Integrated-Optic Polarization Controlling Devices Using Electro-Optic Polymers

Min-Cheol Oh, Wol-Yon Hwang, and Jang-Joo Kim

CONTENTS

I. INTRODUCTION

II. DEVICE CONFIGURATIONS AND OPERATING PRINCIPLES

III. FABRICATION PROCEDURES

IV. DEVICE PERFORMANCE AND DISCUSSIONS

V. CONCLUSION

REFERENCES

ABSTRACT

Integrated-optic polarization controlling devices such as polarizers, polarization splitters, and polarization converters, are proposed and demonstrated in non-linear optic polymers. Poling-induced birefringence in electro-optic polymers is exploited to fabricate the devices. The polymeric waveguide polarizers show low excess losses, and extinction ratios of 20.7 dB and 17.1 dB for TM-pass and TE-pass polarizers, respectively. The polymeric waveguide polarization splitters exhibit TE-TM mode splittings with crosstalk of 14.2 dB and 10.1 dB for TM and TE mode splittings, respectively. The polymeric waveguide polarization converters show successful TE/TM polarization mode conversion with conversion efficiencies of higher than 30 dB. The device employs poling-induced waveguides which have slowly rotating azimuth angle of optic axis along the light propagation direction. The novel polarization converter is insensitive to wavelength and easier to fabricate than the other polarization converters containing periodic structures.

I. INTRODUCTION

Integrated optical waveguide components have been increasingly important in optical signal processings and optical communications. Optical intensity modulators and spatial switches fabricated in $LiNbO_3$, which is the most widely used electro-optic active substrate, have been commercialized and introduced to systems. In recent years, nonlinear optical polymers have been developed for use in polymeric waveguide devices exploiting the electro-optic (EO) properties [1]. Many devices based on EO polymers have been investigated to realize their potential. Because of their excellent velocity matching between microwave and optical signals, high speed optical intensity modulators have been actively investigated and tens of GHz bandwidth have been demonstrated [2]-[4]. It is also possible to integrate the polymeric optical waveguide devices with electronic circuits on a common substrate like Si or GaAs [5]. Moreover, the polymer provides flexibility to realize interesting devices such as a vertically stacked directional coupler [6], a multi-level registered Mach-Zehnder modulator [7], and a focal spot intensity modulator [8].

EO polymer waveguide devices usually consist of the spin-coated three layers; lower cladding, core, and upper cladding. The core layer is a nonlinear medium and has higher refractive index than others. Two electrode layers are located at the bottom and top side of the layers for poling the polymer and modulating the guided-wave. In EO polymers, the electric-field poling at an elevated temperature is an essential process for inducing EO property by breaking the centrosymmetry. The chromophores of EO polymers are aligned along the poling field direction, and the polymer becomes highly birefringent medium. After the poling process, the refractive index of the EO polymer increases for the light polarized along the poling direction, while it decreases for the light polarized perpendicular to the poling direction. Thus, the poling process can be utilized to fabricate channel waveguides supporting single polarization component of either TE or TM modes [9]. The channel waveguides induced by the poling process were designed by using the vectorial beam propagation method which is applicable for the anisotropic media [10]. It was shown that the waveguides induced by the poling have graded index profiles and supports well confined guided mode with single polarization component.

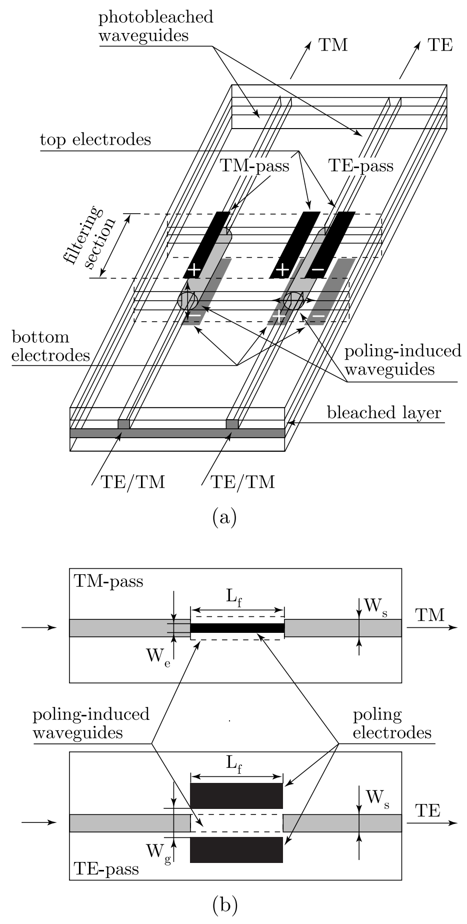
In this work, integrated optic waveguide devices to control the polarization state of the guided wave are demonstrated by exploiting the poling induced birefringence in EO polymers with specially designed poling electrodes. Most of waveguide devices have operating principles dependent on the polarization states of the light signals traveling through the optical fibers or waveguides. Therefore, the polarization control is necessary before the light enters polarization dependent waveguide devices. The basic devices to control the guided-wave polarization are polarizers [11],

