Short hybrid polymer/sol-gel silica waveguide switches with high in-device electro-optic coefficient based on photostable chromophore

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The highest electro-optic (EO) coefficient to date is achieved in short polymeric directional coupler switches based on hybrid EO polymer/sol-gel silica waveguides. Optimized poling conditions in such waveguides give a highest in-device EO coefficient of 160 pm/V at 1550 nm using highly efficient and photostable guest–host EO polymer SEO100. Adiabatic waveguide transitions from the passive sol-gel core to active EO polymer cores surrounding the sol-gel core are shown using EO polymer cores with a coplanar tapered structure. Switching voltages of 8.4 and 10.5 V are achieved for electrodes that are 2.1 and 1.5 mm long, respectively, which are half those of EO switches containing the chromophore AJLS102. [doi:10.1063/1.3662038]

I. INTRODUCTION

Electro-optic (EO) polymer modulators have demonstrated high performance including a large bandwidth of 110 GHz,[1] and a low half-wave voltage (V_π) of 0.65 V at 1550 nm.[2] These results were achieved because of a high in-device EO coefficient of 142 pm/V in Mach–Zehnder (MZ) modulators at 1550 nm, and similar refractive indices of the milliwave and optical waves (e.g., difference of 0.1) of the materials used.[2] Hybrid EO polymer/sol-gel modulators have realized the highest possible in-device poling efficiency (ratio of EO coefficient in a device to maximum EO coefficient experimentally obtained in a single EO polymer film) of ~100% because the electrical conductivity of the sol-gel cladding is two orders of magnitude higher than that of the EO polymer layer.[3] This efficiency has not been easily achieved in all polymeric devices[4] and silicon (Si) slot waveguide structures.[5] A V_π of 1 V at 1550 nm achieved for our hybrid waveguide modulators remained unchanged after they were exposed to air for one month.[3] Moreover, hybrid EO polymer/sol-gel waveguide modulators have a low coupling loss of 0.1 dB with the standard optical fiber SMF-28,[3] and high photostability for optical coupling and waveguiding. Even though the refractive index of the EO polymer core changes by 0.01–0.1 because of photochemical reactions, stable optical transmissions have been achieved using a three-dimensional beam propagation method for hybrid EO polymer/sol-gel silica waveguide modulators.[6] Stable coupling and waveguiding of such hybrid polymeric modulators has been demonstrated for 1200 h in air using an input power of 30 mW.[6] Moreover, the hybrid waveguide approach using simple microstrip metal electrodes has been employed in optical communications designed for high-speed modulation.

Si modulators have been extensively studied for optical interconnections because of the ease with which they integrate with CMOS circuits. A Si MZ modulator has been demonstrated with a 3 dB bandwidth of 12 GHz and a half-wave voltage and length product (V_π L) of 1.3 Vcm (V_π of 2.6 V).[7] Si slot waveguides containing an EO polymer were used as an EO modulator with a relatively short waveguide length, which could find application as optical interconnections in CMOS-compatible electro-optic circuits. Recently, slot waveguides containing both EO polymer

and Si photonic crystals were employed as modulators using slow light waveguides, resulting in a $V_\pi L$ of 0.44 Vmm ($V_\pi = 1.3$ V, $L = 340$ μm).[8] The poling efficiency was improved by increasing the slot width from 75 to 320 nm. An in-device material EO coefficient of 59 pm/V (effective EO coefficient of 735 pm/V in slow light waveguides) was reported with an insertion loss of 23 dB.[8] However, the optical insertion loss of the Si slot/EO polymer waveguide modulators was 10–20 dB higher than that of previous polymeric modulators without a slot waveguide structure.[9,10] The non-metalized slot waveguide had a waveguide loss of 35 dB/cm when a ring resonator modulator was fabricated using doped Si with a resistivity of 0.15 Ωcm.[8] Moreover, the 3 dB bandwidth of the modulator containing the doped Si electrode was much lower than that of polymeric modulators, limiting the speed of EO modulation to the order of megahertz.[10]

