Integrated Optic Devices Based on Nonlinear Optical Polymers

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Abstract—**In the field of integrated optics, nonlinear optical polymeric materials are relative newcomers compared to $LiNbO_3$ and III–V materials. In this paper, we will take a closer look at the state of the art of these polymers, in view of their potential advantages. We will show that these organic materials have many attractive features compared to $LiNbO_3$ and III–V semiconductors with regard to their use in integrated optic circuits, especially since the level of integration is ever increasing. Considering more specifically electro-optic devices, we will describe some of the theoretical backgrounds and basic properties. These polymers have already demonstrated a very high and extremely fast electro-optic effect compared to $LiNbO_3$. We will also show how low-loss waveguides can be fabricated by using easy techniques such as direct UV bleaching. The performance of phase modulators, Mach-Zehnder interferometers, and 2 × 2 space switches built with such polymers is already very promising. The results described in this paper indicate a rapid rate of progress made by this technology, and one can expect that polymers in general and NLO polymers in particular will play an increasingly important role in integrated optics.**

I. Introduction

THE level of integration of integrated optic components has increased continuously over the years. Circuits containing light sources, waveguides, and detectors have been successfully demonstrated. Contrary to the situation in electronic integrated circuits, where silicon technology completely dominates the field, a multitude of materials is currently used in the fabrication of optoelectronic IC's. While III–V semiconductors allow one to integrate all active and passive components, $LiNbO_3$ is still the preferred substrate if one only needs the electro-optic effect, and both glass and silicon are used for purely passive devices. Compared to those inorganic materials, the organic polymers are relative newcomers in the field of integrated optics. In view of their potential advantages and of the rapid advances that have been made in this field, it is certainly worthwhile to take a closer look at the state of the art of this technology.

Flexibility is probably the key reason for developing polymers for photonic applications. Flexibility in molecular engineering allows chemists to come up with polymers that have properties specifically optimized for applications such as waveguiding or electro-optic effects or harmonic generation [1]–[5]. There is flexibility also in the sense that polymers are basically used as spun-on layers that are readily compatible with many substrate materials ranging from silicon to InP.

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Since it is impossible to review all photonic applications of polymers in a single paper, we will limit the scope of this paper to the use of polymeric materials with high second-order nonlinear effects for applications in integrated optic circuits. For other applications using third-order nonlinearities, needed for frequency tripling, all optical switching, and four wave mixing, we only give some references dealing with the characterization and applications (nonexhaustive) [2], [6]–[15].

II. Material Requirements for Integrated Optics

In order to be successfully applied in integrated optics, a material must satisfy many criteria: high transparency; easy processing; accurate waveguide definition; high physical, chemical, mechanical, electrical, and thermal stability; compatibility with other materials used in microelectronics and fiber technology; high electro-optic coefficients; high optical power damage threshold for active waveguide devices; and reasonably low cost. Today no material scores very high on all these criteria, but polymers can be perhaps the first to combine most of these properties, avoiding stringent tradeoffs [6].

Improved insight into the molecular behavior of polymers [4], [16]–[20] has resulted in the synthesis of many new organic materials useful for integrated optics [21]–[25]. Polymers with electro-optic coefficients higher than those of $LiNbO_3$ have already been demonstrated. Most of these measurements, however, were carried out on bulk material or in solution and only a few on multilayers [26]–[28]. For a broad overview of the more chemically oriented research, we refer to [29] and [30].

In polymers, the electro-optic effect is related to a displacement of electrons and not of ions [31], so that a subpicosecond response time can be obtained [1]. A low dielectric constant and high resistivity lower the capacitive losses [28]. Both absorption and scattering losses in waveguides are also expected to be very low [1], and the low refractive index and small refractive index differences allow low coupling losses to optical fibers. Finally, there is almost no restriction on the kind of substrate on which the polymer films can be spun, so large surfaces can be processed at low cost [2].

