Supplemental document accompanying submission to Optica

Title: Hybrid Electro-Optic Modulator Combining Silicon Photonic Slot Waveguides with High-k Radio-Frequency Slotlines

Authors: Christian Koos, Sandeep Ummethala, Juned Kemal, Ahmed Shariful Alam, Matthias Lauermann, Artem Kuzmin, Yasar Kutuvantavida, Sree Harsha Nandam, Lothar Hahn, Delwin Elder, Larry Dalton, Thomas Zwick, Sebastian Randel, Wolfgang Freude

Submitted: 10/3/2020 7:51:25 AM
Hybrid Electro-Optic Modulator Combining Silicon Photonic Slot Waveguides with High-k Radio-Frequency Slotlines

Sandeep Ummethala\textsuperscript{1,2,7}, Juned N. Kemal\textsuperscript{1}, Ahmed S. Alam\textsuperscript{1}, Matthias Lauermann\textsuperscript{1}, Artem Kuzmin\textsuperscript{3}, Yasar Kutuvantavida\textsuperscript{1}, Sree H. Nandam\textsuperscript{4}, Lothar Hahn\textsuperscript{2}, Delwin L. Elder\textsuperscript{5}, Larry R. Dalton\textsuperscript{5}, Thomas Zwick\textsuperscript{6}, Sebastian Randel\textsuperscript{1}, Wolfgang Freude\textsuperscript{1}, Christian Koos\textsuperscript{1,2,*}

\textsuperscript{1}Karlsruhe Institute of Technology (KIT), Institute of Photonics and Quantum Electronics (IPQ), 76131 Karlsruhe, Germany
\textsuperscript{2}Karlsruhe Institute of Technology (KIT), Institute of Microstructure Technology (IMT), 76334 Eggenstein-Leopoldshafen, Germany
\textsuperscript{3}Karlsruhe Institute of Technology (KIT), Laboratory for Applications of Synchrotron Radiation (LAS), 76131 Karlsruhe, Germany
\textsuperscript{4}Karlsruhe Institute of Technology (KIT), Institute of Nanotechnology (INT), 76334 Eggenstein-Leopoldshafen, Germany
\textsuperscript{5}University of Washington, Department of Chemistry, Seattle, Washington 98195, USA
\textsuperscript{6}Karlsruhe Institute of Technology (KIT), Institute of Radio Frequency Engineering and Electronics (IHE), 76131 Karlsruhe, Germany
\textsuperscript{7}email: sandeep.ummethala@kit.edu
\textsuperscript{*}Corresponding author: christian.koos@kit.edu

This document provides supplementary information to “Hybrid Electro-Optic Modulator Combining Silicon Photonic Slot Waveguides with High-k Radio-Frequency Slotlines”. Section 1 describes the details of electromagnetic field simulations for resistively-coupled silicon-organic hybrid (RC-SOH) and capacitively-coupled SOH (CC-SOH) devices, followed by details on the fabrication of CC-SOH Mach-Zehnder modulators (MZM) and on the optical and RF characterization of the underlying amorphous BaTiO\textsubscript{3} films in Section 2. Section 3 provides the derivation of an analytical expression for the field interaction factor and gives details on the estimation of the electro-optic (EO) coefficient \( r_{33} \) of the EO material. This section also explains the frequency-response model of the CC-SOH MZM, which is based on analytical relations that connect the measured electrical S-parameters of CC-SOH MZM to the electro-optic transfer function of the device. In Section 4, we describe details of the pre-emphasis technique that is used in the high-speed signaling experiment. Section 5 finally details design considerations on improving future generation CC-SOH modulators having sub-1 V operation voltages and bandwidths beyond 100 GHz.

1. Field simulations of RC-SOH and CC-SOH devices

Exemplary field profiles of RF and optical modes of typical resistively-coupled silicon-organic hybrid (RC-SOH) and capacitively-coupled SOH (CC-SOH) devices that are depicted in Figures 1(b) and (d) of the main paper were carried out using eigenmode solver of CST Microwave Studio. For both devices, we assumed a slot width \( w_{s} = 100 \) nm, a silicon (Si) rail width \( w_{\text{rail}} = 200 \) nm, a rail height of \( h_{\text{rail}} = 220 \) nm, and a spacing of \( w_{\text{ab}} = w_{\text{bk}} = 1 \) \( \mu \)m between the rails and the metal traces of the ground-signal-ground (GSG) transmission line. To reduce optical losses due to free-carrier absorption (FCA) in the doped Si regions of the RC-SOH device, we assumed a two-level doping profile with a low donor concentration in the rails (\( n_{D0}, \) light green in Fig. 1(a), resistivity \( \rho = 5.5 \times 10^{-4} \) \( \Omega \) m) and a higher concentration (\( n_{D3}, \) dark green in Fig. 1(a), resistivity \( \rho = 1 \times 10^{-4} \) \( \Omega \) m) in the doped Si slabs, see[1] for details. The slab thickness amounts to
In the simulation shown in Fig. 1(b) of the main paper, the doped silicon is modeled as a conductive dielectric with the aforementioned resistivities and a permittivity of $\varepsilon_{Si} = 11.7$. For the CC-SOH devices, we assumed a high-k slab with a thickness of $h_{slab} = 350 \text{ nm}$ and a permittivity $\varepsilon_{r,slab} = 100$, see Section 5 for a more detailed discussion of advantageous device designs. The Si rails are assumed to be undoped and therefore modeled as a pure dielectric with zero conductivity and a relative permittivity $\varepsilon_{Si} = 11.7$. Note that the silicon rails may also be slightly doped to increase the efficiency of the device, see our discussion of improved designs for CC-SOH MZM in Section 5. For RF modelling of the organic electro-optic (EO) material, we assume a relative permittivity $\varepsilon_{r,EO} = 5.68$. For simulating the optical mode profiles, we used the refractive indices of $n_{Si} = 3.5$ and $n_{SiO_2} = 1.44$ for silicon and silicon dioxide at a vacuum wavelength of 1.55 $\mu$m. The high-k dielectric is modelled with a refractive index $n_{slab} = 1.85$, which was the value that we obtained from spectroscopic ellipsometry measurements of the amorphous BaTiO_3 films used in the experiments, see Section 2C and Fig.S1 below. For the organic EO material, we assumed a refractive index of $n_{EO} = 1.9$ at a wavelength of 1.55 $\mu$m as specified in [2].