It is difficult to efficiently pole thin layers of EO polymers (e.g., 100–200 nm) in Si slot waveguides to obtain high in-device EO coefficients of >60 pm/V due to the significant change of leakage currents as a function of slot width.[8] For high-speed optical communications, it is more important to balance the EO modulator in terms of larger bandwidth, lower optical insertion loss, and lower V_π than those of a CMOS circuit. For this application, obtaining a lower V_π and wider bandwidth are considered to be of high priority. For a traveling-wave phase modulator, the 3 dB bandwidth Δf ignoring electrical conductor loss is approximated as[11]

$$\Delta f = \frac{2c}{\pi |N_0 - N_m| L}, \tag{1}$$

where L is the length of the electrodes and N_m and N_0 are the effective refractive index of the milliwave and optical wave, respectively.

Even though the dispersion of the refractive index of EO polymers is 30 times smaller than those of Si and $LiNbO_3$, the electrical loss of the microstrip electrode would limit bandwidths to no greater than 110 GHz. Because a shorter electrode reduces electrical loss, the bandwidth is increased further,[12] so hybrid EO polymer/sol-gel silica waveguides can be used in high-speed modulators. Directional coupler switches composed of EO polymers demonstrated high linearity when applied to 1×2 and cascaded 1×4 digital optical switches using a photobleaching process.[13,14] Therefore, polymeric directional coupler switches have the advantage of high-speed modulation with high linearity as the coupling length is further reduced. Recently, an EO switch based on a short directional coupler with a hybrid EO polymer/sol-gel silica waveguide structure was demonstrated by using a guest–host EO polymer AJLS102/APC (amorphous polycarbonate).[15] The coupling length was reduced by a factor of five, with a transverse transition from the sol-gel core to the EO polymer cores, compared with that of standard directional couplers. Here, we report a hybrid directional coupler containing a photostable chromophore that exhibits the highest in-device material EO coefficient to date, making it attractive for high-speed optical communication applications.

II. DEVICE ARCHITECHTURE

A schematic diagram of a hybrid EO polymer/ sol-gel silica directional coupler switch is shown in Fig. 1. The coupler, which exhibits transverse transitions,[14] was modified with a tapered overcladding to give better coupling with a standard optical fiber. In the passive regions, the sol-gel overcladding covered the sol-gel silica core at the input and the two EO polymer cores at the output. As we demonstrated in a previous report, coupling lengths of 1.5 and 2.1 mm were used to obtain directional coupling between the two EO polymer cores.[15] In this design, we used the guest-host EO polymer SEO100. This polymer is a composite of polycarbonate doped with 35 wt% of dipolar phenyltetraene chromophore, which is a newly developed highly efficient and photochemically stable nonlinear optical (NLO) chromophore[16] as shown in Fig. 2. The polymer composite of SEO100 has a glass transition temperature (T_g) around 140 °C, and its poled single-layer films exhibited exceptional combination of large EO activity (up to 200 pm/V at 1310 nm), relatively low optical loss and good temporal stability at 85 °C. To reduce the switching voltage, the electrode under each EO polymer core was separated to allow dual driving with polarities opposite to those of the applied modulation voltages (Fig. 3). The input light from a standard optical fiber SMF-28 at 1550 nm was coupled to the sol-gel core with a coupling loss of <1 dB, and waveguided light was adiabatically

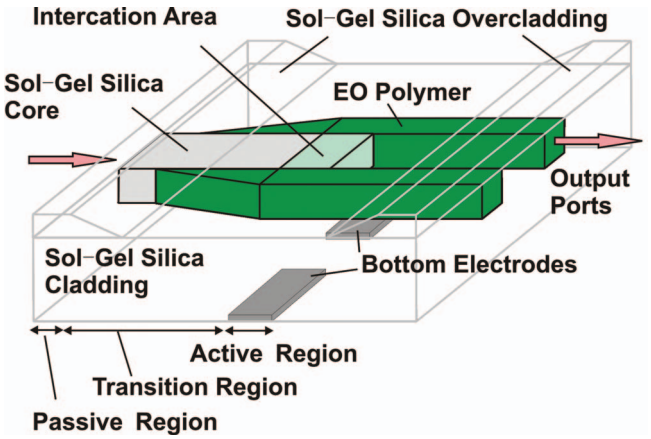

FIG. 1. Schematic diagram of a hybrid EO polymer/sol-gel waveguide directional coupler switch using transverse transitions from the sol-gel core to the EO polymer cores.

