Complementary optical tap fabricated in an electro-optic polymer waveguide

T. E. Van Eck, A. J. Ticknor, R. S. Lytel, and G. F. Lipscomb
Lockheed Palo Alto Research Laboratory, 3251 Hanover Street, O/97-02, B/202, Palo Alto, California 94304

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An active complementary optical tap made in an electro-optic polymer waveguide is reported for the first time. This device is the critical component of an optical railtap, a system capable of providing many optical interconnects with a single laser source. The device was fabricated by selective photobleaching of a uniformly poled polymer layer, and complementary switching was demonstrated.

The increasing density and speed of high-performance integrated circuits are overburdening the capabilities of electrical networks to interconnect them. This is inspiring much interest in optical interconnection networks.[1-5] The development of thin-film organic optical materials[6,7] has added new dimensions to the practical use of integrated optical waveguides for compact, high-performance interconnection networks. These materials allow waveguides and electro-optic waveguide components to be fabricated in layered structures, on a variety of surfaces by procedures familiar within the electronics industry.[8] This development opens up the opportunity to create an evolutionary approach to the utilization of optical technology for interconnecting electrical signals in electronic systems such as wafer scale integrated systems, multichip modules, and circuit boards, in which interconnect lengths are between a millimeter and a meter.

Several approaches to the application of waveguide technology for the realization of optical interconnects for standard electronic products have been proposed,[1,2,9] that generally involve replacing a metallic electrical interconnect with an electrical-to-optical transmitter and optical-to-electrical receiver connected by an optical waveguide. The use of a separate laser diode for each transmitter imposes large costs in terms of power consumption, heat dissipation, real estate, complexity, and reliability. These costs may be reduced if a single laser is used to power many transmitters. We have proposed a system called the optical railtap which uses one laser to power many transmitters.[6] This system uses an optical waveguide "rail" to distribute optical energy to many transmitters (taps), each located within about 1 mm of the electrical pin providing the signal to be transmitted. The transmitters distribute optical signals derived from the electrical signals into a waveguide network routing the signals to receivers, each of which is in turn close to the electrical pin for which the signal is intended. Both the transmitter and receiver have small capacitance by virtue of being located close to the electrical devices that they connect, so the railtap interconnect has a small capacitance regardless of interconnect length or fanout. In contrast, a metallic electrical interconnect has a capacitance proportional to both its length and fanout. Thus for interconnects exceeding a few millimeters in length, the railtap has a much smaller capacitance (higher impedance), so it draws much less electrical current from the signal source. Consequently, the levels of internal heating and noise within the electronic component are reduced, giving designers greater flexibility in specifying high-performance systems. In this letter we demonstrate a novel electro-optic polymer switch which can efficiently perform the function of the transmitter in the optical railtap system.

A tap can be realized in several different configurations, but is fundamentally a type of integrated electro-optic modulator. The basic operation is slightly unconventional, but straightforward. The tap is provided with optical power from the rail and with an electrical signal. Based on the level of the electrical signal, a small optical signal is extracted from the rail and directed to the optical interconnection, i.e., a signal waveguide. Most of the optical power then remains in the rail for use by subsequent taps. To suppress crosstalk of the electrical signal onto the power in the rail, the tap is designed with two complementary outputs, with the optical power always switched into one of the two outputs so that the same fraction of optical power is extracted from the rail regardless of the state of the electrical signal. One of the two outputs may be unused. The function of the railtap could also be achieved with a passive tap followed by a conventional switch, but this would require switching 100% of the light in the tap, and consequently a larger voltage-length product. The railtap has two significant novel properties in contrast to other optical interconnect systems: Many spatially distinct optical signals can be maintained from the energy from a single cw optical source, and, since only a fraction of the available light is modulated by the tap, it is possible to build integrated-optic taps with voltage-length products much less than those for conventional modulators, and with less critical dependence on environmental and operational tolerances. Electrode lengths of order 1 mm using signal levels of 1–5 V are feasible with current-generation electro-optic polymer materials.[10]

