To optimize the cost effectiveness of fiber-optic components, manufacturers would like to integrate all optical functions on a single chip. Unfortunately, system developers have been unable to find a single materials system that can achieve the wide range of functions and high-performance expectations required. Changing the approach to choose the most appropriate material for each function and also to develop an integration-friendly platform for mass production offers manufacturers a different method to achieve high performance at the lowest possible cost.

Polymer is the ideal choice for such an integration platform. This low-cost material is easily manipulated by methods such as embossing, stamping, sawing, wet etching, and dry etching; plus it has a low-cost room-temperature fabrication process. There is some skepticism in the photonic-engineering community regarding polymers, much of it justified by the spotty track record of polymeric components for optical and electro-optical applications. Certainly an infinite number of polymer compositions and formulations can be developed that exhibit a few interesting optical characteristics, but synthesizing a material that meets all performance and reliability requirements for optical networking applications is a precise and demanding discipline mastered by few.

**Low loss performance**
Detractors of polymers often categorize the material as high loss, but that is no longer the case. The waveguide propagation loss of state-of-the-art polymers can be slightly lower than that of silica, and the birefringence is smaller than that of silica by two orders of magnitude. Thermal actuation is power-efficient, as the thermo-optic coefficient $dn/dT$ is 10 to 40 times larger than in silica. High-tech optical polymers are particularly attractive for integrated optics because they involve rapid processing, are cost-effective, and offer high yields. Polymers that do not degrade can be made at elevated temperatures; moreover, the large refractive index contrast offered by the material translates into compact components.

Classes of polymers used in integrated optics include acrylates, polyimides, polycarbonates, and olefins (e.g., cyclobutene). Some polymers, such as most polyimides and polycarbonates, are not photosensitive and are typically processed using photore sist patterning and reactive ion etching. Other polymers can be made photosensitive and as such can be directly photopatterned and wet-etched with a solvent, speeding the fabrication cycle time to tens of minutes per multi-layer optical circuit on a wafer. These materials have an obvious throughput advantage in production.

Optical polymers can be highly transparent, with absorption loss values below 0.1 dB/cm at all the key communication wavelengths (840 nm, 1310 nm, and 1550 nm). Scattering loss can be minimized in polymer waveguides by using direct photopatterning. The minimal roughness produced by this method can be further minimized by the use of a graded index design, which is easily accomplished in direct polymer lithography via interlayer diffusion. The graded index profile results in weak confinement of the optical mode, causing the evanescent tails to penetrate well
into the cladding, which averages out the effect of variations. Unlike planar silica structures, polymer structures can be designed to form stress-free layers regardless of the substrate composition, and these films can be essentially free of stress-induced scattering loss and polarization dependence. These favorable characteristics become apparent above the glass transition temperature \(T_g\) in cross-linked polymer systems.

It is possible to reduce radiation loss using standard integrated optics design rules such as large radii of curvature and adiabatic modal transitions. Designers can minimize fiber pigtail loss by optimizing the alignment of the waveguides to the fiber, by controlling the Fresnel reflections using appropriate index-matching materials at the interfaces, and by matching the mode of the planar waveguide to that of the fiber by tuning the index contrast, index profile, and core dimensions. The total insertion loss in planar polymer components can closely approach the value of the material absorption loss when fabrication techniques are optimized.

Polarization-dependent loss (PDL = loss\(_{TE}\) - loss\(_{TM}\)) varies with processing conditions. The TE loss measured in planar waveguides can be higher than the TM loss when the vertical walls of the core have a higher degree of roughness than the horizontal boundaries, and it can be lower when the vertical evanescent tails overlap with an absorptive substrate or superstrate. Waveguides that are optimized by having minimal edge roughness and a well-confining material stack can have PDL values that are immeasurably small. Birefringence \((n_{TE} - n_{TM})\) can be extremely low in polymers that undergo little molecular orientation during processing, as is common in three-dimensionally cross-linked polymers.

### a question of temperature

The optical and mechanical characteristics of most polymers are not stable enough for operation in communication environments, where temperature and humidity vary. Organic materials may yellow upon thermal aging due to oxidation. The presence of hydrogen in a polymer allows the formation of \(H\)-halogen elimination products, resulting in carbon double bonds that can oxidize. Fortunately, the absorbing species from thermal decomposition are centered near the blue region of the spectrum. Thermal stability can be high at the datacom wavelength of 840 nm and even greater at the telecom wavelengths of 1300 and 1550 nm.

