APPLIED PHYSICS LETTERS **92**, 163303 (2008)

Nonlinear polymer-clad silicon slot waveguide modulator with a half wave voltage of 0.25 V

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(Received 5 February 2008; accepted 25 March 2008; published online 21 April 2008)

We report on an electro-optic modulator fabricated from a silicon slot waveguide and clad in a nonlinear polymer. In this geometry, the electrodes form parts of the waveguide, and the modulator driving voltage drops across a 120 nm slot. As a result, a half wave voltage of 0.25 V is achieved near 1550 nm. This is one of the lowest values for any modulator obtained to date. As the nonlinear polymers are extremely resistive, our device also has the advantage of drawing almost no current, suggesting this type of modulator could operate at exceedingly low power. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2909656]

One of the most important characteristics of Mach–Zehnder modulators is the half wave voltage or V_π required for operation. V_π is the voltage needed for an interarm phase shift of π radians. Lower values for V_π imply that less power is needed to operate the modulator. Several major approaches toward achieving low V_π modulation have recently been pursued. The free-carrier dispersion effect in silicon waveguides has been used.[1,2] Green *et al.*[3] achieved a V_π of 1.8 V with this effect. Modulators based on lithium niobate are also frequently used. Typical commercially obtained V_π values are 4 V.[4] Recently, Mathine and co-workers have demonstrated a nonlinear polymer based modulator with a V_π of 0.65 V.[5,6]

A unique advantage with nonlinear polymers is that an integrated optical circuit can be conformally coated by a nonlinear polymer. This property, when combined with a slot waveguide,[7,8] enables the construction of a uniquely responsive modulator. We have demonstrated nonlinear polymer based tunable slot ring resonators, achieving the exceptionally large tunability of 5.2 GHz/V.[9] The same slot waveguide design can be used to build a Mach–Zehnder modulator. In this work, we use a push-pull configuration in which each arm has an opposing bias, leading to an opposing phase shift.

A slot waveguide consists of two ridges of high index material, in this case silicon, narrowly separated from each other by a trench. The TE optical mode tends to be highly concentrated in the void region between the two ridges due to the dielectric discontinuity.[7] Figure 1 shows the slot waveguide used for the Mach–Zehnder modulator, with the mode pattern plotted, as well as a scanning electron microscope (SEM) micrograph of a part of a device. The precise dimensions are two 300×100 nm arms separated by a 120 nm slot.

Nonlinear polymers typically have very high resistivity of 10^{11} Ω cm.[10] As a result, the two silicon arms are electrically isolated and can be used as modulator electrodes. The voltage drop between the arms occurs across a 120 nm electrode spacing, as opposed to the 5–10 μm that is typically required for modulators involving a nonlinear polymer and metallic contacts.[6,11] This is a fundamental advantage that slot waveguide geometries have for electro-optic modulation.[12]

It is important to contact the silicon arms with an external electrode throughout the length of the Mach–Zehnder device to minimize parasitic resistances. Ideally, one would use a strip-loaded geometry for this,[1,2] but this would then require a separate lithographic step for the slot definition. Instead, we use a segmented waveguide in which a periodic set of small arms touches both waveguide arms. As reported by Wang *et al.*,[13] a segmentation with a periodicity of 0.3 μm and arm size of 0.1 μm is largely transparent to the optical mode; that design is used in this work.

A Mach–Zehnder modulator can be built with these segmented, slotted waveguides. Because the polymer has a second order nonlinearity, the modulator can be operated in push-pull mode, even with no dc bias, effectively doubling the modulator response. The layout of the modulator is shown in Fig. 2, as well as an SEM micrograph of several sections of the modulator. Devices were fabricated with electron beam lithography and dry etching, as detailed in our previous papers.[9,13] The second order nonlinear polymer, consisting of a highly active chromophore (YLD_124) doped 25% by weight into an inert host polymer (APC, poly-[bisphenol A carbonate-co-4,4′-(3,3,5-trimethylcyclohexyl-