A possible way to classify the wide variety of organic nonlinear materials is according to the way thin films are deposited [2], [3], [26], [27], [32], [33]. The thin films can be formed either by organic single crystal growth [34], [35], Langmuir–Blodgett thin film growth [36], plasma polymerization [37], [38], evaporation, or sputtering [39], [40]. Most of the films for integrated optic circuits, however, are deposited by spin coating or dipping a liquid solution of the material. But even then, one can distinguish polyimides [41], polymeric guest–host

systems (highly nonlinear molecules are dissolved in a polymer matrix [42]), polymers with main chain active groups or side chain active groups, liquid crystalline polymers, and cross-linked polymer systems [28], [32]. The way of hardening the film is tightly related to the specific kind of polymer. In the remainder of this paper, we will concentrate on spin-coated layers of polymers for electro-optic integrated optic circuits.

III. Processing of Organic Materials

Comparing nonlinear optical polymers to their main competitor—$LiNbO_3$—one can point out the following advantages for the polymers [43].

- They are easily processed so that the films can be applied by spin coating or dip coating on large surfaces. Standard photolithography, wet etching, dry etching, and metallization processes can be used, and these make the polymer processing compatible with the fabrication and processing techniques of semiconductor materials and devices.
- All processing steps for the deposition and patterning of polymeric layers are low-temperature processing steps.
- The easy processing and compatibility with semiconductor materials means that the polymers can be combined with GaAs or InP OEIC's.

Two problems currently associated with the use of polymers should also be mentioned.

- The short- and long-term stability of polymers especially with regard to temperature should be improved. One can expect that changes in the molecular structure or cross linking of the polymers will enable a stable performance over the normal temperature ranges [43].
- Due to the variety and specific nature of polymers made by different laboratories, standard processing techniques are not yet established. This currently slows the development of polymer processing technology.

IV. Electro-Optic Effect in Polymers

The origin and the behavior of the electro-optic effect in polymers, together with the most important parameters, can easily be described by some semiclassical formulas [4], [31], [33], [42], [44], [45]. The induced molecular dipole moment in the presence of a local electric field (F) can be written as follows (implicit summation convention):

$$\mu_i^{\text{ind}} = \alpha_{ij}F_j + \beta_{ijk}F_jF_k + \gamma_{ijkl}F_jF_kF_l + \cdots .$$

In this equation, α represents the linear polarizability tensor, and β and γ are the higher order hyperpolarizability tensors. From tensor-symmetry relationships, it is clear that only molecules with no center of symmetry can show second-order nonlinearities. At macroscopic level, the induced electric polarization can be expressed in the same way:

$$P_i^{\text{ind}} = \epsilon_0(\chi_{ij}^{(1)}E_j + \chi_{ijk}^{(2)}E_jE_k + \chi_{ijkl}^{(3)}E_jE_kE_l + \cdots)$$

where $\chi^{(1)}$, $\chi^{(2)}$, and $\chi^{(3)}$ are the linear, second-order, and third-order susceptibility tensors. $\chi^{(2)}$ is responsible for the linear electro-optic effect and frequency doubling; E is the applied electric field. When the driving fields approach molecular resonance frequencies, dispersion effects in the hyperpolarizability tensors arise. Therefore, it is often necessary to specify the driving and resultant field frequencies. Because of the high absorption in the range of molecular resonances, most devices will be used in a frequency range far from resonance [4].

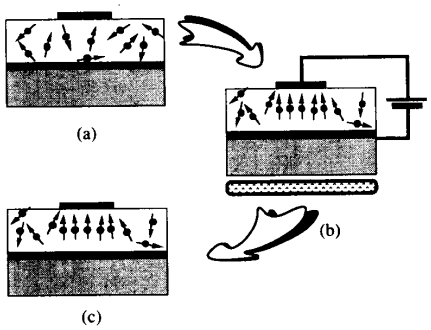

Fig. 1. Schematic view of the poling process. (a) Initially, the dipoles are randomly oriented. (b) When heating the film above the T_g, the dipoles become mobile, and will be aligned by an externally applied electrical field. (c) Cooling down below the T_g, with the field applied, freezes the alignment.