2. Device fabrication

A. Fabrication of CC-SOH MZM waveguide structures

The CC-SOH MZM used in our experiments are fabricated on standard silicon-on-insulator (SOI) substrates, featuring 220 nm-thick silicon (Si) device layers and 2 µm-thick buried oxide (SiO_2) layers. The devices are fabricated in a five-step lithographic process using high-resolution electron-beam (e-beam) lithography (Raith EBPG-5200). In the first lithography step, gold markers are fabricated on the SOI chip to ensure alignment accuracy of better than 50 nm between different exposures. In two subsequent lithographic steps, we fabricate shallow-etched grating couplers and fully-etched Si strip and slot waveguides along with the corresponding strip-to-slot converters. In the fourth lithographic step, ground-signal-ground (GSG) transmission lines made of 150-nm-thick gold are fabricated via a lift-off process using a polymethyl methacrylate (PMMA) and an electron-beam-evaporated gold layer. In the last step, the high-k dielectric BaTiO_3 (BTO) is deposited and structured via a second lift-off process using again PMMA as a mask. For the current device generation, 1 µm-wide amorphous BTO films with a thickness of 150 nm are deposited by room-temperature RF magnetron sputtering using a stoichiometric BaTiO_3 disk with 2-inch diameter as a target. The deposition is carried out at a base pressure of $5 \times 10^{-8}$ mbar, and the working pressure is set to $2.5 \times 10^{-3}$ mbar by controlling the flow rate (30 sccm) of Ar gas. A rather low RF power of 30 W is applied to the target to keep the temperature of SOI substrates below the glass transition temperature of the PMMA mask to enable a proper lift-off. Due to the low process temperature, the BTO thin film is known to be amorphous [3,4], which may be overcome by subsequent annealing [5]. The width of the BTO film is chosen to be 1 µm for good trade-off between the optical losses due to the gold transmission line and the capacitance of the BTO film, see Section 5 for details. Note that, in the current CC-SOH devices, the thickness of the BTO films and the metal electrodes is limited to 150 nm due to limitations of the lift-off process using a single PMMA resist layer. With process optimization and by employing bi-layer resist [6,7], it would be possible to fabricate optimized CC-SOH devices with thicker BTO and metal layers and thus further increased modulation efficiency, see Section 5 for details.

B. Optical losses of CC-SOH MZM

For our current CC-SOH devices, we measure an insertion loss of about 5 dB per grating coupler, a propagation loss of 6 dB/mm in the CC-SOH phase shifter, and an additional 3 dB of loss from other passive on-chip structures such as transport waveguides, strip-to-slot converters, and MMI couplers. This results in a total fiber-to-fiber insertion loss of about 19 dB for a 1 mm-long CC-SOH MZM. Note that these losses can be greatly reduced by optimized designs and fabrication processes. Specifically, systematic optimization of strip-to-slot converters and MMI couplers may allow to reduce the losses of each of these building blocks to 0.02 dB and 0.2 dB, respectively [8], [9], leading to an overall loss contribution of less than 0.5 dB. We also investigated the origin of the rather high propagation losses in the CC-SOH phase shifter. To this end, we measured the attenuation of 500 nm-wide strip waveguides of different lengths that were fabricated in the same process run as the CC-SOH devices, but that were not covered with BTO. For these structures, we also obtained rather high propagation losses of approximately 1 dB/mm, which is much larger than the value of 0.045 dB/mm that can be achieved when fabricating similar strip waveguides using highly optimized foundry processes [10]. We attribute the high loss of our structures to large sidewall roughness caused by a non-optimum fabrication process. The even higher propagation losses of 6 dB/mm measured for the slot-waveguide phase shifters are attributed to the fact that slot waveguides are more prone to roughness-induced scattering losses than strip waveguides. Specifically, ref [5] reports about slot-waveguides with 100 nm slot width and propagation losses of 0.2 dB/mm, which is approximately 3.5 to 6 times higher than the propagation loss of $(0.045 \pm 0.012)$ dB/mm measured for 500 nm-wide strip waveguides that were fabricated in the same process. For our structures, the 6 dB/mm measured for slot waveguides with
100 nm slot width and the 1 dB/mm propagation loss for 500 nm-wide strip waveguides leads also to a ratio of 6. This ratio is in good agreement with the findings in [5] given the fact that the rail width of the slot waveguides presented there amounts to 260 nm, whereas the rails in our structures are only 200 nm, thereby leading to slightly increased propagation losses of the slot waveguides. We further expect that absorption losses in the BTO slabs, which are in direct contact with the silicon rails, can be neglected – sputtered BTO has negligible optical losses in the visible and near infrared spectral range [11–15], which is also confirmed by ellipsometric measurement of the deposited films, see Fig. S1 and Section 2C below. We also checked the potential impact of absorption losses in the gold pads of the GSG transmission line by using electromagnetic simulations (CST Microwave Studio), based on which we estimate a contribution less than 0.1 dB/mm, assuming a width of the BTO slabs of \( w_{\text{slab}} = 1 \mu\text{m} \), see Fig. S8 and the associated discussion in Section 5 for details. In combination with roughness-induced slot-waveguide propagation losses of 0.2 dB/mm [10], the overall propagation loss in the CC-SOH phase shifter might hence be brought down to approximately 0.3 dB/mm. Assuming a 1 mm-long CC-SOH phase shifter and taking into account an additional 0.5 dB of loss from the strip-to-slot converters and MMI couplers [8] [9], on-chip insertion losses of the order of 1 dB might eventually come into reach. These losses can well compete with low-loss RC-SOH devices of much lower bandwidth [16]. In addition, the fiber-chip and chip-chip coupling losses can be greatly reduced by using 3D-printed micro-lenses [17] or photonic wire bonds [18,19].

**Fig. S1:** Refractive index \( n_{\text{BTO}} \) and extinction coefficient \( k_{\text{BTO}} \) of 750 nm-thick amorphous BTO film measured using spectroscopic ellipsometry. Note that the results for the extinction coefficient \( k_{\text{BTO}} \) are not very accurate and should rather be understood as an order-of-magnitude estimate due to limited sensitivity of the measurement technique with respect to optical loss.

**Fig. S2:** CPW structures used for extracting the relative permittivity and the loss tangent of amorphous BTO films. (a) Top-view schematic of the CPW test transmission line with length \( L \) and electrode spacing \( w = 1 \mu\text{m} \). (b) Cross-section of air-filled CPW test structure showing the geometric dimensions. (c) Cross-section of BTO-filled CPW showing the geometric parameters.

**C. Optical properties of the BTO film**

The optical properties of BTO thin films are determined from 750 nm-thick BTO layers deposited on SiO\(_2\)/Si substrates using the same process parameters that are used for fabricating the CC-SOH modulators as described in the previous section. By carrying out spectroscopic ellipsometric measurements, we determine a real part of the refractive index \( n_{\text{BTO}} = 1.85 \) along with a negligible imaginary part (extinction coefficient) \( k_{\text{BTO}} \) at 1550 nm, see Fig. S1. It should be noted that the results for the extinction coefficient \( k_{\text{BTO}} \) are likely not very accurate and should rather be understood as an order-of-magnitude estimate due to limited sensitivity of the ellipsometric measurement technique with respect to optical loss. For evaluating the raw data, the wavelength dependence of \( n_{\text{BTO}} \) and \( k_{\text{BTO}} \) is modeled by a simple Cauchy-type dispersion model [20]. The refractive index extracted from our measurements shows a good agreement with previously published values for amorphous BaTiO\(_3\) layers deposited by room-temperature sputtering [11,15,21]. The slight differences in the indices are attributed to variations of the process parameters such...
as gas pressure in the deposition chamber, which results in composition variations of the deposited material.