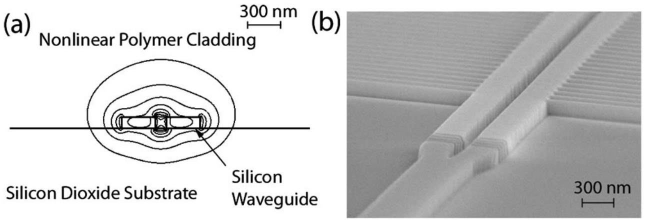

FIG. 1. (a) The diagram of the silicon slot waveguide as used in the Mach–Zehnder modulator described in this work. The modal pattern near 1550 nm is plotted; contours of $|E|$ are shown. (b) SEM micrograph of a slot waveguide, in this case being coupled with to from a ridge waveguide; this mode converter involves tiny gaps which ensure electrical isolation between the two arms. Contacting arms are also present around 3 μm from the ridge/slot junction.

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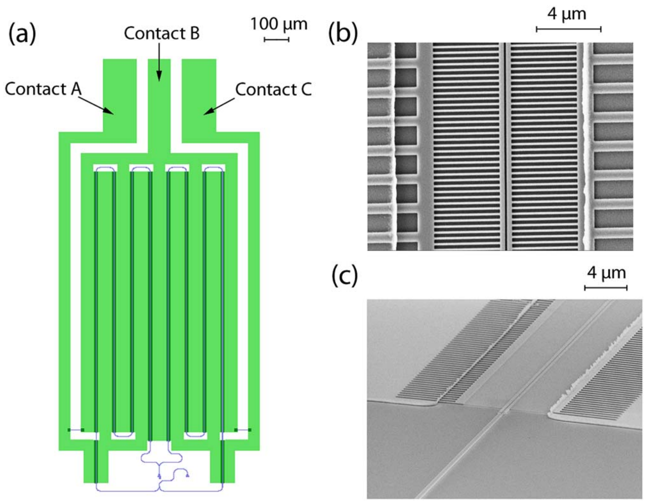

FIG. 2. (Color online) (a) Diagram of the modulator layout. Contacts A, B, and C are shown. Two SEM micrographs [(b) and (c)] show the slotted, segmented region, as well as the location where the silicon makes contact with the electrical layer.

idene) diphenol carbonate]),[9] was used as a coating. Mixing and poling were done in the standard fashion,[14] and a poling field of 150 V/μm was used. Coupling on and off the chip was accomplished via grating couplers,[15] which had a bandwidth of around 40 nm. Total device insertion losses were approximately −40 dB fiber to fiber.

There are three regions in the modulator that are capable of maintaining distinct voltages. During poling operation, contact A is given a voltage of $2V_{\text{pole}}$, contact B a voltage of V_{pole}, and contact C is held at ground. To achieve a poling field of 150 V/μm, V_{pole} was 18 V. This has the effect of symmetrically orienting the polymer in the two Mach–Zehnder arms. During device operation, contact B is driven at the desired voltage, while contacts A and C are both held at ground, leading to asymmetric electric fields in the two arms for a single bias voltage. This is the source of the asymmetric phase response. It is important to note that electrical regions A and C cross the waveguide by means of a slotted ridged waveguide.[16] At the ridge to slot mode converter, a small gap is left that maintains electrical isolation but is optically transparent. This enables the device to be built without requiring any via layers.

A driving voltage from a DC voltage source was applied to contact B, while contacts A and C were held at ground. Figure 3 shows device transmission spectra for various drive voltages. This data is for an unbalanced Mach–Zehnder with arm lengths of 2 and 2.01 cm. This difference in length is the source of the variation in transmission as a function of wavelength with approximately 10 nm periodicity. The more gradual variation is from the grating coupler bandwidth.