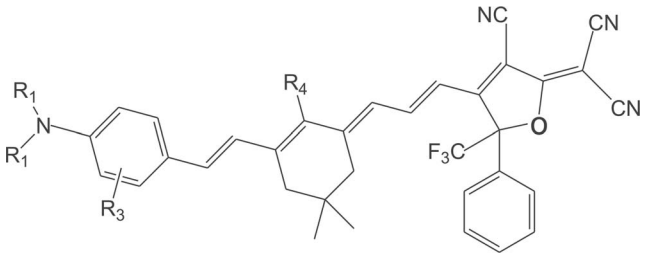

FIG. 2. Molecular structure of dipolar phenyltetraene chromophore for SEO100.

transited into the two EO polymer cores with widths that gradually increased from the passive to the active region.

III. DEVICE FABRICATION PROCESS

The hybrid EO polymer/sol-gel silica waveguide directional coupler was fabricated using the sol-gel process.[3] Methacryloyloxy propyltrimethoxysilane (MAPTMS) doped with an index modifier, zirconium(IV)-*n*-propoxide (ZrPO), was used as the sol-gel solution. Molar ratios of MAPTMS to ZrPO of 95/5 and 85/15 were used for the cladding and core solutions, respectively. A bottom sol-gel layer with a thickness of 3.7 μm was coated on the substrate (100 nm-thick Ti bottom electrode/ 6 μm-thick thermal oxide SiO_2/Si). A sol-gel core with a thickness of 3 μm was coated and wet etched on the bottom layer. A 7 μm-thick sol-gel side cladding was aligned with the core and wet etched to form trenches for the EO polymer, as shown in Fig. 1. The sol-gel waveguide was heated at 150 °C for 1 h to complete the crosslinkage of the sol-gel silica network. A guest–host EO polymer SEO100 (chromophore doping level of 35%) layer with a thickness of 2.7 μm was coated on the sol-gel waveguide and then cured. This layer was poled using a poling voltage of 255 V at 155 °C (Fig. 3(a)), and then the poling electrode was removed using iodine and potassium iodine solution. The directional coupling area between the two EO polymer cores was photobleached using UV radiation (i-line center wavelength 365 nm, 10-11 mW/cm^2) for 2 h through a photomask in a mask aligner to reduce the index by 0.0015 (Fig.3(b)). Theoretical calculations show that a reduced index of the interaction region between the EO polymer cores at the active region optimizes directional coupling for the switching voltage and waveguide loss.[14] A 1.8 μm-thick perfluorinated CYTOP (Asahi Glass) coating was formed on the EO polymer layers as a buffer layer, and then an Au electrode was deposited and patterned on top (Fig. 3(c)). The total electrode distance d, total length L_t, transition length L_{taper}, and active length (electrode length) L_e were 8.3 μm, 10 mm, 3 mm, and