**D. Permittivity of the BTO film at RF frequencies**

As mentioned in Section 2 of the main paper, the RF properties of BTO are crucial for the performance of CC-SOH modulators. Since the material properties of BTO vary substantially depending on the deposition technique and its parameters [22], we perform a dedicated experiment to extract the RF properties of our BTO films. To this end, we fabricate two sets of coplanar waveguides (CPW) with lengths \( L \) of 1 mm, 2 mm, and 3 mm and a gap width of \( w = 1 \mu \text{m} \) between the ground and the signal traces, see Fig. S2 for a more detailed description of the underlying cross-sectional geometries. The first set of CPW only consists of the metal transmission-line strips without any BTO, Fig. S2(b), whereas the second set contains a BTO thin film filling the gaps between the CPW strips, Fig. S2(c). For better comparability to the CC-SOH modulators described in the main paper, we used the same SOI wafers for these test structures and removed the silicon device layer prior to depositing the metal transmission lines and the BTO films. We measure the two-port \( S \)-parameters for all variations of the CPW using a vector network analyzer (VNA, Keysight PNA-X N5247) in the frequency range from 0.01 GHz to 110 GHz. In this measurement, we use the line–reflect–reflect–match [23] calibration technique to perform an on-wafer calibration of the VNA and the associated cables and probes. To remove the impact of the on-chip RF fixtures (RF pads and tapered transitions), we de-embed the measured \( S \)-parameters using the so-called ‘L-2L de-embedding’ technique described in Section 4.6 of [24], which allows us to extract the \( S \)-parameters of the uniform transmission line sections with lengths \( L \) of 1 mm, 2 mm, and 3 mm. From these measurements, we derive the respective complex propagation constant \( \gamma_{\text{BTO}} \) and \( \gamma_{\text{air}} \) of the BTO-filled and air-filled CPW, respectively.

Once the frequency-dependent complex propagation constant \( \gamma_{\text{BTO,m}} = \alpha_{\text{BTO,m}} + j \beta_{\text{BTO,m}} \) is known, the associated effective permittivity \( \varepsilon_{\text{eff,meas}} \) of the mode is can be obtained by

\[
\varepsilon_{\text{eff,meas}}(f) = \left( \frac{\beta_{\text{BTO,m}}}{2 \pi f / c_0} \right)^2.
\]

In this relation, \( c_0 \) denotes the vacuum speed of light. The extracted \( \varepsilon_{\text{eff,meas}} \) obtained from transmission lines of different lengths \( L \) is shown in Fig. S3. Note that the sharp increase of the measured effective permittivity \( \varepsilon_{\text{eff,meas}} \) towards low frequencies is a result of the non-zero resistivity of the metal CPW traces, resulting in the so-called slow-wave effect [25]. The slow-wave effect is a consequence of the fact that, at low frequencies, the penetration depth of the RF fields (“skin depth”) approaches or even exceeds the thickness of the metal transmission-line traces. In this case, magnetic fields can exist also within the metal conductor, which leads to an additional internal inductance that strongly increases the effective permittivity of the RF mode [25,26]. To properly account for resistive metal traces and for the slow-wave effect, we use a commercial electromagnetic solver (CST Microwave Studio) to simulate the dispersion of the RF field to determine the effective permittivity of the BTO-filled CPW. In this simulation, we modelled the gold transmission lines by a material with frequency-dependent complex surface impedance that is calculated using the Hammerstad-Jensen model (“tabulated surface impedance” in CST Microwave studio) [27]. The geometrical cross section of the simulated BTO-filled transmission line corresponds to the one shown in Fig. S2(c). For the gold we assume a conductivity of \( 2.5 \times 10^7 \text{ S/m} \), which was extracted from the measured RF losses using the same numerical model, see Section 2E below. For the BTO, we assume a frequency-independent relative permittivity \( \varepsilon_{r,\text{BTO}} \), which we vary as to find best agreement between the simulated frequency-dependent effective permittivity \( \varepsilon_{\text{eff}}(f) \) of the RF mode and its measured counterpart \( \varepsilon_{\text{eff,meas}} \). We find good agreement for \( \varepsilon_{r,\text{BTO}} = 18 \), which leads to the solid black curve in Fig. S3. Note that the agreement of the measured and the simulated behaviour of \( \varepsilon_{\text{eff}} \) is particularly good at high frequencies, which is the most relevant part for our devices. For low frequencies, the measured effective permittivity \( \varepsilon_{\text{eff,meas}} \) is slightly smaller than its simulated

![Fig. S3: Measured and simulated effective permittivity of the BTO-filled CPW for different lengths \( L \). The sharp rise in the effective permittivity of the CPW originates from resistive metal CPW traces and from the so-called slow-wave effect and does not represent a dispersive behaviour of the underlying dielectric materials. The black curve shows the effective permittivity of the of the CPW simulated using an electromagnetic solver and assuming a frequency-independent relative permittivity \( \varepsilon_{r,\text{BTO}} = 18 \) for the BTO film.](image)
counterpart. We attribute these differences to small deviations between the simulated and the fabricated cross section of the CPW, which become more relevant at low frequencies where RF currents flow in the entire cross section of the metal traces. Note also that our finding of a frequency-independent relative permittivity of $\varepsilon_{\text{BTO}} = 18$ is in good agreement with literature [3, 5, 28, 29], where permittivities $\varepsilon_{\text{BTO}}$ between 14 and 20 were found in the frequency range between 1 kHz and 40 GHz. Regarding future CC-SOH devices, the modulation efficiency can be greatly improved by using polycrystalline BTO films, for which with relative permittivities in excess of 100 [5, 28] have been measured over a few GHz [30].

**E. Dielectric RF loss of the BTO film**

To estimate the loss tangent of the BTO film, we compare the microwave propagation loss measured from the S-parameters of the BTO-filled CPW with that extracted from an electromagnetic simulation. Since the contribution of ohmic losses is unknown, we first extract the frequency-dependent propagation loss of the air-filled CPW loss from the associated electrical S-parameter measurements, see Section 2D above, and compare them with the results of numerical simulations (CST Microwave Studio) for various conductivities. We find very good agreement when assuming a conductivity of $\sigma_{\text{Au}} = 2.5 \times 10^7$ S/m for the 150-nm-thick gold strips, see the blue solid and dashed curves in Fig. S4. In these simulations, we assumed a conductivity of $\sigma_{\text{Si}} = 0.13$ S/m for the bulk Si substrate, as specified by the wafer manufacturer. Note that the conductivity value for deposited gold thin films is smaller than the conductivity of $4.5 \times 10^7$ S/m for bulk gold – a common phenomenon observed in thin gold layers, for which the properties also seem to depend on the process conditions [31]. Using the same conductivity values for gold and the Si substrate, we simulate BTO-filled CPW using a relative permittivity $\varepsilon_{\text{BTO}} = 18$ and different values for loss tangent for the 150 nm-thick BTO film. The CPW losses obtained from the simulations are compared with those extracted from the measured electrical S-parameters of the BTO-filled CPW. Interestingly, the simulations already predict an increase of the RF losses of the BTO-filled CPW with respect to its air-filled counterpart, even when the BTO is assumed to be lossless ($\tan \delta_{\text{BTO}} = 0$), see dotted red curve in Fig. S4. We attribute this finding to the fact that the BTO filling of the CPW leads to an increase of the RF current density in the metal traces that are directly adjacent to the BTO slabs, which increases the ohmic losses. Note that this increase might already be sufficient to explain the measured losses of the BTO-filled CPW within the measurement accuracy. If we additionally vary the loss tangent $\tan \delta_{\text{BTO}}$, the propagation losses increase further – we have included the simulated propagation loss for a loss tangent of 0.03 $\delta_{\text{BTO}} = 0.03 \varepsilon_{\text{BTO}}$ for the 150-nm-thick amorphous BTO film. We determine an upper limit for the BTO loss tangent to be 0.03.