Figure 3 is consistent with a V_π voltage somewhere from 0.2 to 0.3 V. At exactly the V_π value, the minima of the spectrum would coincide with the maxima of the 0 V bias spectrum. The slight ripple visible on the various spectra is probably due to back reflections from the grating coupler and scattering noise from the segmented regions. To more accurately measure the V_π value for the device, the drive voltage was varied for a constant laser wavelength at 1574 nm and the transmission observed. The V_π varied from 0.25 to 0.28 V in two examples, possibly due to thermal drift. Figure 4 shows several traces of the transmission plotted against the bias voltage.

The frequency response of the device was also characterized. This was done by using a sinusoidal function generator and a lock-in amplifier on the output of the modulator. The modulator was biased at a $\pi/2$ bias point, corresponding to 3 dB of extinction, by setting the signal wavelength to the appropriate value, and a 0.2 V peak to peak signal was used. The slight variation in the response below 1 kHz is likely due to slight glitches in the lock-in and function generator.

The device does begin to show severe falloff around 1 kHz. This is likely due to *RC* time constant implied by the capacitor formed by the slot waveguide in each Mach–Zehnder arm. Electrical testing with control structures revealed that the resistance of these small silicon regions is much higher than expected; typical resistances across a 400 μm length of ridged, segmented waveguide were well in excess of $10^9\ \Omega$, often so high as to be immeasurable. The capacitance of a 400 μm long slot waveguide is 12 fF, and so an *RC* time constant could easily approach a millisecond. Further fabrication work is expected to remedy this deficiency. In particular, it should be possible to build segmented and slotted waveguides with intrinsic speed limitations of

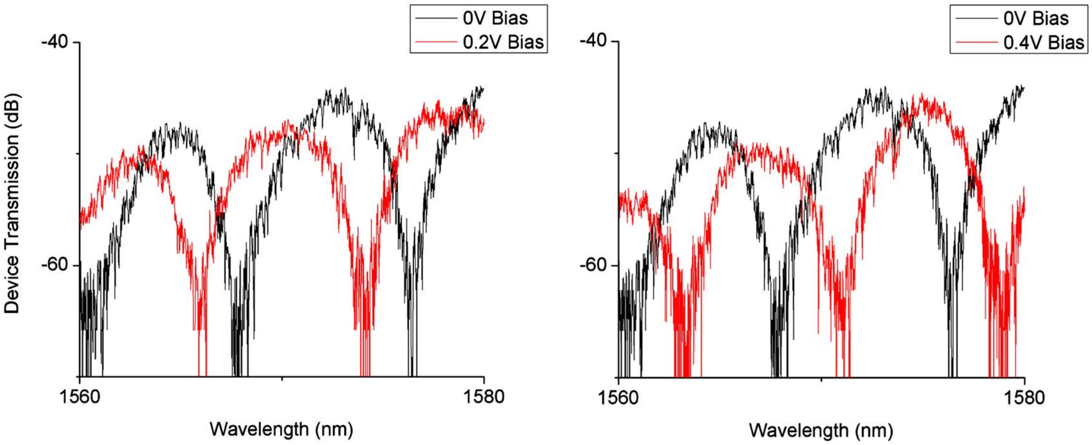

FIG. 3. (Color online) Transmission through the Mach–Zehnder device as a function of wavelength, for various modulator drive voltages. As can be seen, a 0.2 V bias is just short of the V_π voltage, while a 0.4 V bias is substantially past this point.