[12], polarization splitters [13]-[15] and polarization converters [16], [17], and they have been actively investigated in $LiNbO_3$, III-V material, Si, and glass substrates. However, there is no report about polarization controlling devices fabricated in EO polymers. Compared to the polarization controlling devices in other substrates, the fabrication procedures of the polymeric devices are rather simple and the fabrication cost would be low. Furthermore, they can be integrated with other functional devices realized in EO polymers, and there is a large potential to create advanced novel polymeric waveguide devices.

The device configurations and operating principles of the polymeric waveguide polarizer, the polarization splitter, and the polarization converter are described in Section II. Fabrication procedures of the three devices are similar and summarized in Section III. Measurement results of the device performances are discussed in Section IV. Finally, summary of the experimental results and conclusions are drawn in Section V.

II. DEVICE CONFIGURATIONS AND OPERATING PRINCIPLES

1. Polymeric Waveguide Polarizer



(a)

(b)

Fig. 1. Schematic diagrams and top-views of the TM-pass and TE-pass polymeric waveguide polarizers. The waveguides formed by photobleaching serially connects the two types of poling-induced waveguides.

Schematic diagrams and top-views of the two polarizers are shown in Fig. 1. In both input and output sections, there are photobleached waveguides which support both TE and TM modes. Selective bleaching under UV-light decreases the refractive index of the polymer and forms channel waveguides in the un-bleached area. To fabricate a TM-pass polarizer, two vertically aligned electrodes are used for poling the polymer. The poling induced birefringence produces a birefringent channel waveguide whose optic axis is aligned in the vertical direction. This vertically poled wave- guide can confine only TM modes. Hence, the TM mode can pass the filtering section while the TE mode is radiated.

In a TE-pass polarizer four electrodes are used for the horizontal poling of the polymer instead of conventional coplanar electrodes. The four electrodes produce an electric field which is aligned horizontally in the core layer of the waveguide and provide better uniformity of the poling-field direction than the coplanar electrodes [10]. After the electric-field assisted poling, a horizontally poled channel waveguide is formed. The refractive index of poled region is enhanced for TE modes and decreased for TM modes. Hence, the horizontally poled waveguide acts as a TE-pass polarizer.

For the low loss polarizers, the mode profiles of each waveguide should be matched. In vertical direction, the mode profile is determined by the refractive indices of the three layers forming the planar waveguide. On the other hand, the lateral mode profile is dependent on the device parameters and poling conditions. With parameters fixed by the dimensions of photomasks, it is necessary to find appropriate bleaching times and poling voltages to obtain matched mode profiles between the different waveguides.

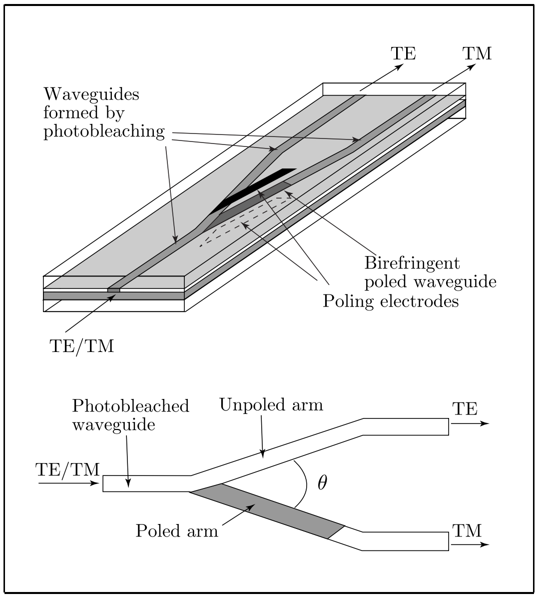


Fig. 2. Schematic diagrams and top-views of the polymeric waveguide polarization splitter. The two poling electrodes pole a branch of the Y-shaped waveguide to be birefringent.

2. Polymeric Waveguide Polarization Splitter

The schematic diagram and top-view of the polymeric polarization splitter are shown in Fig. 2. It has basically Y-shaped channel waveguide structure which is formed by selective photobleaching of the core layer. Additionally, one arm of the Y-branch waveguide is vertically poled by using the two electrodes as shown in Fig. 2. The poled region becomes birefringent. Thus, compared to the unpoled arm, the refractive index of the poled arm is enhanced for the TM polarized lights, while decreased for the TE polarized lights. When the light launched at the input, the TM and TE modes are separated to the poled and unpoled arms, respectively, because of the mode evolution effect [18].