**F. Residual conductivity of the BTO slabs**

The BTO layers used in our devices are amorphous and may exhibit a residual conductivity that might impair the dynamics of the CC-SOH devices by long RC time constants. To investigate this effect, we applied a DC voltage between the signal and the ground pads of our structures and tried to measure the associated DC current. We did this both with the CC-SOH modulator structure, for which the signal trace of the transmission line is separated from each ground trace by a pair of BTO slabs with a gap in between, see Fig. 1(c), and with the CPW test structures according to Fig. S2, which either have no BTO at all or a continuous BTO slab between the metal traces. In all these experiments, the measured DC current was of the order of 10 nA, even for an applied DC voltage of 40 V, with no clear dependence on the device structure or on the presence of the BTO slabs. We may hence extract a lower limit of the order of few GHz for the resistance of the BTO slabs – but it is presumably much higher since the BTO is very likely not the main
source of the DC currents, which were also measured for the structure without the BTO. Still, these findings may confirm our notion that a residual conductivity of the BTO can be safely neglected for our devices. This is in line with the finding that we did not observe any slow dynamics in the electro-optic response of the CC-SOH MZM that could be related to the impact of non-zero resistivity of the BTO. Specifically, accounting for the frequency-dependent roll-off according to Fig 2(d), the “low-frequency” $U_p$ of 1.3 V measured with a 300 Hz triangular drive signal, Fig 2(c), is still effective for the high-speed transmission experiments, where the eye diagrams shown in Fig. 3(b) were generated with a peak-to-peak drive signal of 1 V.

3. Field interaction factor, electro-optic coefficient, and bandwidth of CC-SOH MZM

A. Field interaction factor and $U_p L$ product

CC-SOH devices combine a silicon photonic slot waveguide for optical frequencies[32] with a high-k dielectric slotline for RF frequencies[33]. This leads to strong EO interaction of the RF and the optical fields, which can be quantified by a field interaction factor $\Gamma_s$, obtained from an overlap integral of the optical and the RF field. The following section provides a derivation of these equations.

In general, the presence of the electric RF field will lead to an anisotropic change $\Delta\varepsilon_{r,o}$ of the relative permittivity tensor that is seen by the optical field. The optical fields can be represented by the vectorial electric and magnetic eigenmode fields $\mathbf{E}_o(x,y)$ and $\mathbf{H}_o(x,y)$ by a slowly varying complex envelope $A_o(z,t)$ [34],

$$E(x,y,z) = A_o(z,t) \frac{E_{o}(x,y)}{\sqrt{P_o}} e^{j(\omega t - \beta_0 z)},$$

$$H(x,y,z) = A_o(z,t) \frac{\mathbf{H}_{o}(x,y)}{\sqrt{P_o}} e^{j(\omega t - \beta_0 z)}. \tag{S2}$$

In this relation, $\omega_0$ is the optical carrier frequency and $\beta_0$ the associated wavenumber of the optical mode. $A_o(z,t)$ represents a complex power amplitude with unit $\sqrt{W}$, and $P_o$ denotes the power that is associated with the vectorial optical mode fields $\mathbf{E}_o(x,y)$ and $\mathbf{H}_o(x,y)$,

$$P_o = \frac{1}{2} \iint \text{Re}\{E_{o}(x,y) \times \mathbf{H}_{o}^{*}(x,y)\} \cdot \mathbf{e}_z \, dx \, dy. \tag{S3}$$

Similarly, the electric and magnetic RF fields can be represented by

$$E_{RF}(x,y,z) = A_{RF} \frac{\mathbf{E}_{RF}(x,y)}{\sqrt{P_{RF}}} e^{j(\Omega t - \beta_{RF})},$$

$$H_{RF}(x,y,z) = A_{RF} \frac{\mathbf{H}_{RF}(x,y)}{\sqrt{P_{RF}}} e^{j(\Omega t - \beta_{RF})}. \tag{S4}$$

where $\Omega$ is the RF frequency of the applied signal and $B$ the associated wavenumber of the RF mode with vectorial electric and magnetic mode fields $\mathbf{E}_{RF}(x,y)$ and $\mathbf{H}_{RF}(x,y)$. $A_{RF}$ represents the complex power amplitude of the RF wave with unit $\sqrt{W}$ and $P_{RF}$ denotes the power that is associated with the RF mode fields,

$$P_{RF} = \frac{1}{2} \iint \text{Re}\{E_{RF}(x,y) \times \mathbf{H}_{RF}^{*}(x,y)\} \cdot \mathbf{e}_z \, dx \, dy. \tag{S5}$$

According to Eq. (1.57) and Eq. (1.58) in [34], the modulation of the optical wave can be described by a change of the associated complex amplitude according to

$$\frac{\partial A_o(z,t)}{\partial z} = -j \frac{\omega}{4P_o} \iint [\Delta \varepsilon(x,y,z) \varepsilon_{o}(x,y)] \cdot \mathbf{e}_z \, dx \, dy \, A_o(z,t), \tag{S6}$$

where $\Delta \varepsilon(x,y,z) = \varepsilon_0 \Delta \varepsilon_{r,o}(x,y,z)$ denotes the anisotropic perturbation of the relative-permittivity profile for the optical field, that arises as a consequence of the electrical RF field. Note that this relation is formulated with respect to a retarded time frame, see Eq. (1.54) in [34]. To quantify the perturbation of the relative permittivity, we express it through the associated change $\Delta \eta$ of the permittivity tensor $\eta = \varepsilon_{r,o}^{-1}$ which, for small perturbations, is related to $\Delta \varepsilon_{r,o}$ by

$$\Delta \varepsilon_{r,o} = -\varepsilon_{r,o} \Delta \eta \varepsilon_{r,o} \tag{S7}$$

Within the organic electro-optic material, the change $\Delta \eta$ of the permittivity tensor is related to the electric field of the RF wave via the electro-optic tensor $\eta_{io}$ according to Eq. (11.2.13a) in [35]. Note that, for organic EO materials, the electro-optic tensor $\eta_{io}$ is defined with respect to a local coordinate system, for which the axis $l = 3$ is given by the local poling direction of the EO material. This poling direction is induced by a static electric field that is applied to the transmission-line electrodes at an elevated temperature. For simplicity, we assume that the RF electric field is predominantly transverse, i.e., $E_{RF,i} = 0$, that the transverse components $E_{RF,x}$ and $E_{RF,y}$ are in phase and can thus be represented as real numbers, and that the static poling field can be approximated by the real-valued vector field $E_{RF}(x,y)$. We further assume that only the dominant $\gamma_3$ coefficient of the organic EO material plays a role and that all other coefficients $\eta_{lm}$ with $l,m \neq 3$ can be neglected. Accounting for the local transformation between the coordinate system of the EO tensor and the $(x,y,z)$-system of the device, approximating the EO material in absence of an electric field by an isotropic medium with refractive index $n_{EO}$, and neglecting any walk-off between the optical and the RF field, Eq. (S16) can be rewritten as
\[ \frac{\partial A_{EO}(x,t)}{\partial z} = -j \Delta \beta_{EO} A_{EO}(x,t), \]

\[ \Delta \beta_{EO} = -\frac{\epsilon_{eff} n_{EO}^2}{2P_0} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_{EO}(x,y) E_{RF}(x,y) \cos^2 \theta(x,y) \, dx \, dy \]  

\[ \tag{S8} \]