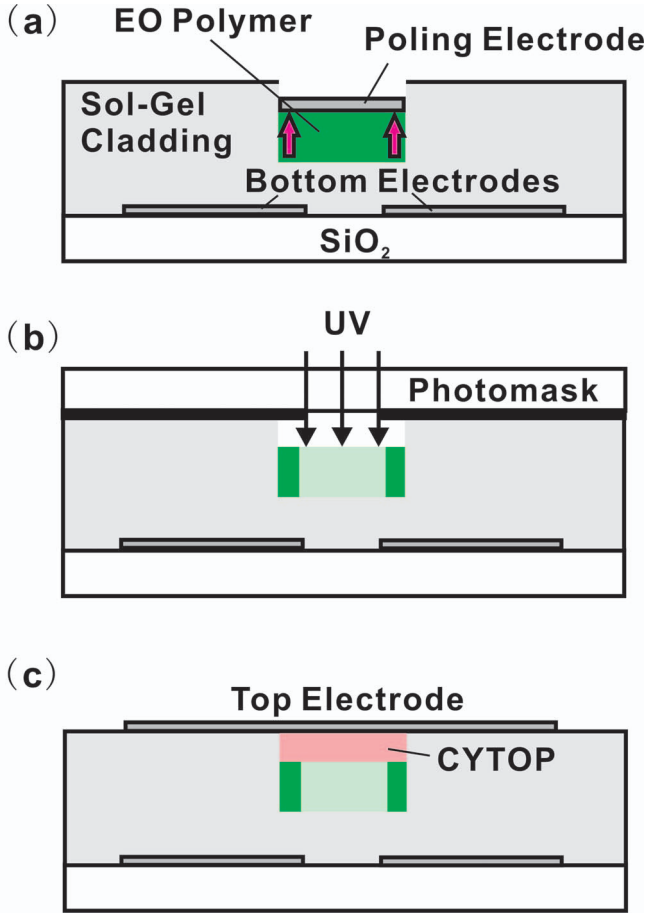

FIG. 3. Cross-sectional view of poling of the EO polymer and photobleaching of the interaction region between the EO polymer cores. (a) Poling using bottom and top electrodes. (b) Photobleaching of the interaction region by UV radiation through a photomask. (c) Fabricated directional coupler.

1.5–2.1 mm, respectively. The refractive indices for the sol-gel core, sol-gel cladding, EO polymer, and buffer CYTOP layer were 1.500, 1.487, 1.705, and 1.328, respectively.

The reduced refractive indices of SEO100 and AJLS102/APC were measured using a prism coupling method, as shown in Fig. 4. The indices for SEO100 and AJLS102/APC were reduced from original values of 1.705 and 1.628 by 1.284×10^{-5}/min and 1.4×10^{-4}/min, respectively. In terms of UV radiation, the modified chromophore in SEO100 has higher photostability than AJLS102 by more than one order of magnitude. Therefore, it is anticipated SEO100 will give higher photostability at 1550 nm for optical throughput and higher stability for driving voltage. The optical output from the directional coupler was calculated using the three-dimensional beam propagation method, as shown in Fig. 5. In these directional coupler switches, the switching voltage (V_s) is defined as the voltage required to change the output power from a minimum to a maximum, which is different from that of ring resonator switches because of the different characteristics of the output power. For a device with r_{33} of 160 pm/V at 1550 nm, an electrode distance d of 8.3 μm, and an overlap integral Γ of 80%, V_s was 10 V.

IV. MEASUREMENT OF SWITCHING VOLTAGE AND OPTICAL LOSS

The output power from the directional coupler was measured to experimentally determine V_s. The output light from the standard fiber SMF-28 was controlled so that it was linearly polarized in the transverse magnetic (TM) mode using a polarization controller and coupled into the sol-gel

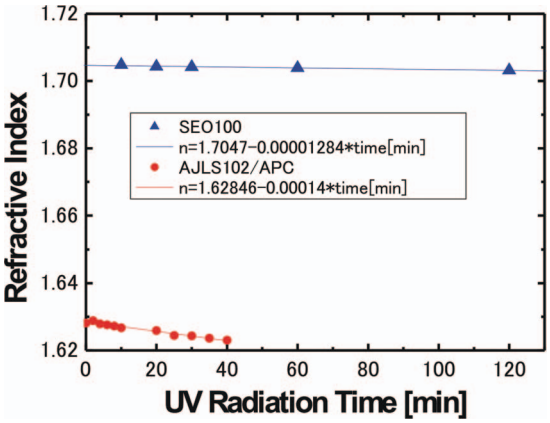

FIG. 4. Change in refractive index of EO polymer doped with SEO100 (closed triangles) and AJLS102/APC (closed circles) *versus* UV radiation time. The UV radiation has an i-line center wavelength of 365 nm and an intensity of 10-11 mW/cm^2.

