (blue line in Fig. 4) and a remarkably high stability of the material against dielectric breakdown. For the highest applied poling field of 312 V/μm, we find an EO coefficient of $r_{33} = 98$ pm/V. The voltage-dependent transmission of the MZM is depicted in Fig. 3(b) and we extract $U_{\pi} = 1.22$ V. Note that for this material, the achieved in device EO coefficient r_{33} is even higher than its bulk-material counterpart: In bulk reference samples, EO coefficient of $r_{33} = 90$ pm/V were measured at a poling field of $E_{\text{poling}} = 90$ V/μm [31].

TABLE I

SUMMARY OF MEASURED EO COEFFICIENTS. COMPARISON BETWEEN IN-DEVICE VALUES AND VALUES ACHIEVED IN PARALLEL-PLATE POLED BULK REFERENCE SAMPLES. FOR POLING, THE SAMPLES WERE HEATED TO THE GLASS TRANSITION TEMPERATURE T_g

Material	n	Bulk material		In-device			$U_\pi L$ [Vmm]	T_g [°C]
		r_{33} [pm/V]	r_{33}/E_{poling} [nm ² /V ²]	r_{33} [pm/V]	r_{33}/E_{poling} [nm ² /V ²]	$n^3 r_{33}$ [pm/V]		
YLD124(25wt.%)/PMMA	1.7	118 [17]	1.27 [17]	30	0.23	147	4	105
PSLD41	1.72	90 [31]	1.04 [31]	98	0.26	499	1.22	103
YLD124(25wt.%)/PSLD41	1.73	285 [30]	2.85 [30]	230	0.92	1190	0.52	97

Even though this corresponds to a much higher poling efficiency γ of $r_{33}/E_{\text{poling}} = 1.04 \text{ nm}^2/\text{V}^2$, the achievable EO coefficient is smaller due to the early onset of dielectric breakdown, which limits the maximum applicable poling field to $\sim 100 \text{ V}/\mu\text{m}$ in bulk PSLD41.

C. Binary Chromophore Organic Glass

Finally, we investigate the mixture of 25wt.% YLD124 and 75wt.% PSLD41 on a slot waveguide sample. We find a remarkably high poling efficiency γ of $r_{33}/E_{\text{poling}} = 0.92 \text{ nm}^2/\text{V}^2$ ($E_{\text{poling}} < 200 \text{ V}/\mu\text{m}$, black line in Fig. 4). Again, we observe excellent stability of the material against dielectric breakdown. Above a poling field of $250 \text{ V}/\mu\text{m}$, the achieved EO coefficient appears to saturate to a value of $\sim 200 \text{ pm/V}$. Fig. 3(c) shows the voltage-dependent transmission behavior of a 1 mm-long MZM. The π -voltage is $U_\pi = 0.58 \text{ V}$. In the best case we achieved an EO coefficient of $r_{33} = 230 \text{ pm/V}$ ($U_\pi L = 0.52 \text{ Vmm}$), by poling with a field strength of $250 \text{ V}/\mu\text{m}$. This is the highest reported EO coefficient in an SOH device, and it even exceeds the previously reported record value of a fully organic MZM, where 137 pm/V were measured [34]. Note that a significantly larger poling efficiency is observed in the bulk BCOG ($2.85 \text{ nm}^2/\text{V}^2$), but also here, low in-device poling efficiency is compensated by the fact that higher poling field can be applied in the slot waveguide as compared to the bulk material. The observed increase in poling efficiency of the BCOG as compared to the neat PSLD41 and to YLD124 in PMMA is in good agreement with results obtained in bulk material, where the binary chromophore system YLD124/PSLD41 was found to have an r_{33} coefficient (285 pm/V) that exceeds even the sum of the r_{33} coefficient of its constituents [30].