If we consider biaxial materials with the coordinate system chosen along the principal axes, we have the following relationships between the linear electro-optic coefficients r_{ijk}, second harmonic coefficients d_{ijk}, and $\chi^{(2)}$ [22], [46]:

$$\chi_{ijk}^{(2)}(-\omega;\ \omega,\ 0) = -\tfrac{1}{2}\,\epsilon_{ii}(\omega)\,\epsilon_{jj}(\omega)\,r_{ij,k}(-\omega;\ \omega,\ 0)$$

$$\chi_{ijk}^{(2)}(-2\omega;\ \omega,\ 0) = 2\,d_{ijk}(-2\omega;\ \omega,\ 0)$$

where ϵ represents the diagonal relative dielectric permittivity tensor. The change of the ϵ tensor, and hence of the refractive index ellipsoid, is related to the r coefficients by

$$\Delta(\epsilon^{-1})_{ij} = \sum_k r_{ij,k}E_k.$$

Permutation symmetry allows a contracted notation of r_{ijk} into r_{lk} [22]. Macroscopic second-order nonlinear effects are not present if the material has a symmetry inversion center. Unfortunately, most of the organic crystals crystallize in a centrosymmetric way [2], [47], while an amorphous polymer film also shows inversion symmetry at macroscopic level. Ordering can be induced in the film by "poling" [27], [31]. In the poling process, the film, being heated up to its glass transition temperature T_g (the temperature at which the polymer goes from its rigid glassy state into its mobile rubbery state), is brought in a strong electric field [42]. The interaction of the field causes an alignment of the molecular dipoles, which is frozen in by cooling down in the presence of the field below the T_g (Fig. 1). The relation between the macroscopic $\chi^{(2)}$ and the molecular β can, in first approximation, be given by [48]

$$\chi^{(2)} \approx N\beta F\,\langle\cos^3\theta\rangle$$

where N is the density of nonlinear groups, and F is a local field correction factor. The factor $\langle\cos^3\theta\rangle$ represents an average over all the molecules, with θ the angle of the dipole with respect to the electric field, in the assumption that the nonlinear group can be idealized by a "one-dimensional" hyperpolarizable fragment. It is a measure for the degree of polar ordering which is given by μ_0E/ckT in the case of poling (μ_0 is the permanent dipole moment, k the Boltzmann constant, and T the temperature in Kelvin). Depending on the specific type of polymer system, c is a constant between 1 and 5 [28], [45]. The initially isotropic film becomes uniaxial after poling, with the optical axis parallel to the direction of the poling field [(∞mm) sym-

metry class]. The electro-optic tensor has the following form (contracted notation):

$$\begin{bmatrix} 0 & 0 & r_{13} \\ 0 & 0 & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{13} & 0 \\ r_{13} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

V. Waveguide Properties of Nonlinear Optical Polymers

If a nonlinear optical polymer is to be used for an integrated optic modulator or switch, it also needs to satisfy a number of basic properties for waveguiding; these are appropriate confinement in transversal and lateral direction as well as low absorption. In terms of these properties, nonlinear optical polymer waveguides are rather similar to passive polymer waveguides. The first reports on passive waveguides in organic thin films, and comparative results of several materials and techniques, date from the early 1970's [37], [38], [49]–[52]. Losses well below 1 dB/cm (best value: 0.04 dB/cm) have been measured for the fundamental modes in slab waveguides. For nonlinear optical polymer waveguides, similar results have been reported recently, although absorption levels are generally higher than for passive polymers. This is caused by the highly nonlinear organic compounds which are strongly colored and absorb at shorter wavelengths [19].

The transversal confinement in polymeric waveguides is generally obtained by using a stacked multilayer of different polymers or materials such as SiO_2, Si_3N_4, or SiO_xN_y [6] with different refractive index, or by using modified versions of the same polymer. A technological problem can be that subsequent polymeric layers dissolve each other or cause cracks.

To obtain lateral confinement for waveguides in thin films, different techniques exist. The differences are mostly imposed by specific material properties. Standard techniques like dry etching [2], [33] can be used to fabricate standard configurations like rib waveguides, strip waveguides, or inverted rib waveguides. Losses around 6 dB/cm have been reported for inverted rib polymeric waveguides (monomodal operation at 1300 nm) fabricated on top of a GaAs or Si substrate covered by a PECVD SiO_2-layer [6], [53] or below 3 dB/cm using a UV curable epoxy as cladding layers [54]. Other more complex schemes use local ion exchange in low index glass to achieve an inverted strip loaded guide in the polymer [55] and wet processing of polymer gelatin [56], [57], or solvent-assisted indiffusion of nonlinear molecules to obtain graded index guides, with mode profiles compatible with graded index fibers [58], [59]. Losses of a few dB/cm are reported. In all these experiments, it is not always clear to what extent the losses are due to either absorption or scattering.