The performance of the polarization splitters based on the mode evolution effect are mainly dependent on the magnitude of the birefringence and the splitting angle. The beam propagation method is employed to design the device parameters. Numerical simulations have shown that the crosstalk can be less than -20 dB [19].

3. Polymeric Waveguide Polarization Converter

The polarization converter in this work is composed of three sections: a polarizer, a rotator, and an analyzer, as shown in Fig. 3. The poling electrodes of the TE and TM mode waveguides are connected by a slowly varying structure. All four electrodes are poled at the same time. This results in a horizontal field in the polarizer section, a slowly rotating field in the rotator section, and a vertical field in the analyzer section, as shown in the cross-sections of Fig. 3. Because of the birefringence induced by poling, a channel waveguide is formed with higher index for TE polarization in the polarizer section, due to the horizontal electric field at this location. Hence, the polarizer section operates as a TE-pass filter. The polarization rotator section has a slowly varying electrode structure which makes the optic axis rotate from horizontal to vertical direction. Then the azimuth angle of the poling induced optic axis is slowly changed along the propagation direction by following the external poling field direction. Hence the polarization angle of the guided-wave is also adiabatically rotated along the poled optic axis direction. It is unnecessary to control the optic axis precisely in the rotator section as long as the optic axis is varying slowly enough to suppress

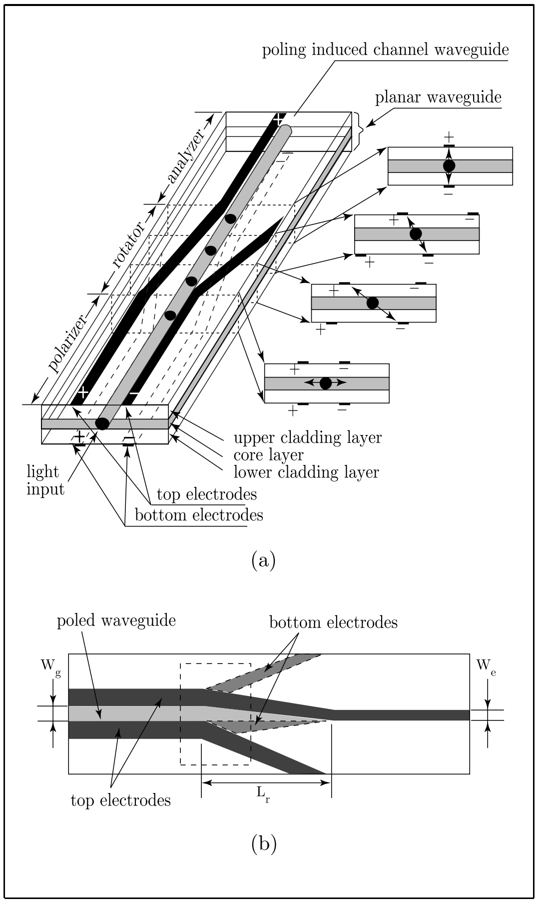


Fig. 3. Schematic diagram of the proposed polarization rotator. Cut-views show the major direction of the poling field or the optic axis of the poling induced waveguide for the given electrode structure.

the excess scattering loss. The final section is an analyzer which is poled by two vertically aligned electrodes. In contrast to the polarizer section, the analyzer section has an enhanced index profile only for TM polarization, and it works as a TM-pass filter.

When the light is coupled into the input end of the device, a TE polarized guided-mode is evolved in the polarizer section. As the light propagates along the rotator section, the polarization of guided mode rotates gradually from TE to TM mode following the optic axis direction. This resembles the polarization rotation in the twisted nematic liquid crystal. Finally, a TM polarized guided mode is extracted from the analyzer section. Since the device contains no periodic structures, it is much less sensitive to wavelength, channel dimensions and polarizing structures than the devices containing such structures [16], [17]. It may be noted that this device can operate under multimode conditions since the poled polymer waveguide supports only one polarization component.

III. FABRICATION PROCEDURES

The fabrication procedures are illustrated in Fig. 4. On a thermally oxidized Si wafer, bottom electrodes are constructed by vacuum evaporation of Ti-Au and by lift-off process. The EO polymer used in this work is the PMMA based copolymer with a stilbene derivative as a side chain (poly((4-dimethylamino-4'-nitro-stilbene methylmethacrylate)$_x$-co-(methyl-methacrylate)$_{1-x}$); P2ANS) which is supplied by Hoechst-Celanese Co. For the lower cladding and core layers, P2ANS(x= 0.35) and P2ANS(x= 0.5) are spin-coated to be 4.0 μm and 3.0 μm, respectively. Then, the core layer is selectively photobleached under UV light to form the photobleached channel waveguides [20]. However, the polarization converter does not need this photobleaching process because the channel waveguide is formed by the poling itself. For the upper cladding layer, a UV-curable epoxy, NOA61 (Norland Optical Adhesive 61) is spin-coated to be 2 μm and cured by exposing under the UV light.