Several device designs were considered for a complementary tap, and a very simple design was chosen for the initial demonstration. More complex designs will likely be required to achieve the performance required for practical interconnects, but this structure is an appropriate step in demonstrating and characterizing primary operational behavior. This device, illustrated in Fig. 1, has a single-mode waveguide signal channel disposed on either side of a

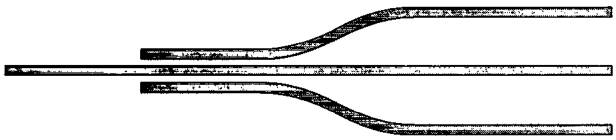

FIG. 1. Complementary tap mask pattern.

single-mode rail. The signal channels run parallel to the rail closely enough for the optical field from the rail to couple to them. Electro-optic modulation of the refractive index in the channels can modulate the coupling of the light from the rail into either or both of the side channels. After a short coupling distance, the signal channels are flared away from the rail to make each optical signal distinct.

Several devices were fabricated using the waveguide structure and processing steps illustrated in Fig. 2. The substrate was a silicon wafer coated with an aluminum ground plane. The polymer waveguiding layers consist of a 2-μm-thick film of the active material sandwiched between 4-μm-thick acrylate cladding layers above and below. A gold layer was evaporated on top. The active material was a side-chain polymer with 4-dimethylamino-4′-nitrostilbene (DANS) as the nonlinear molecule, and was provided by Akzo Research Laboratories.[11] The structure was uniformly poled by applying an electric field of 50 V/μm between the metal layers, while heating to 130 °C, near the glass transition temperature, and cooling back to room temperature.[7,12] The poling partially aligns the nonlinear molecules, inducing both a Pockels effect and a birefringence. Material measurements at a wavelength of 1.3 μm indicate that with these poling conditions, the electro-optic coefficient is $r_{33} = 14$ pm/V and the refractive indices are $n_{TM} = 1.658$ and $n_{TE} = 1.565$.

The channel waveguides were defined by selective photobleaching.[13,14] The gold layer was patterned photolithographically, using a pattern like the one in Fig. 1 as a mask.

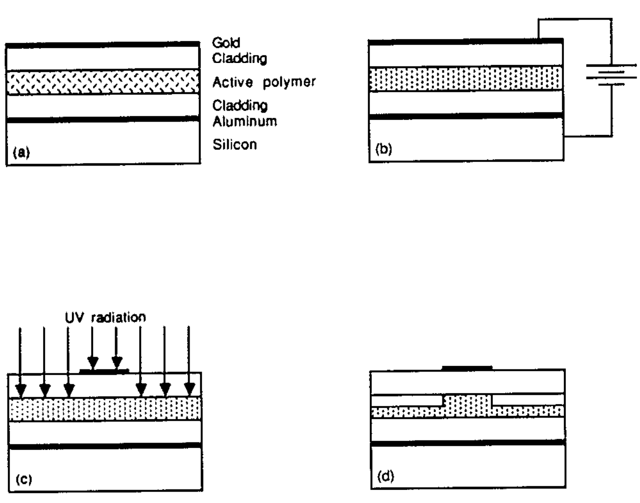

FIG. 2. Device structure and processing steps. (a) Device structure after deposition of waveguiding and metal layers, (b) active molecule alignment by poling, (c) selective photobleaching with a gold mask, (d) final electro-optic channel waveguide.