The most promising and flexible technique for obtaining lateral confinement, however, makes use of chemical transformations induced by UV irradiation. This exposure can increase the refractive index by changes in density due to photopolymerization of residual monomers [60]–[62]. In this way, very low fiber-to-waveguide coupling loss ($\sim$ 1 dB) [63] and a star coupler were demonstrated [64]. Attempts to make this technique suitable for mass production were already demonstrated [65]. Other techniques include direct laser writing [66] photooxidation of polyalkylsilines (decreasing the refractive index) [67], "photolocking" (locking of dopants in a polymermatrix under influence of UV) [49], [68], and diffusion of low molecular weight constituents into local polymerizing regions [69], [70].

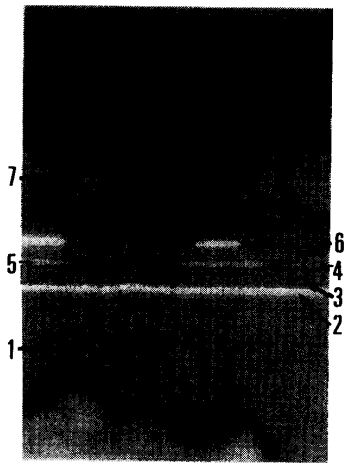

Fig. 2. Microscope picture (with interference contrast) of the polished endface of a polymeric waveguide layer structure. The scale is in μm. (1) glass substrate, (2) the uniform underelectrode, (3) the undercladding layer, (4) the bleached core layer, (5) the waveguide (unbleached), (6) the upper cladding and the Au stripes used for bleaching, and (7) UV curing epoxy.

In the framework of the European RACE 1019 Project (Polymeric Optical Switches), a sidechain polymer furnished by AKZO is used at our laboratory [71]. The structure of the sidechains, highly polarizable DANS molecules, can be changed by UV-exposure allowing a decrease in refractive index [72], [73]. Waveguides are now formed by exposing the polymeric layer through a mask. The result is a completely planar surface, with extremely smooth waveguides and very low scattering losses. This process also allows us to tune devices, fabricated on transparent substrates, after complete fabrication. Using this UV bleaching, waveguides have been fabricated with losses lower than 1 dB/cm at 1.3 μm [71]. A similar technique was reported in [74], with relatively high waveguide losses, however.

Although, in comparison to III–V materials and $LiNbO_3$, the technology for fabricating waveguides in polymers is very new, these results are already quite reasonable. For InP–InGaAsP rib waveguides, typical losses are below 1 dB/cm at $\lambda = 1.5$ μm, but values below 0.2 dB/cm have already been reported [76], [77]. For Ti-diffused waveguides in $LiNbO_3$, losses can still be lower: typical results are around 0.3 dB/cm at $\lambda = 1.3$ μm [78], with best results down to 0.1 dB/cm [79]. The low refractive index of polymers (1.6–1.7) does, in principle, facilitate coupling of light in or out of a waveguide. In practice, however, some extra problems have to be solved since cleaving along crystallographic planes (as in III–V) is not possible. Initially, prism coupling was used to excite the different guided modes in the film [37], [38], [51], but the risk of damaging the layers is very high. The technique is still used [71] because it allows a fast investigation of the propagation constants, and hence the refractive index profile, together with the electro-optic coefficients [80]. Apart from the prism coupling, grating

couplers are also used. The gratings are defined either by holographic exposure of a photoresist followed by dry etching in the cladding [40], [81], or directly in the polymer using the photosensitivity of the polymer [40], [49], [74], [82]–[84]. For device applications, butt coupling at a carefully prepared and polished facet remains the most convenient technique. In Fig. 2, a photograph of an endface of a waveguide is shown. The different polymeric layers and the bleached waveguides can be seen.