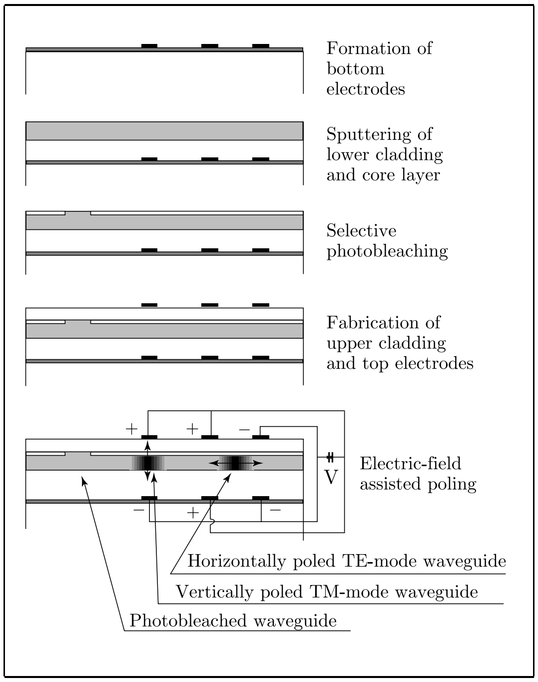


Fig. 4. Fabrication procedures of the photobleached and poling-induced waveguides in EO polymers.

After each spin-coating the polymer is baked sufficiently. The top electrodes are formed by the same way as the bottom electrodes. Over the top electrodes, the photoresist is spin-coated and baked completely. It serves as an electrical insulating layer to prevent the air-breakdown between adjacent top electrodes of the TE-pass polarizers during the poling. The device is poled on a hot-plate at 135°C by applying poling voltages across the electrodes. Finally, the sample is cleaved for the light coupling.

IV. DEVICE PERFORMANCE AND DISCUSSIONS

1. Polymeric Waveguide Polarizer

To find the appropriate bleaching time and poling voltage for matched mode profiles, the guided mode profiles of the three waveguides were observed by a CCD-camera. A schematic diagram of the measurement setup is drawn in Fig. 5. Fig. 6 (a)-(c) shows the lateral mode profiles of the three waveguides at the wavelength of 1.3 μm. A well confined single mode was obtained for the bleached waveguide with strip width W_s of 6 μm after bleaching for 24 hours with the light intensity of 8 mW/cm^2. The vertically poled waveguide has electrode width W_e of 4 μm and the horizontally poled waveguide has electrode-gap width W_g of 6 μm. They were poled at 400 V. It is shown that the three different waveguides have similar guided mode profiles. The measured spot sizes are 12.0 μm, 11.9 μm, and 12.4 μm for the vertically-poled, the horizontally-poled, and the photobleached waveguides, respectively. By integrating these waveguides, polarizers with low excess loss were fabricated.

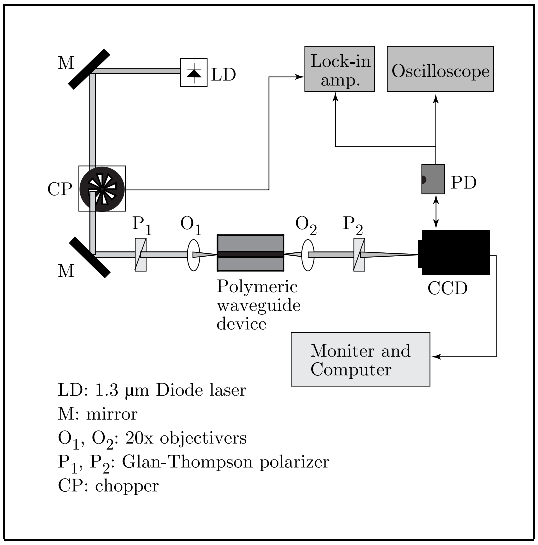


Fig. 5. A schematic diagram of the optical measurement setup. Two Glan-Thompson polarizers are located at the input and output plane of the polymeric waveguide device.

