ILLUSTRATION BY JOSEF GAST

integration g

Polymer offers fabrication and economic advantages for photonic integrated circuits.

By Ray Chen,
University of Texas

Photonic integrated circuits (PICs) offer opportunities for economies of production, functionality, and size. Several inorganic materials capable of multiple functions (such as modulation, switching/attenuation, wavelength conversion, and amplification) are under intensive investigation, including lithium niobate ($LiNbO_3$), silicon dioxide (SiO_2) on silicon, and III-V compound semiconductors. A number of obstacles impede the success of further applications using single-crystal materials. Such materials exhibit polarization-dependent loss for many active and passive devices. Sharp and polarized absorption and emission lines result in an amplification bandwidth too narrow to be useful for multiple wavelength systems such as wavelength division multiplexers and bit-parallel multi-wavelength interconnects.[1] Such characteristics also limit their use for optical gain circuits in specific fiber systems unless polarization converters are used.[2] These materials are strictly substrate selective due to the lattice matching required for single-crystal thin-film growth. Finally, the fabrication costs associated with these materials are very high, which seriously jeopardizes the commercialization of the end products.

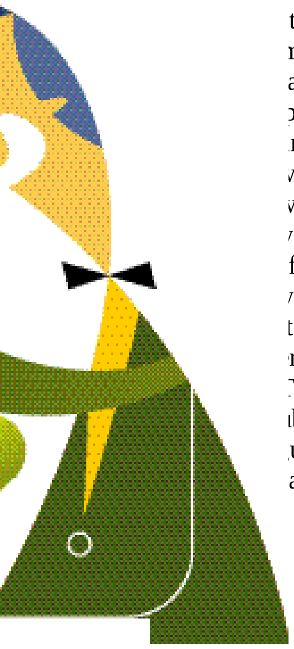
Polymeric materials offer advantages over the aforementioned materials. Polymers are usually in an amorphous state that can provide a wider bandwidth of amplification if an appropriate gain mechanism is identified. The microstructure can be easily engineered to provide desired optical parameters such as bandwidth of transparency, high electro-optic (EO) coefficient values, and temperature stability for specific applications. The thermal-optical (TO) coefficient ($\Delta n/\Delta T$) of polymeric material is more than one order of magnitude larger than that of SiO_2; as a result, a polymer-based thermal optical switch can potentially perform both switching and variable attenuation functions simultaneously. In the case of metropolitan-area-network applications that require arrays of optical switching devices with millisecond switching times, a combined switch and variable optical attenuator is very attractive from the viewpoint of cost and power consumption. Finally, unlike any of the inorganic materials that cannot be transferred to other substrates, the polymeric passive and active devices proposed herein can be easily integrated on any surface of interest.

The major drawback of using polymeric materials for multifunctional PICs is the long-term stability. The EO coefficient of the material is not stable enough to make a reliable EO waveguide device. Further research efforts are needed to solve this problem.

In combination with the demonstrated high-speed modulation capabilities of polymeric devices, the above collection of characteristics makes polymers quite promising for integrated optics applications.[3] A number of research groups, including our group at the University of Texas (Austin, TX), are developing the capabilities of polymer integrated-optic devices.

switching

To demonstrate multifuctionality, we have built discrete polymer-based photonic PICs that can be integrated into a multifunctional device capable of modulation, post-modulation gain control, and switching/variable attenuation with independent addressability (see figure 1 on page 26). Section A of the module performs electrical-to-optical signal conversion (modulation), and section B performs EO or TO switching/attenuation depending upon the system speed requirement. For a network switch, TO technology is sufficient, whereas for a packet switch that demands nanosecond switching times, EO technology is a must.



Our team doped sections A and B with an EO chromophore t can be index-modulated by an applied electric field. tion C is a gain region with rare-earth-ion dopants. The nping beam λ_2 propagates collinearly with the signal beam and then converts into λ_1; for example, in a waveguide ped with neodymium ions (Nd^{+3}), the λ_2 is 790 nm mping wavelength) and λ_1 is 1060 nm (signal and gain velength) while in an erbium-doped waveguide, pump velength is 980 or 1480 nm, and the signal and gain velength is 1550 nm (C-band). The optical waves carrying for optical pumping are provided through two separate veguide arms, introduced via two directional couplers within tion C. Externally pumped, rare-earth-doped solid-state rs provide reliable and efficient optical sources.

The compatibility of polymer thin films with different bstrates of interest provides us with a universal thin-film, uided-wave device module suitable for many different system applications. Harold Fetterman's RF photonics group at the University of California, Los Angeles has demonstrated modulation speeds of more than 100 GHz in polymer devices. Our group has demonstrated TO and EO switches with sub-nanosecond and 1-ms switching times, respectively.

n goes plastic

To explore polymer performance, we designed, fabricated, and tested a 2 × 2 total-internal-reflection (TIR) polymeric switch with an X-junction. A heat-induced refractive-index perturbation creates the total internal reflection effect (TIR) through which the light beam is deflected. The horn structure at the intersection generates a collimated beam to facilitate the TIR effect with a minimum insertion loss. We simulated the performance using the beam-propagation method. We also characterized the device, measuring crosstalk below –28 dB and switching power of about 132 mW, which can be lowered to 20 mW by improving the driving efficiency.