In these relations, \( \Delta \beta_{EO} \) denotes the (complex) amplitude change of the modal propagation constant due to the modulating RF field (of complex) power amplitude \( A_{RF} \), and \( \theta(x,y) \) is the local angle between the optical and the RF electric field vectors. \( A_{EO} \) denotes the cross-sectional area that is filled by the organic EO material. Without loss of generality, we may assume that \( A_{RF}, \Delta \beta_{EO} \in \mathbb{R} \), which allows us to rewrite Eq (S7) in terms of the associated RF voltage amplitude \( U_{RF} = A_{RF} \sqrt{Z_{RF}} \). where \( Z_{RF} \) is the line impedance of the RF transmission line. For better comparability to conventional RC modulators, we express the phase shift \( \Delta \phi \) introduced along an EO section of length \( L \) by the electric field \( U_{RF}/w_s \) that would be generated by the RF voltage \( U_{RF} \) within a slot of width \( w_s \),

\[ \Delta \phi = \frac{1}{2} \frac{\epsilon_{eff} n_{EO}^2}{w_s} U_{RF} k_0 L \Gamma_s, \]  

\[ \tag{S9} \]

where \( k_0 \) is the vacuum wavenumber of the optical field, and where the field interaction factor \( \Gamma_s \) is given by,

\[ \Gamma_s = \frac{n_{EO} w_s}{2 Z_{RF} P_0 \sqrt{Z_{RF}}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_{EO}(x,y) E_{RF}(x,y) \cos^2 \theta(x,y) \, dx \, dy. \]  

\[ \tag{S10} \]

In this relation, \( Z_0 = 377 \Omega \) is the free-space wave impedance. Not that, for a push-pull MZM, the phase difference of the optical signals at the end of the two MZM arms is twice the phase shift \( \Delta \phi \) calculated in Eq (S9). The \( U_s L \)-product of a push-pull MZM is hence related to the EO coefficient \( \gamma_{33} \) of the organic material by

\[ U_s L = -\frac{w_s \lambda}{2 \epsilon_{eff} n_{EO}^2 \Gamma_s}, \]  

\[ \tag{S11} \]

where \( \lambda \) denotes the vacuum wavelength of the optical field. Note that these relations are general and can be widely applied to any EO modulator structure. In our CC-SOH devices, the high-permittivity BTO slabs lead to a local enhancement of the electrical RF field \( E_{RF}(x,y) \) within the EO material in the slot, which increases the associated field interaction factor \( \Gamma_s \). Section 5 provides a more detailed discussion on how the field interaction factor \( \Gamma_s \) of CC-SOH structures can be increased by appropriate device design.

B. Electro-optic coefficient and poling efficiency of fabricated CC-SOH Mach-Zehnder modulator

To estimate the EO coefficient \( \gamma_{33} \) of our CC-SOH structures from the measured \( U_s L \) product, we need to evaluate Eqs (S10) and (S11). In a first step, we use an electromagnetic mode solver (CST Microwave Studio) and calculate the field profiles of the optical and RF eigenmodes of the CC-SOH modulator along with the associated RF line impedance \( Z_{RF} \). The basic cross section of the structure is illustrated in Fig 1(c) of the main manuscript. In these calculations, we use a silicon rail width \( w_{rail} = 200 \text{ nm} \), a rail height \( h_{rail} = 220 \text{ nm} \), a slot width \( w_s = 100 \text{ nm} \) along with a BTO slab of height \( h_k = 150 \text{ nm} \) and width \( w_{hk} = 1 \mu\text{m} \), see Fig 1(c) of the main manuscript. We further assume a vacuum wavelength of \( \lambda = 1550 \text{ nm} \) for the optical signal along with refractive indices of \( n_{Si} = 3.5, n_{SiO_2} = 1.44, n_{BTO} = 1.85 \) and \( n_{EO} = 1.9 \) for the silicon, the silicon dioxide, the BTO, and the organic EO material YLD124, respectively. For the calculating the RF field, we assume a GSG transmission line with a metal height \( h_k = 150 \text{ nm} \). The width of the signal trace and of each ground trace amounts to 7 \( \mu\text{m} \) and 60 \( \mu\text{m} \), respectively, and the conductivity of the gold is set to 2.5\times10^7 S/m, see Section 2E above. For the silicon, the silicon dioxide (BOX), the EO material, and the BTO, we assume permittivities of \( \epsilon_{Si} = 11.7, \epsilon_{SiO_2} = 3.9, \epsilon_{EO} = 5.68 \), and \( \epsilon_{BTO} = 18 \), respectively. For the simulation of the RF field, the transmission-line traces are modelled as a lossy metal, in which the electromagnetic behaviour of the metal is approximated by assuming a skin depth that is much smaller than the metal thickness. In contrast to the Hammerstad-Jensen model [27] ("tabulated surface impedance" in CST Microwave studio), that was needed for quantitatively correct modelling of the effective permittivity \( \epsilon_{eff} \) and the RF losses, see Section 2D and 2E above, the lossy-metal model allows to account for the true 3D geometry of the metal, which is important for obtaining the correct distribution of the associated RF mode fields. Evaluation of Eq. (S10) with the calculated mode fields leads to a field interaction factor of \( \Gamma_s = 0.048 \) for our current device generation. Using the measured \( U_s L \) product of 1.3\,V\,nm, see Fig 2(c) of the main paper, we then evaluate Eq. (S11) to obtain an EO coefficient of \( \gamma_{33} = 180 \text{ pm/V} \) for the organic EO material YLD124. Furthermore, we estimated the strength of the poling field that can be expected in the slot when applying a DC voltage of 600 V between the two floating ground traces of the GSG transmission line, leading to a poling voltage of \( U_p = 300 \text{ V} \) between the signal and each of the floating ground traces. For simplicity, we assumed that the transverse distribution of the associated static electric field can be approximated by the electric field of the RF mode at low frequencies, leading to a field strength of approximately 450 V/\mu m within the slot for an externally applied poling voltage of \( U_p = 300 \text{ V} \). For a slot with width \( w_s = 100 \text{ nm} \), 45 V would hence drop across the slot, which corresponds to 15% of the
The device is an improved device having 600 nm-thick transmission lines that feature smaller RF losses, see Section 5 for details.

Overall applied poling voltage $U_p$. This number illustrates clearly that the current structures leave vast room for further improving the interaction of the RF field with the EO material in the slot, e.g., by using polycrystalline BTO films with higher permittivities $\varepsilon_{r,BTO}$ in excess of 100. As explained in Section 5, improved CC-SOH structures can provide field interaction factors $\Gamma_s$ in excess of 0.3, which is more than six times higher than the currently achieved value of 0.048. Still, the BTO slabs of the current devices already contribute significantly to enhancing the electro-optic interaction – removing the BTO slabs would decrease the field interaction factor by approximately a factor of two to values below 0.025.