To measure the polarization filtering efficiency, the polarization of the input light was set to have both TE and TM components. Then, the output light from the device was passed through a Glan-Thompson polarizer and detected by a photodiode. The power in each polarization component of the output light was measured by rotating the Glan-Thompson polarizer to a proper position. As the function of poling voltages, the polarization extinction ratio of each filter was mea-

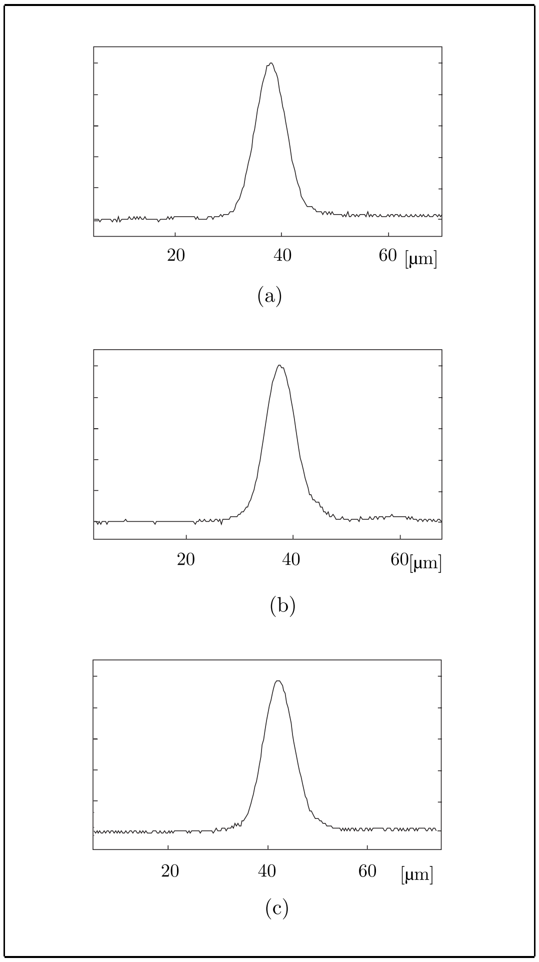


Fig. 6. Guided mode profiles of (a) the waveguide photobleached for 24 hours with W_s of 6 μm, (b) the horizontally poled waveguide with W_g of 6 μm, and (c) the vertically poled waveguide with W_e of 4 μm . They were poled by applying 400 V between 9 μm thick polymer film. The profiles are well matched to demonstrate waveguide polarizers with low loss.

sured as shown in Fig. 7. To measure the excess loss of the device, straight waveguides were also fabricated next to the polarizers by the photobleaching method. For the TM polarized input light, the output powers from the TM-pass polarizers and the bleached waveguides were measured respectively. The excess loss was calculated by subtracting the output power of the polarizer from that of the bleached waveguide. The excess loss of the TE-pass polarizer was also measured similarly. The measured excess losses are also plotted in Fig. 7. The TM-pass polarizer with $W_e = 4$ μm, $W_s = 6$ μm, and $L_f = 1$ μm exhibited the best performance at the poling voltage of 400 V. The polarization extinction ratio was 20.7 dB and the excess loss was 0.18 dB. For the

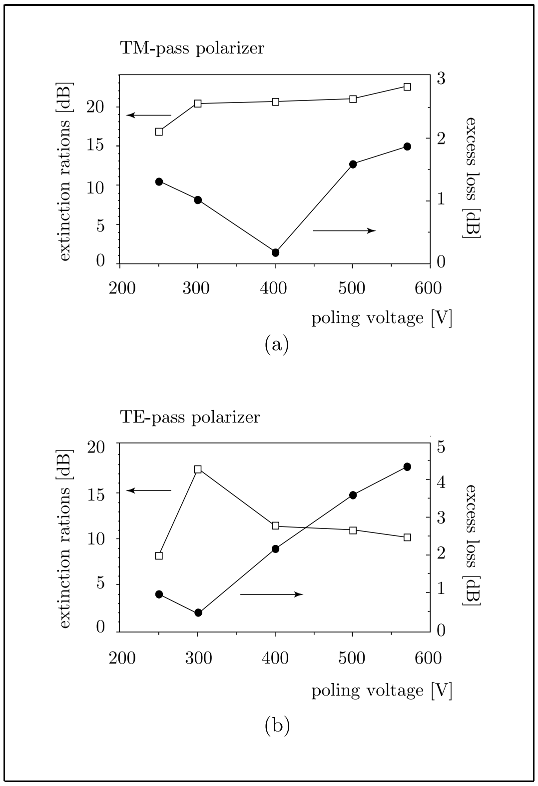
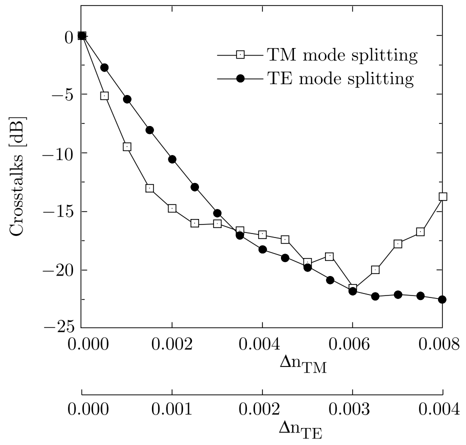


Fig. 7. Measured polarization extinction ratios and excess losses of the TM-pass and TE-pass polarizers.