D. Discussion

A summary of the poling results is shown in Table I. From the experiments, we can conclude that the in-device poling efficiencies of all three investigated organic materials are a factor 3–4 smaller than the values obtained for the respective bulk samples. Nevertheless, the achievable in-device r_{33} -coefficient may be very close to or even higher than the bulk-material reference when using structurally engineered chromophores as PSLD41. This is enabled by enhanced material stability against dielectric breakdown in SOH slot waveguides as compared to bulk references, which allows to apply stronger poling fields. We attribute this to thin film effects and to a low number of defects in the slot region. An interesting finding of this material comparison is that EO material concepts that were developed for high poling efficiency

Fig. 5. Measured frequency response of a 1 mm-long MZM with 50Ω termination (blue) and of a $250 \mu\text{m}$ -long non-terminated MZM. No gate voltage has been applied.

in bulk materials also result in an increase of EO activity in SOH devices, as observed for the BCOG. Furthermore, the in-device $n^3 r_{33}$ figure of merit ($U_\pi \propto (n^3 r_{33})^{-1}$, see Eq. (1) of YLD124/PSLD41 is 1190 pm/V and is clearly superior to those of conventional EO materials such as GaAs ($n^3 r_{33} \approx 60 \text{ pm/V}$ [35]) and LiNbO₃ ($n^3 r_{33} \approx 400 \text{ pm/V}$ [36]).

V. DYNAMIC CHARACTERIZATION

The measurements of the last section were performed at dc modulation voltages. To demonstrate that the increased EO coefficient can also be exploited at higher frequencies, we measure the frequency response of devices coated with the binary chromophore mixture YLD124/PSLD41 and perform data transmission experiments using on-off-keying (OOK) at data rates of up to 40 Gbit/s .

A. Frequency Response

The frequency response is measured using a CW laser, a vector network analyzer (VNA), and a high-speed photodiode. The VNA was calibrated prior to the measurement in order to compensate for the frequency-dependent transfer function of the setup and the response of the photodiode. Fig. 5 depicts the measured electrical-optical-electrical (EOE) response of a 1 mm-long modulator that is terminated by a 50Ω load (blue), and of a $250 \mu\text{m}$ -long non-terminated modulator (red). The 6 dB-EOE-bandwidths are 18 GHz and 22 GHz , respectively, and are comparable to those of samples that are coated with guest-host materials. We can therefore conclude that the bandwidth of the device is not detrimentally influenced by the application of the BCOG. The bandwidth of the modulator could

Fig. 6. NRZ OOK eye diagrams. Measured Q^2 -factors, extinction ratios (ER) and bit error ratios (BER) are denoted in the figures PRBS length $2^{31}-1$. (a) Operation at 30, 35, and 40 Gbit/s obtained from a 250 μm -long MZM without termination. The drive voltage across the slot is $4.2 V_{pp}$, the bias voltage amounts to 2.8 V. The ER exceeds 10 dB up to 35 Gbit/s. At 40 Gbit/s we measure a BER of 2×10^{-6} . (b) Operation at 25 and 40 Gbit/s obtained from a 1 mm-long terminated MZM using a drive voltage of $1.5 V_{pp}$. A low signal quality is achieved at 40 Gbit/s due to the small EO bandwidth of 18 GHz. Applying a gate field [11] of 0.15 V/nm between the substrate and the transmission increases the bandwidth of the device from 18 to 25 GHz. This way the signal quality improves, and a BER of 2×10^{-8} is measured at a data rate of 40 Gbit/s.

be further improved by either increasing the doping concentration in the silicon slabs, by adding a second doping section of higher doping concentration close to the slot waveguide, or by applying a gate field that generates a highly conductive electron accumulation layer in the silicon slabs, see [11] for a more detailed discussion. A direct increase of the doping concentration to a value of $1 \times 10^{18} \text{ cm}^{-3}$ in the slot waveguide section should boost the bandwidth to 27 GHz. At the same time the free-carrier absorption losses would increase from 1.3 to 1.9 dB/mm [25], which corresponds to only a small increase of insertion loss by 0.6 dB for a 1 mm-long MZM. For a 250 μm -long MZM, the loss penalty is less than 0.2 dB.