VI. Electro-Optic Polymeric Devices

Going from passive waveguides toward active electro-optic devices not only implies the use of electrodes, but will also strongly influence the fabrication scheme of the device. Polymeric devices have an additional degree of freedom here as compared to $LiNbO_3$ or III–V devices. In $LiNbO_3$ devices, electrodes can only be put on top of the device. In III–V devices, the substrate (or epitaxial layers on top of it) can act as an additional electrode. In the case of the polymers, we have the possibility of using patterned electrodes on both sides of the waveguide structure, without any problem. Another advantage is the possibility of defining polymeric waveguide layers on top of finished chips. This allows for easy integration of an active polymeric waveguide with a microelectronics driver circuit or optoelectronic device (laser diode or detector), which in other materials is only possible by special techniques such as selective and/or nonplanar epitaxial growth or ELO (epitaxial lift off) [85], [86]. An example of such an integration is described in [87], where we have demonstrated the monolithic integration of a polymeric channel waveguide with a GaAs–AlGaAs GRINSCH laser diode (Fig. 3). A somewhat different approach, using a slab polyimide-based passive waveguide in combination with a GaInAsP laser, is given in [88]. Such an integration with electro-optic polymers is not only very important for future optical networks, but also opens new possibilities toward extended cavity lasers and tunable laser diodes.

Although the low refractive index of polymers, in comparison to $LiNbO_3$ or III–V, is advantageous for coupling light into optical fibers, it has a strong influence on the electrode-to-waveguide core spacing. This spacing needs to be sufficiently large to avoid absorption of light from the mode tail. This implies, however, that the electric field in the core for a given voltage is relatively low. In this respect, highly conductive but optically transparent polymers would be very useful as a cladding material, but to our knowledge these do not exist at the present moment. To illustrate the influence of the metal electrodes, the structure of Fig. 4 was used to model the modal loss. In Fig. 4, the propagation loss (dB/cm) is shown both for TE and TM polarization as a function of the thickness of the core layer (t, horizontal axis) and of the thickness of the cladding layers (c, vertical axis). Single-moded operation (at $\lambda = 1.3$ μm) is only obtained with a thickness of the core layer left to the dashed line (<1.15 μm). The electrodes are Au ($n_{Au} = 0.408 - j\ 8.305$), and refractive the index contrast between core and cladding layer is 0.1. It is clear that, especially in the case of TM polarizations, thick cladding layers are necessary to lower the propagation loss. Another disadvantage of the low refractive index is that the phase shift induced by an electric field in a waveguide scales with the third power of the refractive index. Therefore, polymers need to have very high electro-optic coefficients to compete in electro-optic efficiency with high index materials. As an example, we compare the phase shift in two identical active devices—made in polymers ($n = 1.6$), and made in $LiNbO_3$ ($n = 2.25$); assuming an identical electro-optic coefficient, length, and field strength, we find that the phase shift in the polymeric device is only 36% of that in $LiNbO_3$.

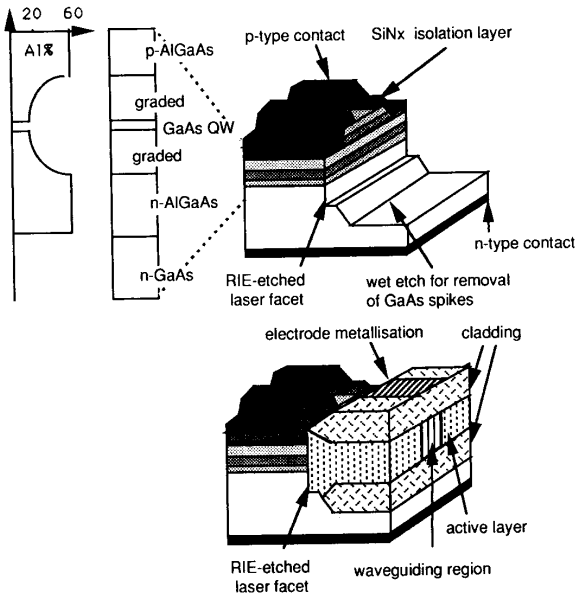

Fig. 3. Schematic view of the structure of the GRINSCH-MQW (Graded Refractive INdex Separate Confinement Heterostructure MultiQuantum Well) laser diode with etched mirror, monolithically integrated with a polymeric stripe waveguide.