TE-pass polarizer with $W_g = 6$ μm, $W_s = 4$ μm, and $L_f = 3$ μm, the extinction ratio of 17.1 dB and the excess loss of 0.42 dB were obtained when it was poled by 300 V [21].

2. Polymeric Waveguide Polarization Splitter

In order to test the device, the polarization of input light with 1.3 μm wavelength was set to be either TE or TM mode. Then, the output light from each arm of the polarization splitter was detected by a photodiode. The optical power of the arms are compared to obtain the crosstalks. Fig. 8 represents the measured crosstalk of the polarization splitters together with the BPM simulation results. The fabrication conditions and device parameters are also summarized in the Table of Fig. 8. For the best sample with total branch angle of 1/100 radian, we obtained crosstalk of -14.2 dB and -10.1 dB for TM and TE mode splittings, respectively. The device was poled by applying 400 V between 8.5 μm thick polymers, and the poling induced birefringence was estimated to be 0.0089 by referring to the experimental results of [22]. The excess loss was measured by comparing the throughput of the device with that of the straight waveguides which were fabricated on the same substrate. It was as large as 3 dB [19].



(a)

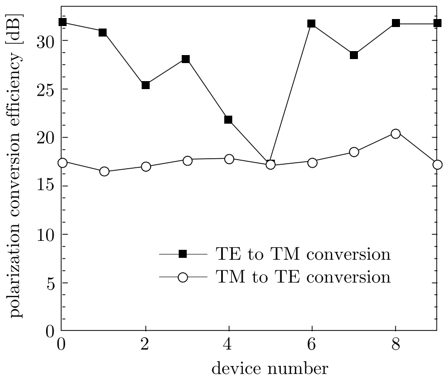
Samples	Input polarization	Crosstalks (measured)	Poling fields	Δn_{TM} (estimated)	Δn_{TE} (estimated)
PS-I	TM TE	−10.1 dB −8.6 dB	35.3 V/μm	0.0045	0.0021
PS-II	TM TE	−14.2 dB −10.1 dB	47.1 V/μm	0.0080	0.0037

(b)

Fig. 8. (a) Calculation results based on the BPM simulation, (b) Measured crosstalks and fabrication conditions of the polarization splitters.

3. Polymeric Waveguide Polarization Converter

To determine how device parameters affect the results, 10 devices were fabricated with different parameters as denoted in the table of Fig. 9. To test the fabricated device, TE polarized light from a 1.3 μm diode laser was launched to its input end. The light from its output end, passing through a Glan-Thompson polarizer, was detected with a photodiode. The power in each polarization component was measured by rotating the Glan-Thompson polarizer to the appropriate angle. For TE to TM mode conversion, the measured polarization extinction ratio was higher than 30 dB for



(a)

device #	d0	d1	d2	d3	d4	d5	d6	d7	d8	d9
L_r (mm)	3	3	3	3	3	4	4	4	4	4
W_g (mm)	10	8	8	6	6	6	6	8	8	10
W_e (mm)	8	8	6	6	4	4	6	6	8	8

(b)

Fig. 9. Measured conversion efficiencies of the polymeric waveguide polarization converters with different device parameters. Both TE to TM conversion and TM to TE conversion are measured for 10 devices with different device parameters.

the best device. To measure the excess loss of the device, we also fabricated vertically poled waveguides on the same substrate using the same poling condition, and the output power was measured and compared with that of the polarization converter. The excess loss was less than 1 dB for all the devices. The TM to TE mode conversion efficiency was also measured by reversing the light propagation direction and changing the input polarization to TM mode. The measured results are also shown in Fig. 9. The polarization extinction ratio higher than 20 dB was obtained. However, the results are worse than the case of TE to TM mode conversion. The vertical poling electrode structure is almost ideal for TM polarization so that the quasi-TM mode of the waveguide has negligible TE component. On the other hand, the horizontal poling which is less ideal than the vertical poling supports the quasi-TE mode that retains a little TM component. This fact may be the reason of the lower conversion efficiency for the TM to TE mode conversion [23].

V. CONCLUSION

A series of polarization controlling waveguide devices such as polarizers, polarization splitters, and polarization converters have been demonstrated in EO polymers. Poling-induced birefringence in EO polymers was utilized to fabricate the waveguide devices.

The polymeric waveguide polarizers exhibited low excess loss and good polarization extinction ratios. The mode profiles of the poling induced waveguides were well matched with that of the photobleached waveguide so that the excess loss was smaller than 0.5 dB for both polarizers. The extinction ratios of 20.7 dB and 17.1 dB were obtained for TM-pass and TE-pass polarizers, respectively.