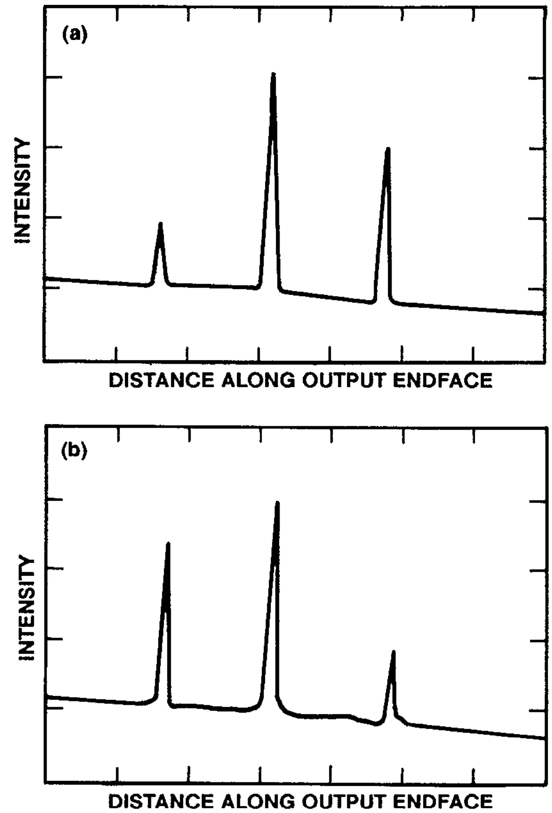

FIG. 3. Complementary switching between taps (arbitrary units). (a) With voltage applied to the left channel, light is switched into the right channel. (b) With voltage applied to the right channel, light is switched into the left channel.

The wafer was exposed to ultraviolet radiation from the mercury lamp of a mask aligner, with a total exposure of 190 J/cm^2. The ultraviolet radiation passes through the cladding layer and is absorbed in the active polymer, altering the DANS molecule and reducing the refractive index of the polymer. The effective index of the bleached material was reduced by $\Delta n_{TM} = -0.008$, so the masked area, with a higher index, acts as a channel waveguide. We have not made loss measurements with these waveguides, but others have measured losses of channel waveguides made with the same material and a similar fabrication process, and report 1 dB/cm loss in unpoled channels, and higher loss in poled channels.[14] The gold lines used to define the channels were also used as drive electrodes. Endfaces were made by cleaving the silicon substrate. Light from a 1.3 μm laser diode polarized for the TM mode was endfire coupled into the input channel waveguide. At the output the light was imaged onto a video camera.

Figure 3 shows the oscilloscope trace of a single video line of the imaged endface of a complementary tap. The center peak represents the light in the rail, and the left and right peaks represent the light in the taps. This device had 5 μm channels and 3 μm gaps and a 1 mm coupling length. With no voltage applied most of the light was coupled into the taps. In order to demonstrate complementary modulation, complementary voltages were applied to the right and left channels of the device. As shown in Fig. 3, applying 200 V to the left channel and 0 V to the right switches light into the right channel, while applying the positive voltage to the right channel switches light into the left. Light in the center channel is the same in both cases, demonstrating that crosstalk will not be passed from one tap to downstream taps. This is the first demonstration of the complementary tapping function that is required for an optical railtap.

The frequency response of a similar device was tested. For this test the voltage was applied to only one channel, the center channel, and the other channels were held at ground. A photodetector was coupled to the output channel. The device showed a response up to at least 100 MHz, and was RC limited by the capacitance of the large contact pads and coaxial cables. The capacitance of the device itself is calculated to be less than 1 pF, implying that switching speeds greater than 1 Gbit/s may be ultimately obtained.

Analysis of this device in terms of two coupled modes qualitatively explains some of the observed behavior.[15] With two propagating coupled modes, the energy can be transferred completely from one mode to the other only if both modes have the same propagation constant; if the propagation constants are different then only partial energy transfer is possible. In the device described here most of the light was coupled into the taps when no voltage was applied, and an applied voltage changed the propagation constant of one channel, making the coupling into the taps incomplete. The operation of this device has been quantitatively modeled fairly accurately using both eigenmode decompositions and a beam propagation method.[10]

The drive voltage and modulation depth used here are much higher than would be used in a practical interconnect system, primarily because we have greatly exaggerated the modulation depth for clarity of the effect. In addition, the materials were poled at very modest levels. The devices were designed for ease of fabrication and testing rather than optimum performance, resulting in a much smaller extinction ratio and larger drive voltage than desired. Continuing refinements in the poling conditions, materials properties, waveguide definition, and switch design are improving the performance of these types of modulators.

In conclusion, we have fabricated an electro-optic polymer waveguide switch by uniform poling and selective photobleaching. The switch taps off a fraction of the optical power into one of two complementary outputs, passing on the rest to additional switches downstream. This type of device is the critical component of an optical railtap, a system which can use a single optical source to drive many optical interconnects.

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