**C. Bandwidth of CC-SOH Mach-Zehnder modulator**

The frequency response of the CC-SOH MZM is measured in the frequency range from 0.01 GHz to 110 GHz using a vector network analyzer (VNA, Keysight PNA-X N5247). A calibration kit for 1 mm-connector is used to shift the measurement reference plane from the network analyzer ports to the end of the connected coaxial cables using a short-open-load-through (SOLT) calibration procedure. The RF signal from the VNA is coupled to the ground-signal-ground (GSG) pads of the CC-SOH MZM using a GSG probe (Cascade Infinity Probe 1110-A-GSG-100). The other end of the MZM transmission line is terminated by a second probe connected to a 50 Ω impedance. Spurious reflections at the coplanar transmission line of the CC-SOH MZM are avoided by a tapered transition that provides an impedance matching between the contact pads and the phase shifter section. We exploit the unbalanced arm lengths of the MZM to adjust the device to the quadrature operating point by tuning the wavelength of the feed laser. The intensity-modulated output of the CC-SOH MZM is detected by a calibrated high-speed photodiode (HHL, C05-W36), and the output signal is recorded by the second port of the VNA. The photodiode has a 3 dB bandwidth of 78 GHz, followed by a smooth roll-off, which allows to perform measurements up to 110 GHz, where the transfer function drops by 9 dB with respect to the low-frequency range. The EO response $S_{21,EO,meas}$ of the CC-SOH MZM can be de-embedded from the measured overall transmission $S_{21,overall}$ by taking into account the frequency response of the photodiode and of the RF probes, leading to the red curve in Fig. S5, which is equivalent to Fig. 2(d) of the main paper. For a 1 mm-long CC-SOH MZM, we measure a 3 dB EO bandwidth of 76 GHz.

To confirm the directly measured EO dynamics, we also estimate the EO transfer function from the electrical scattering parameters. To this end, we measure the electrical $S$-parameters by connecting the second port of the VNA to the RF probe that was earlier used as a termination of the CPW. For calibration and de-embedding, we apply the line-reflect-reflect-match [23] and the ‘L-2L de-embedding’ technique, described in Section 4.6 of [24]. The transfer function of the RF fixtures, i.e., the on-chip metal contact pads and the tapered transitions to the metal strips of the transmission line, are de-embedded by using $S$-parameter measurements of CC-SOH MZM of different modulator lengths. Based on this, we extract the complex propagation constant $B_s$ as well as the complex line impedance $Z_c$ of the CC-SOH transmission line. For estimating the EO response of the traveling-wave modulator, we use the equivalent circuit shown in Fig. S6. We assume a device of length $L$ and a complex RF impedance $Z_s$, driven by an RF source of internal impedance $Z_t$ at RF modulation frequency $\Omega_m/2\pi$ and voltage amplitude $U_d$, and
terminated by an impedance \( Z \). The instantaneous voltage seen by the optical signal at a particular position on the line is then given by Eqs. 1 – 5 in [36],

\[
U(x, \alpha_m) = \frac{U_d}{2} \left( 1 + \rho_1 \right) e^{-j \beta_{L}L} \left( e^{-j (R_e - R_o) x} + \rho_2 e^{j (R_e - R_o) x} \right) e^{-j \beta_{L}L} + \rho_1 \rho_2 e^{j \beta_{L}L} \\
\rho_1 = \frac{Z_e - Z_s}{Z_e + Z_s} \\
\rho_2 = \frac{Z_o - Z_e}{Z_o + Z_e} \\
B_o = \frac{\Omega_m}{c_0} \eta_{g, \text{opt}} \\
B_e = \frac{\Omega_m}{c_0} \eta_{e, RF} + j \alpha_m 
\]

(S12)

(S13)

(S14)

(S15)

(S16)

In these relations, \( \alpha_m \) is the amplitude attenuation constant of the RF signal, \( \eta_{g, \text{opt}} \) denotes the optical group refractive index, \( \eta_{e, RF} \) is the effective index of the RF signal, and \( c_0 \) is the speed of light in vacuum. The phase shift experienced by an optical wave traveling through the modulator is directly proportional to the voltage experienced by it along the length of the phase shifter. To simplify the analysis, it is convenient to work with the average voltage along the length \( L \) of the modulator, see Eq. 17 in Ref. [37],

\[
U_{\text{avg}}(\Omega_m) = \frac{1}{L} \int_{0}^{L} U(x, \Omega_m) \, dx \\
= \frac{U_d \cdot (1 + \rho_1)}{2 \left( e^{-j \beta_{L}L} + \rho_1 \rho_2 e^{j \beta_{L}L} \right)} \left( U_+ + \rho_2 U_- \right), \\
\text{where} \\
U_+ = e^{+j \beta_{e} \sin \phi_1} \quad \phi_1 = \frac{(B_e - B_o) L}{2} \\
U_- = e^{+j \beta_{e} \sin \phi_2} \quad \phi_2 = \frac{(B_e + B_o) L}{2} 
\]

(S17)

(S18)

Note that Eq. (S17) accounts for the impact of RF propagation loss, the impedance mismatch of the modulator transmission line with respect to the source and the termination, as well as velocity mismatch of the RF and the optical waves of the traveling-wave modulator. The optical group refractive index \( \eta_{g, \text{opt}} = 2.8 \) needed in Eq. (S15) is numerically calculated using a commercially available optical mode solver (CST Microwave Studio).

For relating the frequency-dependent decay of the average voltage \( U_{\text{avg}} \) to the phase modulation of the optical signal, we exploit the fact that the relative permittivity \( \varepsilon_{\text{RFC-SOH}} = 18 \) is constant over the frequency range of interest, Section 2D. Since the transverse dimensions of the RF transmission lines are much smaller than the RF wavelength, we may hence assume that the RF field profiles change only marginally with modulation frequency \( \Omega_m \). The amplitude of the phase modulation is hence directly proportional to the average voltage \( U_{\text{avg}}(\alpha_m) \) on the transmission line, and the EO frequency response can be written as

\[
m(\Omega_m) = \frac{U_{\text{avg}}(\Omega_m)}{U_{\text{avg}}(0)} 
\]

(S19)

We finally obtain the dB-values of the EO response derived from the electrical scattering parameters of the CC-SOH MZM as

\[
S_{21,\text{EO,der}} = 20 \log_{10} \left( m(\Omega_m) \right). 
\]

For a device with a phase shifter length of \( L = 1 \, \text{mm} \), the results are indicated by a blue dotted line in Fig. S5. The EO response \( S_{21,\text{EO,der}} \) derived from the electrical scattering parameters is in fair agreement with its directly measured counterpart \( S_{21,\text{EO,meas}} \), thus confirming the validity of the approach.

Furthermore, we investigate the limiting factors for the bandwidth of the CC-SOH MZM. From the numerically calculated value of \( \eta_{g, \text{opt}} \) and the mean RF effective index \( \eta_{e, RF} = 2.2 \) averaged over the frequency range 0.01 GHz … 110 GHz, the velocity-mismatch-limited 3dB-bandwidth of a CC-SOH device is given by Eq. 2 in Ref. [38],

\[
f_{\text{vm}} = 1.4 \left( \frac{c_0}{\pi \eta_{g, \text{opt}} - \eta_{e, RF} \Omega_m} \right). 
\]

(S20)

For our 1 mm-long CC-SOH devices, we estimate a velocity-mismatch-limited 3dB frequency of \( f_{\text{vm}} = 220 \, \text{GHz} \). It is thus clear that the bandwidth limitation of 76 GHz observed in our
current measurements cannot be caused by velocity mismatch but must arise from the non-optimum electrical design of our first-generation device, in particular from the high RF propagation loss.