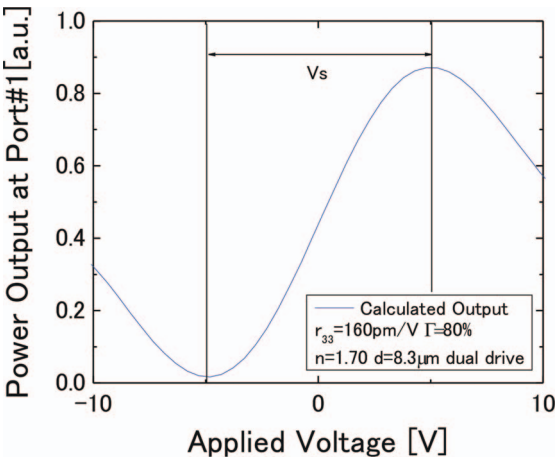

FIG. 5. Calculated optical output power from port 1 using a three-dimensional beam propagation method for the directional coupler switch with dual driving. The device parameters are r_{33} = 160 pm/V, mode overlap integral Γ = 80%, refractive index of the EO polymer = 1.70, and electrode distance = 8.3 μm.

waveguide in the passive region. After light propagated through the directional coupler, the output light from one port was collected using the objective lens of a microscope and focused on a detector. The top electrode was grounded and a driving voltage with opposite polarity was applied to the separated bottom electrodes. The power at the detector was monitored on an oscilloscope with an applied triangular voltage waveform, as shown in Fig. 6. The output power from the directional coupler was modulated with an applied voltage at a frequency of 1 kHz. From the relationship between the applied voltage and output power, V_s of 8.4 and 10.5 V was measured for L_e of 2.1 and 1.5 mm, respectively, with an optical insertion loss of 15 dB (TM mode) at 1550 nm without using an refractive index taper[15] of the EO polymer at the transition region. *Vs* was 19.5 V for the coupler containing AJLS102 with an L_e of 1.5 mm,[15] which indicates that *Vs* was reduced by a factor of 2 compared with SEO100. This is consistent with separately poled EO polymers SEO100 that had EO coefficients that were twice as high as those obtained with AJLS102/APC using the ellipsometric method. In this device, the refractive index taper of the EO polymer was not used by photobleaching because it is a simple process for photostable EO polymers such as SEO100. When the refractive index of the SEO100 is reduced gradually from the active to the passive region (see Fig. 1) in a device submitted to a longer photobleaching time, the insertion loss would be reduced to the range of 10 dB, which was previously demonstrated with AJLS102/APC. The *Vs Le* product was 1.58 Vcm for the device using SEO100. Because the measured *Vs* was similar to the calculated

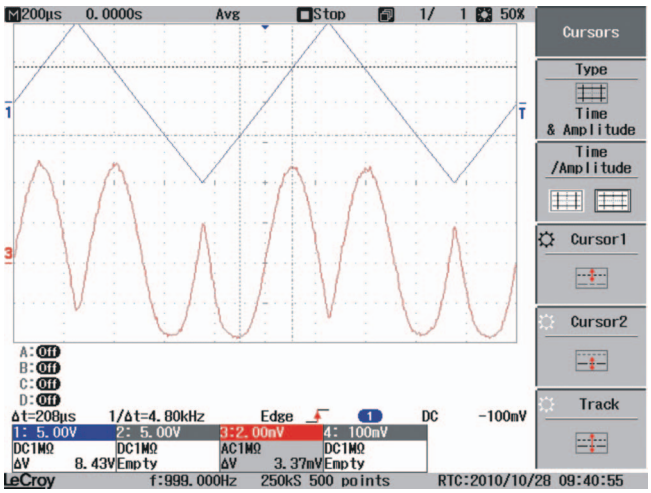

FIG. 6. Measured low-frequency transfer function at 1 kHz for transversely tapered hybrid switches at 1550 nm. $V_s = 8.4$ V ($d = 8.3$ μm, $L_a = 2.1$ mm) for switches containing chromophore in SEO100. Top: Applied triangular voltage waveform. Bottom: Optical output from the switch.

results presented in Fig. 6, the in-device EO coefficient r_{33} was estimated to be 160 pm/V at 1550 nm when Γ was assumed to be 80%.

V. CONCLUSION

In summary, the highest in-device EO coefficient reported to date of 160 pm/V was achieved in a short directional coupler switch having the latest photostable chromophore in SEO100. Such a high EO coefficient and short electrode length will be attractive for use in ultrahigh-speed EO modulators with low switching voltages.

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