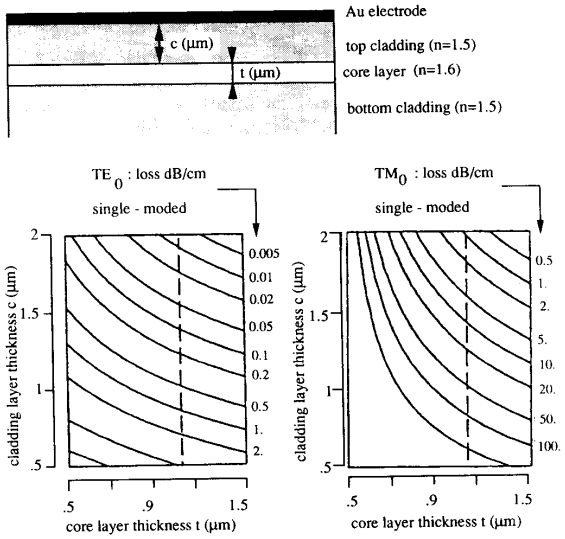

Fig. 4. Calculated loss curves (in dB/cm) for the fundamental modes (TE and TM) propagating in the waveguide, due to the presence of an absorbing Au electrode, as a function of the thickness of the core layer (t) and the cladding layer (c). The refractive index of the core and the cladding are, respectively, 1.6 and 1.5.

In thin films based on dissolved polymers (spin coating or dip coating), the active groups have to be ordered by poling in an

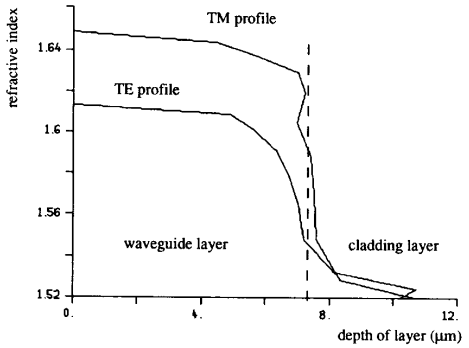

Fig. 5. Measured refractive index profile of a poled polymeric waveguide as a function of the depth of the layer (by means of the IWKB method). The layer shows birefringence.

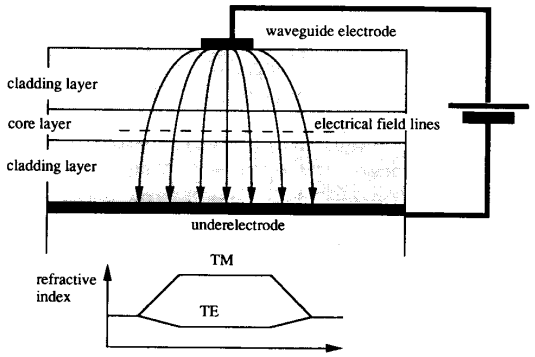

Fig. 6. Fabrication of a poling induced waveguide. By applying a field between a small metallic stripe and the underelectrode during poling, a waveguide is formed that shows lateral confinement for TM modes, but antiguiding for TE modes.

electric field. As a result, the film also becomes birefringent [89]. This effect can be quite large, as is shown in Fig. 5, which gives the refractive index profile both for the TE and the TM mode (measured by prism coupling and calculated with the IWKB method [90]). Poling can take place in two ways: "field poling" or "corona poling." The latter has the advantage that much higher field strengths can be achieved (limited by the breakdown field strength of the gas in which the poling takes place) [91]. The former, however, can easily be carried out using the metal electrodes, already present on the film for electro-optic modulation. If the poling field is applied by means of a metallic stripe over the layer structure (Fig. 6), a waveguide is formed that guides only TM light and shows antiguiding for TE light. In the case that no breakdown occurs under the waveguide, this method is of course the easiest way to define smooth waveguides [89], [92], [93]. The problem of the electrical breakdown, and hence of the local destruction of the device, is the most severe drawback of the field poling process. Very good material quality and fabrication of the devices in clean-room environment can reduce the risk.