In general, RF propagation loss has two main contributions – ohmic loss and dielectric loss. As discussed in Section 2E above, the BTO thin film has a negligibly small loss tangent $\tan \delta_{\text{BTO}} = 0.03$. This results in a bulk BTO loss of only 0.38 dB/mm, which is much smaller than the overall RF propagation loss of 45 dB/mm at 50 GHz, see red curve in Fig. S7. We hence conclude that ohmic losses of the metal traces of the transmission line must have significant impact. As mentioned in the main manuscript, these traces were fabricated using a lift-off process with a thin photoresist, which limited the thickness of the gold layer to a rather small value of approximately 150 nm. To confirm the notion that this leads to strong ohmic RF losses, we simulate the RF mode of the CC-SOH device using the same technique as described in Section 2E. For the BTO, we assume again a relative permittivity $\epsilon_{r,\text{BTO}} = 18$ and a loss tangent $\tan \delta_{\text{BTO}} = 0.03$, and we also consider the conductivity of the bulk Si substrate, for which a value of $\sigma_{\text{Si}} = 0.13$ S/m was specified by the wafer supplier. In our simulations, we vary the conductivity of the gold traces, and we find best agreement with the measured losses for a value of $\sigma_{\text{Au}} = 2.6 \times 10^7$ S/m, see red and blue curves in Fig. S7. This value agrees well with the gold conductivity of $\sigma_{\text{Au}} = 2.5 \times 10^7$ S/m obtained from the characterization of the CPW test structures, Section 2E. Based on these findings, we conclude that the RF propagation loss of the current CC-SOH devices arises from the ohmic loss of the thin gold traces in the underlying transmission line, and that these limitations can be overcome by using thicker metal layers, see Section 5 below for improved design devices.

4. Pre-emphasis of the drive signals in the high-speed signaling experiments

In the high-speed signaling experiments, we use digital pre-emphasis of the drive signals to compensate for the frequency roll-off of the AWG, of the subsequent RF amplifier, of the 6dB attenuator, and of the bias-tee, see Section 4 and Fig. 3(a) of the main paper. The required correction is extracted from a back-to-back measurement of the electrical signal, in which the AWG is operated without any pre-emphasis to generate a test signal. This test signal is then sent through the subsequent RF amplifier, the 6 dB attenuator, and the bias-tee, see left part of Fig. 3(a) of the main paper, before being recorded by a real-time oscilloscope (RTO). To estimate the digital pre-emphasis that needs to be applied at the transmitter, the frequency spectrum of the recorded signal is then compared to that of the ideal (transmitted) spectrum. For the data transmission experiment, the CC-SOH modulator, the corresponding RF probe, the optical transmission link, the photodetector as well as another RF amplifier are then added, leading to the full setup shown in Fig. 3(a) of the main manuscript. None of these elements was part of the signal path during the calibration measurement – they are hence not compensated by the estimated pre-emphasis.

5. Improved designs of CC-SOH modulators

The experimental results presented in the main manuscript were obtained with first-generation devices that leave vast room for improvements with respect to modulation efficiency and bandwidth. In this section, we shall further investigate the potential of the CC-SOH concept by numerical simulations of devices with improved designs, in which we adjust the various geometrical parameters defined in Fig. 1(c) of the main paper. Regarding the modulation efficiency, the $U_z L$ product of the devices may be greatly reduced by using polycrystalline BTO layers with relative permittivities $\epsilon_{r,\text{BTO}} \geq 100$ [5,28], which is much larger than the value of $\epsilon_{r,\text{BTO}} = 18$ in our current devices. In addition, the dimensions of the BTO slabs may be adapted to find an optimum trade-off between different design goals. Specifically, increasing the height $h_{\text{BTO}}$ beyond the current value of 150 nm will be instrumental to improve the overlap of the RF field and the optical field and thus to further increase the field interaction factor $\Gamma_z$. On the other hand, a thicker BTO will increase the transverse capacitance of the line and thus lead to a reduced line impedance $Z_{\text{RF}}$. In combination with a given operation voltage of the MZM dictated by the required phase shift, this will increase the RF power consumption. For the width $w_{\text{BTO}}$ of the BTO slabs, choosing a small value leads to an increased coupling capacitance $C_s$ and thus an increased modulation efficiency, but also results in larger interaction of the

![Fig. S8: Optical loss due to interaction of the guided light with the metal traces of the RF transmission line as a function of the BTO slab width $w_{\text{BTO}}$. For $w_{\text{BTO}} \geq 1 \mu$m, the loss contribution of the transmission line is less than 0.1 dB/mm and can thus be neglected.](image-url)
In a first step of our design considerations, we estimate the optical propagation loss introduced by the interaction of the evanescent field with the metal transmission lines. To this end, we assume the BTO slabs and the metal traces to have the same height \( h_m = h_{hk} = 150 \text{ nm} \) and calculate the contribution to the optical propagation loss as a function of the width \( w_{hk} \) of the BTO slabs, see Fig. S8. We find that, for values of \( w_{hk} \geq 1 \mu m \), the loss contribution of the metal trace is below 0.1 dB/mm and can thus be neglected. In the subsequent simulations, we fix the width of the BTO slab to the value of \( w_{hk} = 1 \mu m \).

As a next step, we simulate the CC-SOH devices by treating the Si rails as pure dielectrics with zero conductivity and by setting the BTO height \( h_{hk} \) and the metal height \( h_m \) to the same value, which is swept between 100 nm and 1 \mu m, see Fig. S9. In these simulations the width of the BTO and of the signal trace are kept to constant values of \( w_{hk} = 1 \mu m \) and \( w_{sig} = 4 \mu m \), respectively. The field interaction factor \( \Gamma_s \) for different BTO/metal heights \( h_m = h_{hk} \). The field interaction factor reaches a plateau at \( \Gamma_s = 0.17 \) for \( h_m = h_{hk} > 600 \text{ nm} \), see Fig. S9(a). This saturation is caused by the fact that an increasing height of the BTO slabs and the metal traces distributes the RF electric field into regions of the organic EO material, which do not contain significant optical power. At the same time, the RF losses and the impedance of the transmission line go down with increasing values of \( h_m = h_{hk} \) due to the increased transverse capacitance and the reduced ohmic losses of the metal traces, see values calculated at 50 GHz in Fig. S9(b). It turns out that, for a line impedance \( Z_{RF} = 50 \Omega \), the heights of the BTO slabs and the metal should be chosen to \( h_m = h_{hk} = 300 \text{ nm} \), which leads to non-optimum RF loss and field interaction factors, as indicated by circles in Fig. S9. Thicker layers with \( h_m = h_{hk} > 600 \text{ nm} \) would lead to much better modulation efficiency and less RF loss, but the line impedance \( Z_{RF} \) would drop below the desired value of 50 \( \Omega \). This may be fixed by using slightly thinner BTO slabs.

For the next design iteration, we therefore set the height of the metal traces to a fixed value of \( h_m = 600 \text{ nm} \) and we again sweep the height the height \( h_{hk} \) of the BTO slabs between 100 nm and 1 \mu m, see Fig. S10. In addition to the non-conductive Si rails, we also consider the case of a slight doping in the rails designed for a resistivity of approximately \( \rho = 5.5 \times 10^{-3} \Omega \text{m} \) [1]. This conductivity should eliminate the electric field within the Si rails and thus increase the field in the EO material accordingly, see field plots in the insets of Fig. S10(a). The chosen resistivity should
RF loss of CC-SOH modulator for different slab heights. The respective field interaction factor and to an RF propagation loss of about 1.7 dB/mm at 50 GHz, see blue traces and blue circles in Fig. S10(a), (b), and (c). This field interaction factor is only slightly smaller than the value of Γ_{RF-SOH} = 0.38 that can be achieved for conventional RC-SOH devices, see dashed black curve in Fig.S10(a). We may hence conclude that the CC-SOH concept can reach similar modulation efficiencies as RC-SOH devices, for which U/L products down to 0.32 Vmm were demonstrated [39], while offering bandwidths in excess of 100 GHz.

