Single-Mode Nd^{3+}-Doped Graded-Index Polymer Waveguide Amplifier

Ray T. Chen, Maggie Lee, Srikanth Natarajan, Chuan Lin, Z. Z. Ho, and Dan Robinson

Abstract—**We report the first graded index (GRIN) polymer waveguide amplifier working at 1.06 μm wavelength using Nd^{3+}:photolime gel material combination. Throughput intensity at 3.8 mW at 1.06 μm corresponding to 8.5 dB gain was observed when employing a 40 mW pumping laser beam operating at 790 nm. The gain medium is a 2.2 cm waveguide active region with Nd^{3+} concentration of $1.03 \cdot 10^{20}$ / cm^3. The graded index (GRIN) characteristic of the photolime gel thin film provides a universal means for implementing polymer-based photonic integrated circuits (PIC's) on any substrate of interest.**

RECENTLY, intense research on single-mode rare-earth doped fiber lasers and amplifiers [1] has led to the development of a myriad of novel communication systems. Introducing rare earth ions (REI's) into thin-film waveguides also provides waveguide lasers in Ti:$LiNbO_3$ waveguides [2] and in various glass waveguides [3]–[5]. These new thin-film waveguide devices have opened a brand new research area in integrated photonics. However, there are a number of intrinsic limitations associated with these material systems. First, glass waveguides have no electrooptic (EO) effect; therefore, an active device cannot be made using these substrates. Second, $LiNbO_3$ waveguides have significant walk-off between the refractive indexes of microwaves and optical waves. Consequently, the modulation speed of $LiNbO_3$-based EO modulator, which can provide input optical signal for the waveguide amplifier, is limited to $\sim$ 40 GHz [6]. Third, the waveguide fabrication methods for $LiNbO_3$ and glass substrates are not universal. They are not transferable to other substrates. For instance, Si and GaAs are the most frequently-used substrates for optoelectronics. $LiNbO_3$ and glass waveguide lasers cannot be implemented on these substrates as amplifiers without violating the monolithic integration preference.

Photo lime gel-based polymer waveguide presented herein is an excellent guiding medium due to its wide transmission bandwidth (300 nm to 2700 nm) [7]. The GRIN characteristic of this material allows the formation of high quality (loss < 0.1 dB/cm) single-mode passive and active devices on an array of substrates [8]. In this paper, we report the first GRIN polymer waveguide amplifier working at 1.06 μm wavelength using Nd^{3+}-doped photolime gel as the active medium. The polymer introduced herein is soluble in water. As a result, the chemical compounds containing rare-earth ions (REI's) can be mixed with the host polymer as long as they are hydrophilic. The doping concentrations should be below the level of microscopic clustering [5], which quenches the active ions.

There are other quenchers which shorten the lifetime of metastable states of active ions. The most serious quenchers are the admixed O–H groups whose concentration must be less than $3\text{–}5 \times 10^{18}/cm^3$ [4] for a glass waveguide amplifier. The existence of O–H groups generates a number of intermediate states between the transition states. Such states, primarily from water molecules, significantly reduce the lifetime of metastable states. The general rule of thumb is that the lifetime of the excited state will be temperature dependent if the gap is less than ten times the effective photon frequency and completely quenched if less than four times [5], [9]. Water molecules within the photolime gel can be significantly eliminated using the dehydration process shown in Fig. 1. Such dehydration process provides us with not only a GRIN polymer waveguide [7] with minimum H_2O molecules, but also a much higher temperature dynamic range (-100°C to 180°C) [10] which ensures device survivability under intense pumping situations. This will prevent the intake of water molecules after the dehydration process. As far as the distribution of the water molecules within the dried Nd^{3+}-doped polymer thin film is concerned, the observed index profile of the thin film showed an unchanged graded index profile which excludes the possibility of redistribution of water concentration within the film. Experimental data for GRIN films with and without Nd^{3+} ions demonstrated the same GRIN profile; therefore, the existence of Nd^{3+} does not impose any difficulty in removing the Nd^{3+} hydration shell.

Similar to polymer waveguide preparation, Nd^{3+}/photolime gel was spin-coated on top of a substrate. The optimum Nd^{3+} concentration was experimentally determined to be $1.03 \cdot 10^{20}/cm^3$. On standing at temperatures below 30°C, solutions containing more than 1% photolime gel become rigid through material cross-linking and exhibit rubber-like mechanical properties. The gelation process holds for both pure gel and doped gel alloy. The

Manuscript received June 15, 1993; revised August 30, 1993. This work was supported by the SDIO/IST, the Army Strategic Defense Command and the University of Texas, Austin.

R. T. Chen, M. Lee, S. Natarajan, and C. Lin are with the Microelectronics Research Center, Department of Electrical and Computer Engineering, University of Texas, Austin, Austin, TX 78712.

Z. Z. Ho and D. Robinson are with the Physical Optics Corporation, Torrance, CA 90505.

IEEE Log Number 9213376.