Single-mode polymer-based guided-wave devices offer increased gain over that of bulk devices due to enhanced optical confinement, which is also compatible with optical-fiber communication systems. Intensive research on single-mode, rare-earth-doped fiber lasers and amplifiers in the past few years has led to the development of myriad active devices such as erbium-doped fiber amplifiers for communications around 1550 nm. Currently, there is no equivalent polymer-waveguide-based device, and several groups are working on it.

interconnects

Another pivotal application for PICs is board-level guided-wave optical interconnects in which polymer-based channel-waveguide arrays turn out to be the only way through which guided optical signals can be routed among different substrates. The speed and complexity of integrated circuits (ICs) increases rapidly as technology advances from very-large-scale ICs to ultra-large-scale ICs. Increases in the number of components per chip, chips per board, modulation speed, and degree of integration are forcing designers to confront the limitations of electrical interconnects, which include speed, packaging, fanout, and power dissipation.

Multichip module technology allows designers to provide higher data transfer rates and circuit densities. The use of copper and materials with lower dielectric constants can extend the use of electrical interconnects for the next several years. However, the interconnection roadmap published by International Sematech (Austin, TX) still predicts a major bottleneck by 2006. Optical interconnects will be one of the major alternatives for upgrading speed whenever conventional electrical interconnection fails to provide the required bandwidth.

For board-level optical interconnects, polymer-based channel waveguide arrays can be coated, processed, and then fully embedded with thin-film vertical-cavity surface-emitting lasers (VCSELs) and metal-semiconductor-metal (MSM) photodetectors. Such an approach provides the full compatibility with microelectronic packaging due to the full encapsulation of the optical layer.

Polymer-based material has exclusive advantages for system integration using guided-wave optical interconnection. It can achieve relatively large interconnection distances and can be spin-coated on a myriad of substrates. Various organic polymers

TECHNOLOGIES

Features	Polymer-Based	Glass-Based	GaAs	$LiNbO_3$
Planar Waveguide	Yes	Yes	Yes	Yes
Channel Waveguide	Yes	Yes	Yes	Yes
Electro-optic Modulator	Yes[a]	No[i]	Yes	Yes
Propagation Loss at 1.55 mm (dB/cm)	0.1	0.1	0.2 - 0.5	> 0.1
OEIC Size	Unlimited [b]	Limited [b]	Limited [b]	Limited [b]
Formation of Multiplexed Grating	Yes[c]	Yes	No	No
Implementation on Other Substrates	Easy[e]	Difficult [f]	Difficult [f]	Difficult [f]
Thermo-optical Coefficient (Δn/ΔT, /°C)	$>10^{-4}$	$\sim10^{-5}$	$<10^{-5}$	$\sim10^{-5}$
Waveguide Lens	Yes	Yes	Yes	Yes
Dielectric Constant Dispersion	Low [g]	High	High	High
Potential Modulation Speed	> 100 GHz [h]	N/A[i]	~ 60 GHz	~ 60 GHz
Fabrication Cost	Low	Medium	High	High
Moldability	Yes	No	No	No
Waveguide Amplifier	Yes	Yes	Yes	Yes

[a] Nonlinear polymer with γ33 larger than $LiNbO_3$ and GaAs has been reported.

[b] Polymer can be implemented on any large substrate while GaAs- and $LiNbO_3$-based OEICs are limited by the crystal dimension.

[c] High index modulation of same polymeric material allows us to multiplex hundreds of gratings on the same area for 1-to-many fan-out (useful for high-speed clock signal distribution).

[d] Up to 1250 channels/cm on polymer 500 channels/cm on GaAs and 333 channels/cm on $LiNbO_3$ were reported.

[e] Thin film coating.

[f] By definition GaAs- and $LiNbO_3$-OEICs are thick film devices which are difficult to transfer to other substrates.

[g] Polymer dielectric constant is controlled by electron oscillation which has very small dispersion from microwave to optical wave.

[h] Small dielectric constant dispersion gives very small walk-off between microwave and optical wave.

[i] At present stage, the EO coefficient for glass-based waveguide devices is too small (~1 PM/V) to be practical for such an application.