Taking the above considerations, we also investigate the impact that an increased thickness of the metal traces would have on our current CC-SOH devices. To this end, we assume undoped Si rails along with 150 nm-thick BTO slabs having and 600 nm-thick metal traces. The width of the signal trace is kept to w_{sig} = 7 µm. From this simulation, we extract the line impedance and the microwave propagation loss and then calculate the electro-optic (EO) response according to the model described in Section 3C. The result is shown as a green trace in Fig.S5 and in Fig.S2(d) of the main paper, corresponding to a bandwidth of more than 100 GHz. This clearly indicates that the performance of the experimentally demonstrated devices can be greatly improved by appropriate device designs.

References

1. H. Zwickel, S. Singer, C. Kieninger, Y. Kutuvanavida, N. Muradyan, T. Wahlbrink, S. Yokoyama, S. Randel, W. Freude, and C. Koos, “Verified equivalent-circuit model for slot-waveguide modulators,” Opt. Express 28, 12951–12976 (2020).
2. W. Heni, C. Haffner, D. L. Elder, A. F. Tillack, Y. Fedoryshyn, R. Cottier, Y. Salamin, C. Hoessbacher, U. Koch, B. Cheng, B. Robinson, L. R. Dalton, and J. Leuthold, “Nonlinearities of organic electro-optic materials in nanoscale slots and implications for the optimum modulator design,” Opt. Express 25, 2627 (2017).
3. S. S. Park, “Properties of BaTiO3 films sputter deposited on PET for pulse power capacitors,” Ferroelectrics 457, 97–104 (2013).
4. G. S. Raju, Dielectrics in Electric Fields (CRC Press, 2017).
5. Q. X. Jia, Z. Q. Shi, and W. A. Anderson, “BaTiO3 thin film capacitors deposited by r.f. magnetron sputtering,” Thin Solid Films 209, 230–239 (1991).
6. J. Golden, H. Miller, D. Nawrocki, and J. Ross, "Optimization of Bi-layer lift-off resist process," in 2009 International Conference on Compound Semiconductor Manufacturing Technology, CS MANTECH 2009 (2009).

7. S. Krátky, M. Horáček, P. Meluzín, V. Kolařík, M. Matějka, J. Oulehla, and Z. Pešić, "Lift-off technology for thick metallic microstructures," in METAL 2017 - 26th International Conference on Metallurgy and Materials, Conference Proceedings (2017), pp. 1298–1302.

8. R. Palmer, L. Allotta, D. Korn, W. Heni, P. C. Schindler, J. Bolten, M. Karl, M. Waldow, T. Wahrbrink, W. Freude, C. Koos, and J. Leuthold, "Low-loss silicon strip-to-slot mode converters," IEEE Photonics J. 5, 2200490 (2013).

9. W. Bogaerts, S. K. Selvaraja, P. Dumon, J. Brouckaert, K. De Vos, D. Van Thourhout, and R. Baets, "Silicon-on-insulator spectral filters fabricated with CMOS technology," IEEE J. Sel. Top. Quantum Electron. 16, 33–44 (2010).

10. S. K. Selvaraja, P. De Heyn, G. Winnoth, P. Ong, L. Lepage, C. Cailler, A. Rigny, K. K. Bourdelle, W. Bogaerts, D. Van Thourhout, J. Van Campenhout, and P. Absil, "Highly uniform and low-loss passive silicon photonic devices using a 300nm CMOS platform," in Optical Fiber Communication Conference, OFC 2014 (2014), p. Th2A.33.

11. L. Scholtz, P. Šutta, P. Calta, P. Nováč, M. Solanská, and J. Müllérova, "Investigation of barium titanate thin films as simple antireflection coatings for solar cells," Appl. Surf. Sci. 461, 249–254 (2018).

12. M. Cardona, "Optical properties and band structure of SrTiO3 and BaTiO3," Phys. Rev. 140, 651–655 (1965).

13. J. Xu, J. Zhai, X. Yao, J. Xue, and Z. Huang, "Dielectric and optical properties of BaTiO3 thin films prepared by low-temperature process," J. Sol-Gel Sci. Technol. 42, 209–212 (2007).

14. A. Karvounis, F. Timpu, V. V. Vogler-Neuling, R. Savo, and R. Grange, "Barium Titanate Nanostructures and Thin Films for Photonics," Adv. Opt. Mater. 8, 1–20 (2023).

15. A. K. Sharma, B. G. Priyadarshini, B. R. Mehta, and D. Kumar, "An amorphous barium titanate thin film improves light trapping in Si solar cells," RSC Adv. 5, 59881–59886 (2015).

16. C. Kieninger, C. Füllner, H. Zwickel, J. Kutsvantava, J. N. Kemal, C. Eschenbaun, D. L. Elder, L. R. Dalton, W. Freude, S. Randel, and C. Koos, "Silicon-organic hybrid (SOH) Mach-zehnder modulators for 100 Gbd PAM4 signaling with Sub-1 db phase-shifter loss," Opt. Express 28, 24693–24707 (2020).

17. P. I. Dietrich, M. Blaicher, J. Reuter, M. Billah, T. Hoose, A. Hofmann, C. Caer, R. Dangel, B. Offrein, U. Troppenz, M. Moehrle, W. Freude, and C. Koos, "In situ 3D nanoimprint of free-form coupling elements for hybrid photonic integration," Nat. Photon. 12, 241–247 (2018).

18. M. Billah, M. Blaicher, T. Hoose, P. I. Dietrich, P. Marin-Palomo, N. Lindenmann, A. Nesic, A. Hofmann, U. Troppenz, M. Moehrle, S. Randel, W. Freude, and C. Koos, "Hybrid integration of silicon photonic circuits and InP lasers by photonic wire bonding," Optica 5, 876–883 (2018).

19. M. Blaicher, M. R. Billah, J. Kemal, T. Hoose, P. Marin-Palomo, A. Hofmann, Y. Kutsvantava, C. Kieninger, P. I. Dietrich, M. Lauermann, S. Wolf, U. Troppenz, M. Moehrle, F. Merget, S. Skacel, J. Witzens, S. Randel, W. Freude, and C. Koos, "Hybrid multi-chip assembly of optical communication engines by in situ 3D nano-lithography," Light Sci. Appl. 9 (2020).

20. V. A. Shvets, V. N. Kruchinin, and V. A. Gritsenko, "Dispersion of the refractive index in high-k dielectrics," Opt. Spectrosc. 123, 728–732 (2017).

21. M. Wöhrlecke, V. Marrello, and A. Onton, "Refractive index of BaTiO3 and SrTiO3 films," J. Appl. Phys. 48, 1748–1750 (1977).

22. S. Gevorgian, Ferroelectric in Microwave Devices, Circuits and Systems (Springer, 2009).

23. A. Davidson, K. Jones, and E. Strid, "LRM and LRRM calibrations with automatic determination of lead inductance," in 36th ARFTG Conference Digest. (1990), Vol. 18.

24. E. Lourandakis, On-Wafer Microwave Measurements and de-Embedding (Artech House, 2016).

25. G. E. Ponchak and A. N. Downey, "Characterization of thin film microstrip lines on polyimide," IEEE Trans. Components Packag. Manuf. Technol. Part B 21, 171–176 (1998).