The polymeric polarization splitters exhibited crosstalk of −14.2 dB and −10.1 dB for TM and TE mode splittings, respectively. The broadening of the poling fields and the nonuniform angle of the local poling fields may be the reasons of the lower splitting efficiency than the numerical simulation.

TE/TM polarization mode conversion was successfully demonstrated in the polymeric waveguide polarization converter. A specially designed poling electrodes are used to form a poling-induced waveguide whose optic axis is slowly rotating along the light propagation direction. The output polarization conversion efficiency was higher than 30 dB for TE to TM mode conversion. The fabricated polarization converter is insensitive to wavelength in principle. It is also easier to fabricate than the other polarization converters containing periodic structures.

The performances of the polymeric polarization controlling devices can be compared with that of the devices made from other materials. The polymeric polarization converter exhibited superior performance while other devices had the lower performance. However, they are the first experimental demonstration of the polymeric devices with the polarization controlling functions. By modifying the device structures, the performance can be obtimized for the real applications.

The three devices are basic components for the advanced optical signal processings which requires the polarization state control of the light signal. Furthermore, advanced functional devices like polarization independent waveguide devices could be realized in polymers by employing the polymeric polarization controlling devices.

REFERENCES

[1] L. A. Hornak, Ed., *Polymers for Lightwave and Integrated Optics: Technology and Applications.* New York: Marcel Dekker, 1992, pp. 321-500.

[2] C. C. Teng, “Traveling-wave polymeric optical intensity modulator with more than 40 GHz of 3-dB electrical bandwidth,” *Appl. Phys. Lett.,* vol. 60, pp. 1538-1540, 1992.

[3] S. Ermer, W. W. Anderson, T. E. Van Eck, D. G. Girton, J. A. Marley, A. Harwit, S. M. Lovejoy, and D. S. Leung, “Progress toward practical polymer electro-optic devices,” *Organic Thin Films for Photonics Applications*, Portland, Oregon, USA, 1995, paper WA2-1, pp. 285-288

[4] W. Wang, D. Chen, H. R. Fetterman, Y. Shi, W. H. Steier, and L. R. Dalton, “40 GHz polymer electrooptic phase modulators,” *IEEE Photon. Technol. Lett.,* vol. 7, no. 6, pp. 638-640, 1995.

[5] J. S. Cites, P. R. Ashley, and R. P. Leavitt, “Integration of nonlinear optical (NLO) polymer waveguides with indium gallium arsenide p-i-n photodiodes,” *Organic Thin Films for Photonics Applications*, Portland, Oregon, USA, 1995, paper WB1-2, pp. 298-301.

[6] M. Hikita, Y. Shuto, M. Amano, R. Yoshimura, S. Tomaru, and H. Kozawaguchi, “Optical intensity modulation in a vertically stacked coupler incorporating electro-optic polymer,” *Appl. Phys. Lett.,* vol. 63, no. 9, pp. 1161-1163, 1993.

[7] T. A. Tumolillo, Jr. and P. R. Ashley, “Multilevel registered polymeric Mach-Zehnder intensity modulator array,” *Appl. Phys. Lett.,* vol. 62, pp. 3068-3070, 1993.

[8] Min-Cheol Oh, Shogo Ura, Toshiaki Suhara, and Hiroshi Nishihara, “Integrated-optic focal-spot intensity modulator using electrooptic polymer

waveguide," *IEEE J. Lightwave Technol.*, vol. 12, no. 9, pp. 1569-1576, 1994.

[9] J. I. Thackara, G. F. Lipscomb, M. A. Stiller, A. J. Ticknor, and R. Lytel, "Poled electro-optic waveguide formation in thin film organic media," *Appl. Phys. Lett.*, vol. 52, no. 13. pp. 1031-1033, 1988.

[10] Min-Cheol Oh, Sang-Shin Lee, and Sang-Yung Shin, "Simulation of polarization converter formed by poling-induced polymer waveguides," *IEEE J. Quantum Electron.*, vol. 31, no. 9, pp. 1698-1704, 1995.

[11] P. G. Suchoski, T. K. Findakly, and F. J. Leonberger, "Low-loss high-extinction polarizers fabricated in $LiNbO_3$ by proton exchange," *Optics Lett.*, vol. 13, no. 2, pp. 172-174, 1988.

[12] D. Jiang, F. Zhou, P. J. R. Laybourn, and R. M. De La Rue, "Buried optical waveguide polarizer by titanium indiffusion and proton-exchange in $LiNbO_3$," *IEEE Photon. Technol. Lett.*, vol. 4, no. 8, pp. 881-883, 1992.