The resistance of polymers to water incursion is critical since water is highly absorptive at telecom wavelengths. Manufacturers have developed polymers that stand up to conditions of 85°C and 85% relative humidity, and some polymers passed the Telcordia 1209 and 1221 environmental tests. Polymers, in fact, have become so reliable that they are no longer the limiting factor in component lifetime. Accelerated aging tests performed on our polymers show no degradation when baked at 200°C for 2000 hours, and transmission increases as fabrication stresses relax.

![Figure 1: Optical transmission values in pigtailed, 10-cm single-mode waveguides show no degradation when baked at 200°C for 2000 hours, and transmission increases as fabrication stresses relax.](image)

### identifying devices

Most of the work going on globally in integrated polymer components is in the areas of switches, attenuators, filters, modulators, lasers, and amplifiers. Here is a sampling.

#### Switches

Thermo-optic \(N \times N\) switches can be interferometric switches based on directional couplers or Mach-Zehnder interferometers (MZIs), or they can be digital optical switches (DOSs) based on X junctions or Y junctions. The most widely used switch design is the Y-junction-based DOS because of its simplicity and its digital behavior. The small \(dn/dT\) of silica is not compatible with DOS-based \(16 \times 16\) switches, so planar \(16 \times 16\) switches to date have been based on MZIs, which use less power but do not exhibit digital behavior. The first DOS-based \(16 \times 16\) switch was produced in polymer. This switching matrix consists of 480 \(1 \times 2\) with small radii of curvature. Polymers also allow simple high-speed fabrication of 3-D circuits with vertical couplers, needed with high-index-contrast waveguides where 2-D circuits would require dimensional control, resolution, and aspect ratios that are beyond the levels achievable with today’s technologies.

Furthermore, the unique mechanical properties of polymers allow them to be processed by unconventional forming techniques such as molding, casting, stamping, and embossing, which permit rapid, low-cost shaping for both waveguide formation and material removal for grafting of elements such as active films, Faraday rotators, or half-wave plates.

The production of commercially viable polymeric optical components is a complex task. A viable telecom polymer...
switches, interlinked with 704 S-bends that intersect at 227 locations to provide a strictly nonblocking connectivity.

The final $16 \times 16$ switch matrix measures $4 \text{ cm} \times 10.4 \text{ cm}$. All 256 switching states can be addressed independently at the same drive power. Each path is defined by heating eight heaters, so 128 heaters are continuously being used. Because the crosstalk is not limited by the switches, an extinction of 15 dB per $1 \times 2$ stage already yields sufficient effective extinction due to the concatenation of the eight switching/combining stages. At a power dissipation of 50 mW per D O S, the insertion loss is 6 dB and the extinction is 30 dB, mainly limited by the crosstalk due to crossings in the design. The total electrical power consumption is 6.4 W.

### Tunable Filters

Tunable filters can be based on Bragg gratings. By alternating the refractive index in a waveguide periodically about an average effective refractive index $n$, we create an in-line series of weakly reflecting mirrors (a Bragg grating) of spacing $\Lambda$. The cumulative effect of the mirrors is to maximally reflect wavelengths $\lambda$, equal to $1/N$ multiples of $2n\lambda$, where $N \geq 1$ is an integer indicating the order of the grating period. Gratings in planar polymers can be produced by a variety of techniques such as casting, molding, embossing, e-beam writing, and photochemical processes. The first three techniques produce surface-relief gratings while the last two typically produce bulk index gratings. Photochemical fabrication processes induce an index modulation through two-beam interference. This effect can be achieved through the use of either interference of split laser beams or a phase mask in which two beams corresponding to the $'1'$ and $'1'$ diffracted orders interfere.

The grating is tuned by a heater. The value of $dn/dT$ in the polymers used is $-3.1 \times 10^{-4}/^\circ \text{C}$ (about 30 times larger than in glass), resulting in a tuning rate of $-0.36 \text{ nm}/^\circ \text{C}$. This characteristic permits tuning across the entire erbium C band (1528 to 1565 nm) using a temperature range of about $100^\circ \text{C}$.