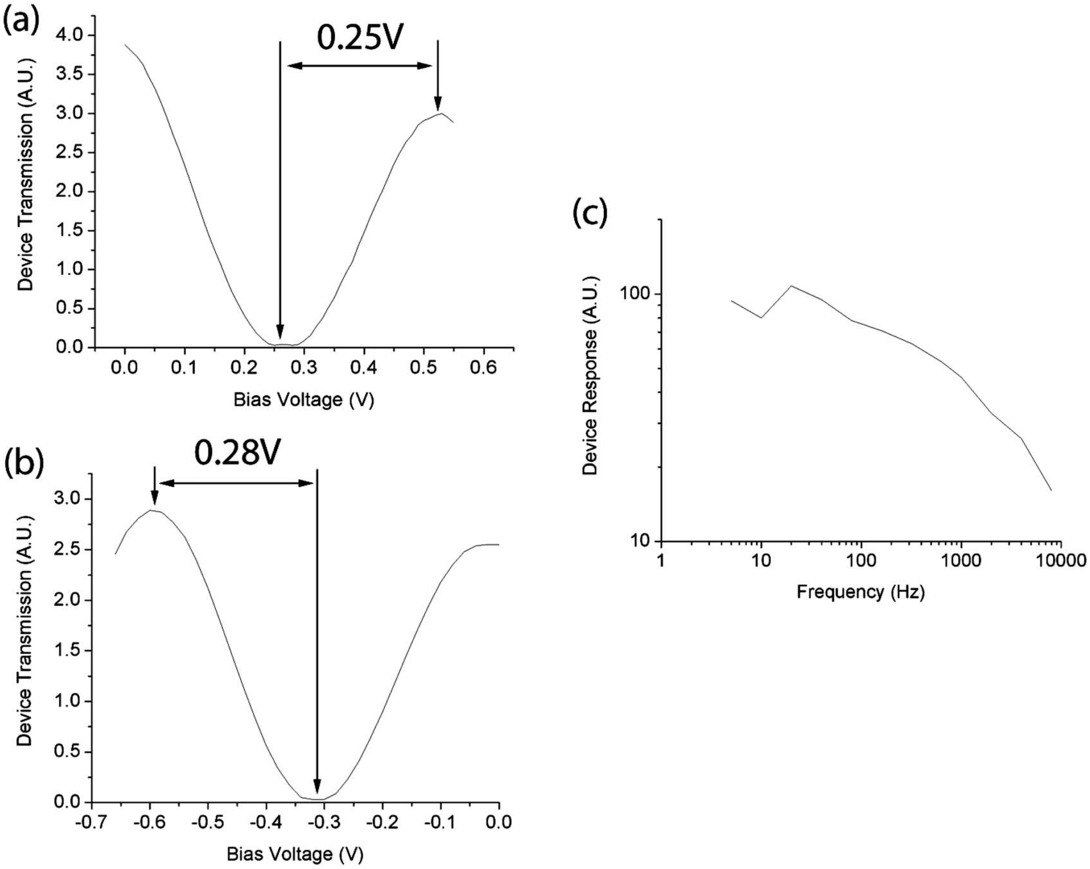

FIG. 4. [(a) and (b)] The transmission through the device as a function of bias voltage. V_π values of 0.25 and 0.28 V are observed. (c) The frequency dependence of the device. There is minimal falloff until around 1 kHz.

70 GHz.[13] Along with the ultrafast response of YLD_124,[9] this should make it possible to build modulators with exceptionally high bandwidth. The $V_\pi L$ figure of merit for this modulator can be calculated as 0.5 V cm. From this, one can calculate the r_{33} value achieved in the polymer[12] to be 30 pm/V. This is lower than the optimal r_{33} of 100 pm/V for YLD_124. It is likely that the polymer in the slot was not fully poled.[6]

The small amount of cross-slot current in the device causes the power consumption to be negligible for steady drive voltage. In future realizations, since the slot waveguide modulator would be constructed on a silicon platform, the driving circuitry could be placed next to the modulator, obviating the need for a transmission line. In this case, an impedance matching resistor would not be needed and a sufficiently short Mach–Zehnder could have exceptionally low power consumption. An r_{33} of only 30 pm/V was obtained for the devices tested. As a result, if the r_{33} values of 170 pm/V that have been demonstrated elsewhere[6] are obtained here, the V_π value should decrease by nearly a factor of 6. All of this suggests that slot waveguide-based nonlinear polymer modulators may prove to be an attractive approach for integrated electro-optic modulators.

The authors would like to acknowledge support from the Air Force Office of Scientific Research Young Investigator Program, under grant FA9550-08-0101, the NSF-sponsored MDITR STC Center, the DARPA EPIC program, and from Tektronix. Fabrication for this project was performed using the facilities at the Cornell Nanoscale Facility.

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