[13] P.-K. Wei, and W.-S. Wang, "A TE-TM mode splitter on lithium niobate using Ti, Ni, and MgO diffusions," *IEEE Photon. Technol. Lett.*, vol. 6, no. 2, pp. 245-248, 1994.

[14] J. J. G. M. van der Tol, J. W. Pedersen, E. G. Metaal, Y. S. Oei, H. van Brug, and I. Moerman, "Mode evolution type polarization splitter on InGaAsP/InP," *IEEE Photon. Technol. Lett.*, vol. 5, no. 12, pp. 1412-1414, 1993.

[15] R. M. de Ridder, A. F. M. Sander, A. Driessen, and J. H. J. Fluitman, "An integrated optic adiabatic TE/TM mode splitter on silicon," *IEEE J. Lightwave Technol.*, vol. 11, no. 11, pp. 1806-1811, 1993.

[16] J. J. G. M. van der Tol, F. Hakimzadeh, J. W. Pedersen, D. Li, and H. van Brug, "A new short and low-loss passive polarization converter on InP," *IEEE Photon. Technol. Letters*, vol. 7, no. 1, pp. 32-34, 1995.

[17] Y. Shani, R. Alferness, T. Koch, U. Koren, M. Oron, B. I. Miller, and M. G. Young, "Polarization rotation in asymmetric periodic loaded rib waveguides," *Appl. Phys. Lett*, vol. 59, no. 11, pp. 1278-1280, 1991.

[18] W. K. Burns, and A. F. Milton, "Mode conversion in planar-dielectric separating waveguides," *IEEE J. Quantum Electron.*, vol. QE-11, no. 1, pp. 32-39, 1975.

[19] Min-Cheol Oh, Sang-Shin Lee, Sang-Yung Shin, Wol-Yon Hwang, and Jang-Joo Kim, "Polymeric waveguide polarization splitter based on poling-induced birefringence," *Electron. Lett.*, vol. 32, no. 4, pp. 324-325, 1996.

[20] M. B. J. Diemeer, F. M. M. Suyten, E. S. Trommel, A. McDonach, J. M. Copeland, L. W. Jenneskens, and W. H. G. Horsthuis, "Photoinduced channel waveguide formation in nonlinear optical polymers," *Electron. Lett.*, vol. 26, no. 6, pp. 379-380, 1990.

[21] Min-Cheol Oh, Sang-Yung Shin, Wol-Yon Hwang, and Jang-Joo Kim, "Poling-induced waveguide polarizers in electrooptic polymers," *IEEE Photon. Technol. Lett.*, vol. 8, no. 3, pp. 375-377, 1996.

[22] C. C. Teng, M. A. Mortazavi, and G. K. Boudoughian, "Origin of the poling-induced optical loss in a nonlinear optical polymeric wave- guide," *Appl. Phys. Lett.*, vol. 66, no. 6, pp. 667-669, 1995.

[23] Min-Cheol Oh, Sang-Yung Shin, Wol-Yon Hwang, and Jang-Joo Kim, "Wavelength insensitive passive polarization converter fabricated by poled polymer waveguides," *Appl. Phys. Lett.*, vol. 67, no. 13, pp. 1821-1823, 1995.

Min-Cheol Oh was born in Korea on June 25, 1967. He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Korea Advanced Institute of Science and Technology, Taejon, Korea, in 1990, 1992, and 1996, respectively. He was a research student from 1992 to 1993 at Osaka University, Osaka, Japan. From 1994 to 1995, he served as a research associate in the Research Department of ETRI, which he joined in 1996 as a Senior Researcher. His current research interests include optical waveguide devices for switchings, modulations, wavelength controls, etc.

Wol-Yon Hwang was born in Korea on December 12, 1963. He received the B.S. degree in Physics from the Pusan National University, Pusan, Korea, in 1985, and the M.S. and Ph.D. degrees in physics from the Korea Advanced Institute of Science and Technology, Taejon, Korea, in 1987 and 1990, respectively. In 1990, he joined the Research Department of ETRI as a Senior Researcher. His current research interests include electro-optic waveguide modulator/switch and tunable wavelength filter.

Jang-Joo Kim graduated Seoul National University in 1977 with B.S. and in 1980 with M.S. degrees from the Chemical Engineering Department, respectively. He continued his academic work at Stanford University in California, USA, getting his Ph.D from the Materials Science and Engineering Department in 1986. After 11/2 years of post doctoral work at SRI International in California, USA, he joined ETRI in 1987 as a Senior Researcher. He is currently a Principal Member of Research Staff and the leader of Organic Materials for Electronics and Photonics Team of the institute. His research area covers nonlinear optical organic materials and devices, organic electroluminescent materials and LED, photorefractive organic materials and organized molecular films (Langmuir-Blodgett films). He has co-authored over 50 papers and holds more than 10 patents in those fields.