### Modulators

Some polymer formulations have been designed to have a large electro-optic coefficient (as large as 200 pm/V, the largest value achieved in any material system). These formulations are typically composed of standard polymers (e.g., polycarbonate) impregnated with specialty chromophores (e.g., CLD-1). They exhibit a large electro-optic effect once subjected to poling, a process in which large electric fields ($\sim 200\text{V/\mu m}$) are applied to the material in order to orient the molecules. However, the effect of the poling process has been disappointing in that the result is not stable with time or with environmental conditions, which limits the applications in which polymer electro-optic modulators can be used. Polymers are therefore not ideal for electro-optic functions, at least not yet. Other materials such as lithium niobate (LiNbO$_3$) are better suited to this application and should be considered as a candidate for hybrid integration onto a polymer optical bench.

### Lasers and Amplifiers

Rare-earth doping is widely used to produce lasers and all-optical amplifiers that are simple, reliable, low-cost, and have a wide gain bandwidth. Although rare-earth doping has been typically used in silica (mostly in fiber and to a lesser degree in planar waveguides), research laboratories have been working to develop stable rare-earth-doped polymer lasers and amplifiers. The main rare-earth ions used are thulium (for devices operating at 1450 to 1510 nm) and erbium (for 1530 to 1570 nm). The main issue with rare-earth-doped polymer lasers and amplifiers has been pumping inefficiencies due to the de-excitation of the excited states caused by the IR absorption in the polymer. The high pump powers required to compensate for this absorption adversely affect the stability of the polymer. The use of low-IR-absorption, high-stability polymers in the future can make this technology viable. Today, these functions are better served with other materials, such as silica and LiNbO$_3$.

Laser dyes, such as Rhodamine B, are highly efficient gain media that can be used in liquids or in solids to form either laser sources with narrow pulse width and wide tuning range or optical amplifiers with high-gain, high-power conversion and broad spectral bandwidth. Laser dyes captured in a solid matrix are easier and safer to handle than their counterparts in liquid form. Dye-doped polymers have better efficiency, beam quality, and optical homogeneity than dye-doped silica. Photostability is one of the main concerns in solid-state dye-doped gain media, in which the high-pump intensity can cause a quick degradation of the dye molecule.

### Polymer Optical Bench

Our team has developed a hybrid passive/active integration platform based on a polymer optical bench. This technology allows the production of subsystems on a chip with enhanced...
performance and reliability. Polymer circuits provide the interconnects; the static routing elements such as couplers, taps, multiplexers, and demultiplexers; and the thermo-optically dynamic elements such as switches, VOAs, and tunable notch filters (see figure 2). Inserting crystal-ion-sliced (CIS) thin films of LiNbO$_3$ into the polymer circuit yields half-wave retardation for polarization-independent operation or polarization-mode splitting, and the films enable electro-optic actuation for modulation.

In the CIS process, implantation of highly energetic (~4 MeV) but light He$^+$ particles into a single-crystal bulk material creates a subsurface damage layer in the crystalline material that is preferentially etched away to yield a very thin slice of material. CIS films are typically 5 to 15 $\mu$m thick and exhibit bulk properties. Films of yttrium iron garnet (YIG) and samarium cobalt magnets can be inserted in polymer to magneto-optically achieve nonreciprocal operation, enabling optical isolation and circulation.

It is also possible to insert indium phosphide (InP) and gallium arsenide (GaAs) laser chips or semiconductor optical amplifier chips to generate or amplify light or convert wavelengths. To perform an insertion, we saw the polymer and the silicon substrate to form grooves, which we can “heal” after insertion of the chips or films by filling the gap with a monomer of the type used in the waveguide circuit and curing it, thus providing a refractive index match.

One demonstration that illustrates the potential of this platform is its use to produce a tunable optical transmitter, consisting of a tunable laser, an isolator, and a modulator. This subsystem on a chip includes an indium phosphide/gallium arsenide phosphide (InP/InGaAsP) laser chip coupled to a thermo-optically tunable planar polymeric filter, which yields a tunable external-cavity laser. An integrated magneto-optic isolator consists of a planar polymer waveguide with inserted YIG thin films for Faraday rotation, LiNbO$_3$ thin films for half-wave retardation, polarizers, and magnets. Additionally, an electro-optic modulator, consisting of a LiNbO$_3$ thin film patterned with a Mach-Zehnder interferometer and grafted into the polymer circuit, can operate with less than 5 V at modulation speeds up to 40 GHz.

Overall, polymeric optical components hold the promise to be the low-cost leader in demanding optical network applications. In addition, polymers have been able to achieve in many areas a performance level unattained in other material systems and well within the demands of long-haul telecommunication applications.

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References