B. OOK Modulation

Finally, we perform high-speed transmission experiments using a 250 μm -long non-terminated (“lumped”) MZM and a 1 mm-long terminated MZM, both coated with the mixture YLD124/PSLD41. First, the lumped MZM is investigated. Light from a tunable laser source at 1540 nm is coupled to the modulator. The device is connected to a pattern generator adjusted for a peak-to-peak voltage of $2.1 V_{pp}$ if terminated with 50 Ω . Reflection of the RF wave at the end of the non-terminated device result in nearly a doubling of the in-device drive voltage to roughly $4.2 V_{pp}$. A dc bias voltage of 2.8 V is combined with the RF signal by using a bias-T and the operation point of the MZM is set to the quadrature point. The modulated light is amplified using an erbium doped fiber amplifier and received

using a digital communications analyzer and a bit error ratio (BER) tester. Fig. 6(a) shows recorded eye diagrams of the 250 μm -long MZM for data rates ranging from 30 to 40 Gbit/s. We observe excellent signal quality and extinction ratios (ER) exceeding 10 dB up to a data rate of 35 Gbit/s. At 40 Gbit/s we measure a low BER of 2×10^{-6} and an ER of 9 dB.

Referring to [37] the energy consumption per bit W_{bit} of the non-terminated MZM is given by

$$W_{\text{bit}} = \frac{1}{4} C_d U_{\text{drive}}^2 \quad (3)$$

where U_{drive} is the peak-to-peak drive voltage and C_d is the device capacitance. The modulator has a measured capacitance of 95 fF resulting in an energy consumption of 420 fJ/bit. It is possible to reduce the energy consumption to a few fJ/bit by increasing the modulator length to 1 mm and simultaneously reducing the drive voltage below 400 mV_{pp} as reported in [4]. Note that, in contrast to earlier demonstrations of 40 Gbit/s modulation in SOH devices [11], [14], we did not use a gate voltage to improve the silicon conductivity. Still, a small voltage-length product of 1 Vmm is found for operation at 40 Gbit/s, one order of magnitude below typical values reported for reverse-biased pn-modulators [1], [5].

It should be noted that a slightly better 40 Gbit/s performance was reported in our previous work [38], where the initially small EO bandwidth of the device was increased from 10 to 25 GHz by applying a gate voltage between transmission line and silicon substrate. In this paper, 40 Gbit/s operation was achieved

without the use of a gate voltage. However, the comparison to [38] indicates that the doping concentration and the doping profile need to be further optimized for high-speed operation.

For the 1 mm-long MZM the drive voltage is set to 1.5 V_{pp}. Recorded eye diagrams are depicted in Fig. 6(b). Without the application of a gate voltage [11], the measured 40 Gbit/s eye diagram is hardly open, since the EO bandwidth of this device is only 18 GHz. In analogy to our previous work in [38] we can increase this bandwidth to 25 GHz by applying a gate field of 0.15 V/nm. This clearly improves the quality of the 40 Gbit/s eye diagram and leads to an ER of 9 dB and a BER of 2×10^{-8} .

VI. CONCLUSION AND OUTLOOK

We demonstrate that EO coefficient as high as 230 pm/V can be achieved in SOH devices that use structurally engineered electro-optic organic materials. Using a binary-chromophore organic glass composed of the chromophores YLD124 and PSLD41, we demonstrate an SOH MZM with small voltage-length product of 0.52 Vmm measured at dc. This concept enables 250 μ m long non-terminated modulators suitable for operation at 40 Gbit/s.

For a practical application of SOH devices, the long-term stability of the organic cladding is of high importance. The glass transition temperature of the investigated BCOG is relatively low ($T_g = 97^\circ\text{C}$), resulting in thermally activated re-orientation of the chromophores. One month after poling we measure a degradation of the EO coefficient by 20%. The investigation of aging and temperature stability of various organic materials is subject to ongoing research. We expect that material stability can be significantly improved by synthetically modified chromophores that bear specific crosslinking agents for postpoling lattice hardening or by increasing the molar mass of the chromophores. The viability of the first approach has already been demonstrated for similar EO compounds [39], [40], where material stability of up to 250 $^\circ\text{C}$ has been achieved.

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