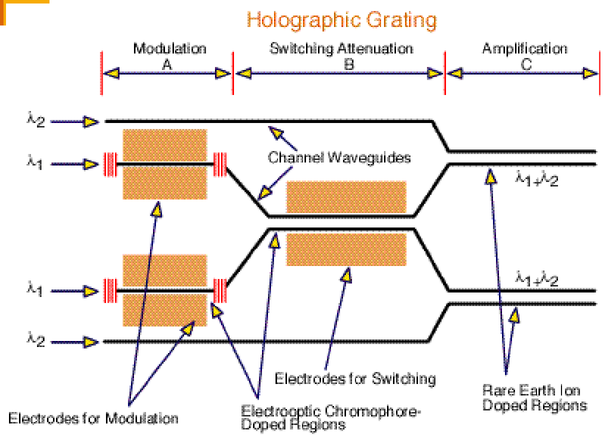


Figure 1 A multifunctional polymer guided-wave module consists of a modulation segment (section A), a switching/attenuation segment (section B), and an amplification segment (section C). λ_1 represents the signal wavelength, and λ_2 represents the pump wavelength.

constitute attractive microelectronic and optoelectronic materials with potential applications as interlayer dielectrics, protective overcoats, α-ray shielding, optical interconnects, or even conductive electrical interconnects. In addition to their ease of processing, polymers possess favorable electrical and mechanical properties such as high resistivity, low dielectric constants, light weight, and flexibility. Microelectronic fabrication temperatures required for wire-bonding and metal-deposition processes impose stringent thermal requirements on polymers. A specialized class of polyimides stands out in this aspect as they exhibit thermal stability to above 300°C with a waveguide propagation loss in the neighborhood of 0.1 to 0.25 dB/cm at 1550 nm.

Two types of waveguide couplers are under investigation for efficiently coupling optical signals from VCSELs to polymer waveguides and then from waveguides to photodetectors: tilted-grating couplers and 45° waveguide coupling mirrors. The surface-normal 1-to-1 coupling scenario in optical waveguides has not been carefully investigated thus far, however. Our group is studying a tilted-grating profile in a planar structure within a thin waveguide layer upon which other lithographically defined electrical interconnection layers can be built. Such a configuration requires the insertion of the optical interconnect layer to be planarized. The tilted grating profile greatly enhances the coupling efficiency in the desired direction.

The grating coupler is intrinsically narrow-band due to the stringent phase matching condition. The 45° coupling mirrors can eliminate such a requirement and offer a high efficiency coupling with an ultra-large bandwidth coverage more suitable for the application described herein. The input coupling efficiency of a micromirror coupler is greater than 90% when a profile-matched VCSEL is used. The output coupling efficiency is almost 100% due to the termination of the waveguiding path. We have built a linear channel waveguide array featuring 12 parallel channels with core dimensions of 50 × 10 μm^2, made with two oppositely faced 45° TIR waveguide couplers. Channel-to-channel separation is 250 mm to ensure compatibility with fiber arrays. Note that the bottom cladding of the waveguide is a low index polyimide. Therefore, such a waveguiding layer can be transferred to any substrate of interest.

Our group has also developed a thin-film silicon MSM photodetector that can be directly integrated into the polymer system architecture described above. Built with 10-μm-thick Si film, the photodetector incorporates an electrode pattern with 2-μm fine lines. The spacing between fingers and the finger width are all 2 μm, yielding a relative photosensitive area of 50%. The device is compatible with high-speed operation because the thin film ensures that the photo-generated electron-hole pairs are only created in the high field region. In addition, the rough back surface scatters the light and traps it inside the thin film to compensate for otherwise low quantum efficiency.

The experimental results conclude that the adjacent MSM interfaces are two Schottky barriers, which serve as two back-to-back diodes. When a bias is applied across the fingers, one junction becomes reverse biased, while the other one becomes forward biased. Electron-hole pairs are photo-generated within the bulk region of the device when it is illuminated with the beam from an 850-nm VCSEL. The application of a bias to the metallic fingers creates an electric field within the underlying semiconductor that acts to sweep the photo-generated carriers out of the device. We measured the device bandwidth using a pulsed laser operating at 850 nm. The electrical signal was picked out by a high-speed probe and fed into a spectrum analyzer to achieve a 5-GHz bandwidth.

Polymer materials offer advantages in the manufacture of multifunctional PICs. Although loss and performance have been issues of concern in the past, current device performance demonstrates that we are moving beyond those limitations. The polymer-based microstructure can be easily engineered to provide specified optical parameters for specific applications. Finally, unlike any of the inorganic materials that cannot be transferred to other substrates, the polymeric passive and active devices reported herein can be easily integrated on any surface of interest. With improvements to the stability of the EO coefficient, polymer PICs will become a valuable tool for photonic engineers. **oe**

SPIE Fellow Ray Chen is a Temple Foundation Endowed Professor at the Microelectronics Research Center of the Electrical and Computer Engineering Department of the University of Texas, Austin, TX. Phone: 512-471-7035; fax: 512-471-8575; e-mail: chen@ece.utexas.edu.

References

1. R. Chen, Optics and Laser Technology, Vol. 25, pp. 347-365 (1993).
2. J. Yang, Q. Zhou, et al., "Polyimide-waveguide-based thermal optical switch using total-internal-reflection effect," Appl. Phys. Lett., November, 2002.
3. R. Chen, Proceedings of IEEE, Vol.88, pp.780-793(2000).