In order to be useful for implementation in integrated optics, one must be able to fabricate devices such as guided wave phase and intensity modulators and switches. Monomodal channel waveguiding is required, as these devices are mainly based on modal interference. So far, only very few groups have achieved this goal. The first attempts to fabricate Y-branch Mach–Zehnder interferometers and directional couplers were reported in 1988 [89], [93]. The waveguides were defined by transverse selective poling. The directional coupler consisted of a bimodal waveguide in the coupling region, covered by a uniform switching electrode. Partial modulation and switching was achieved, and r coefficients between 3 and 16 pm/V (depending on the type of polymer) were reported.

A traveling wave phase modulator designed for operating at 270 MHz was made; modulation was seen till 1 GHz, however [94], [95]. Another group, using an inverted rib waveguide and laterally placed electrodes, achieved phase modulation for both TE and TM modes [92]. Drive voltages around 100 V were required for both groups, however. Recently, single-mode Mach–Zehnder modulators have been fabricated, using a polymer with an r_{33} = 38 pm/V. Half-wave voltages of typically 30 V were reported [96].

In the RACE Project 1019, phase modulators, Mach–Zehnder modulators, and directional couplers have been realized with

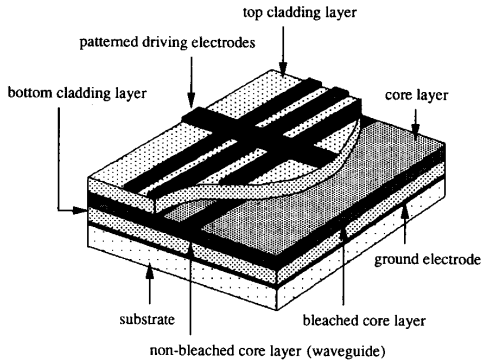

Fig. 7. Schematic drawing of an array of polymeric phase modulators.

very promising characteristics [28], [43], [71], [72], [97]. A schematic view of an array of phase modulators is given in Fig. 7. After evaporation of a uniform Au electrode on the glass substrate, the different layers are desposited by spincoating and covered again by a uniform electrode. The entire multilayer is poled at 170 V/μm at a temperature of 130°C (T_g is 140°C). Then the top electrode is patterned and the monomode waveguides are formed by UV bleaching. Measurements showed an r_{33} value of 34 pm/V at λ = 1.3 μm. The device is 24 mm long, resulting in a dc · V_π of 2 V.

The same technology and processing steps have been used to fabricate Mach–Zehnder interferometers and directional mode couplers. A Mach–Zehnder interferometer with modulation depth in excess of 10 dB for a dc · V_π of 4.4 V over 14 mm long electrodes at λ = 1.3 μm has been fabricated. The resulting r_{33} value is 32 pm/V. On other devices, on–off ratios of more than 20 dB have been measured. Integrated 2 × 2 space switches, based on directional couplers, have also been fabricated (Fig. 8). Processing is comparable to the previously mentioned devices. The switching voltage (from cross to bar state) is only 7.5 V for 14 mm long electrodes, and the best modulation depth is 17 dB (Fig. 9).

Taking into account the very high predicted electro-optic coefficients for future polymeric materials, some studies have been made on the feasibility of waveguide modulators by simply inducing a waveguide with the electro-optic effect [99]. The the-

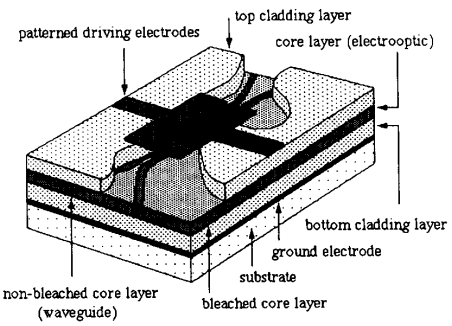

Fig. 8. Schematic drawing of a polymeric directional coupler.

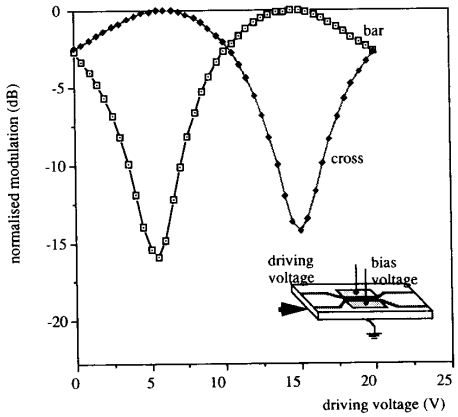

Fig. 9. Normalized modulation characteristic, in decibels, of a waveguide directional coupler for the cross and the bar state as a function of the driving voltage, with a fixed bias over the other driving electrode.

oretical calculations for a directional coupler switch predict very good mode match to optical fibers and on-off ratios down to 26 dB.

Apart from these devices for modulators and switches, nonlinear polymers have many other promising applications such as parametric amplification (in an organic single crystal [100]) and frequency doubling or second harmonic generation (SHG) which is frequently used as a characterization tool (mostly in simple transmission through the film). First results were obtained in guest-host polymer systems (a highly nonlinear molecule dissolved in a polymer matrix) [91], [101], [102], [103] and in polycrystalline organic waveguides [104]. SHG was also studied in main chain polymers [27]. Comparative data for guest-host systems and sidechain polymers are presented in [105]. A key problem in SHG is the phase matching problem of the fundamental and the SHG beam in guided wave applications. In a waveguide configuration, a technique called quasi-phase matched SHG, similar to "periodic domain reversal" in $LiNbO_3$ waveguides [106], was successfully demonstrated in a slab waveguide based on a nonlinear sidechain polymer [107], [108]. In this configuration, the nonlinearity is periodically switched on and off along the waveguide.

One of the main problems with poled polymeric layers is the potential relaxation of the ordering, and therefore, of the electro-optic effect. The aligned nonlinear groups in the guest-host polymers are thermodynamically in nonequilibrium, and will randomize in the polymer matrix. Some studies indeed reported a fast relaxation [109], but others found no significant decay over 1 year [22], [101]. Corona poled films were found to be more stable than field poled films [102]. Today, sidechain polymers are believed to be more stable than guest-host polymers [40], [43], [102], but the poling behavior and the decay of the ordering strongly depend on the parameters used during corona poling [91]. Measurements on a sidechain polymer [108] indicate a decrease in the electro-optic effect to 80% of the original value after 5 years at 70°C. For the polymer used within the RACE 1019 Project, we found a decrease of 20% after 12 h at 100°C, but nearly no decay (within the experimental error) after 100 h at 80° (T_g of the polymer = 140°C). Predictions have been made for the lifetime (50% decay) of this polymer: 2.7 10^5 years at 60°, and 27 years at 80°C [43]. To further increase the thermal stability, cross-linked polymer systems are currently under investigation. By performing the cross linking after poling, the matrix becomes less flexible, thus rendering the relaxation even more difficult [110]-[112].

VII. Conclusions

In this paper, we have shown that polymers have many attractive features with regard to their use in integrated optic circuits. Molecular engineering allows the optimization of the material properties. Spin coating and low temperature processing of polymer layers on many different substrates give a flexibility necessary for complex integration schemes. As a first example, the monolithic integration of a polymer waveguide with a GaAs-AlGaAs laser diode was described.

Considering more specifically electro-optic devices, polymers have demonstrated a very high and extremely fast electro-optic effect compared to $LiNbO_3$. Low-loss waveguides, fabricated by the easy technique of direct UV bleaching, have been used to build phase modulators, Mach-Zehnder interferometers, and 2 × 2 space switches with good performances.

The wide variety of polymers has slowed the development of standard processing techniques and is a continuous challenge in device fabrication. The stability problem of polymers has been a cause for skepticism among many researchers. The latest results are very promising, however, and further improvement can be expected.

It should be emphasized that polymers are newcomers in the field of integrated optics. Looking at the rapid rate of progress made by this technology, one can expect that polymers in general and NLO polymers in particular will play an increasingly important role in integrated optics.

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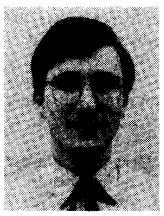

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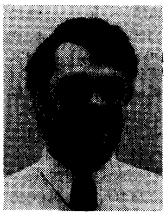

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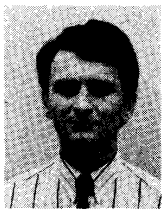
that year, became responsible for the research and processing of devices for optoelectronics, integrated optics, and optical communications at the Laboratory of Electromagnetics and Acoustics, Rijksuniversiteit Gent.



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