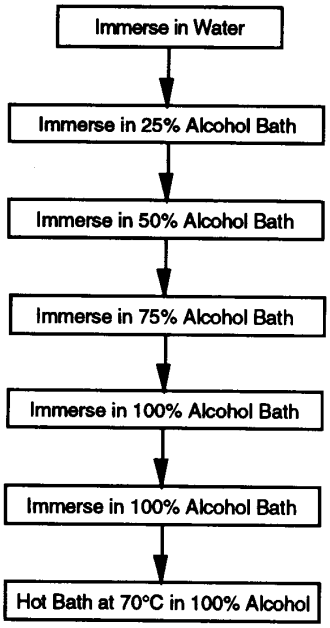

Fig. 1. Depletion of O–H group quenched by dehydration process.

absorption spectrum, which determines the optimum pumping wavelengths, was experimentally confirmed using a spectrophotometer. Two major peaks shown in Fig. 2(a) are in the 750-nm and 790-nm neighborhoods. The film thickness used for this measurement was 250 μm. These absorption peaks are very similar to those shown in the Nd^{3+}:glass ED-2 [11]. Note that, due to the amorphous nature of the host material, i.e. photolime gel, the absorption width of each peak is much wider than an Nd:YAG laser. The fluorescent spectrum of Nd^{3+}:photolime gel thin film was also observed by pumping the active medium using a Ti:Sapphire laser working at 790-nm. The fluorescent spectrum detected by an optical spectrum analyzer is illustrated in Fig. 2(b) where a fluorescent peak centered at 1.06 μm is indicated. It is to be noted that the broadening effect due to the amorphous structure of the photolime polymer thin film is also observed. It is equivalent to the $^4F_{3/2}$ to $^4I_{11/2}$ transition of an Nd^{3+}:glass laser. A wider fluorescent spectrum increases the laser threshold since a larger population inversion is required to obtain the threshold value for amplification. However, this broadening effect has an advantage. A broader line offers the possibility of obtaining and of amplifying shorter light pulses. In addition, it permits the storage of larger amounts of energy in the amplifying medium for the same linear amplification coefficient.

The setup for the demonstration of GRIN polymer waveguide amplifier is shown in Fig. 3 where the Nd^{3+}-doped waveguide amplifier, 1.06 μm YAG laser and Ti-Sapphire laser are clearly indicated. The interaction length, i.e. the waveguide region for the two collinear counterpropagating laser beams, is 2.2 cm. The propagation loss for the 40-mW pumping laser beam working at

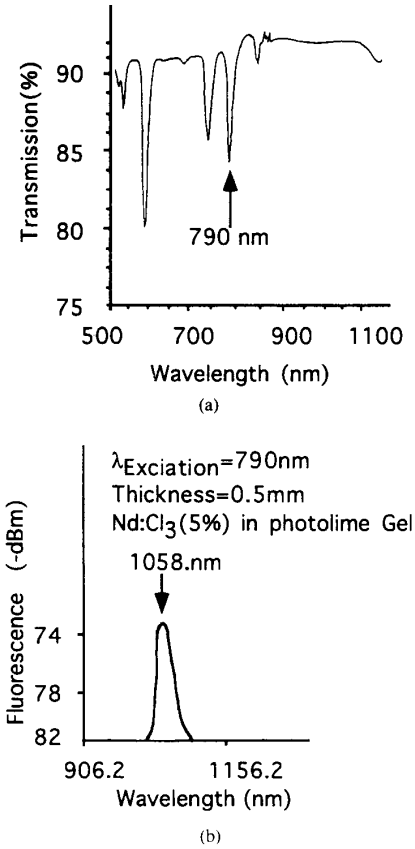

Fig. 2. (a) Absorption and (b) fluorescent spectrum Nd^{3+}-doped photolime gel and thin film.

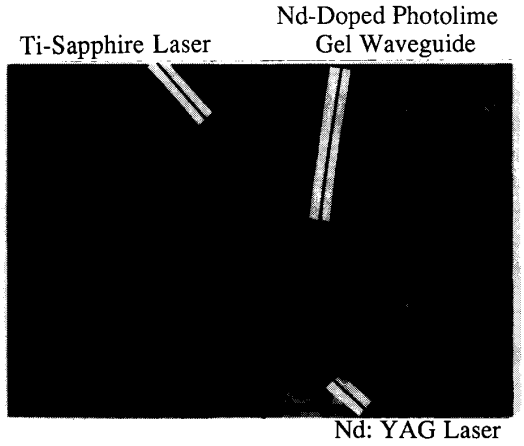

Fig. 3. Setup for the demonstration of GRIN polymer waveguide amplifier.

790-nm was measured to be 9.3 dB/cm which was resulted from absorption of the active medium. It is around two orders of magnitude higher than the pure photolime gel waveguide. The pumping laser beam and the 1.06 μm

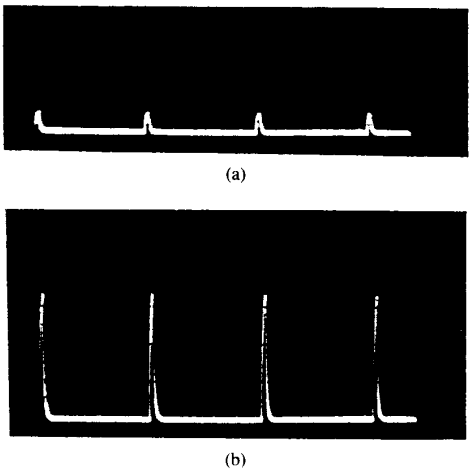

Fig. 4. Measured results of the GRIN polymer waveguide amplifier; 8.5 dB gain is clearly shown at 100 Hz.

Nd:YAG laser beam were both coupled into the Nd^{3+}:photolime gel waveguide using the prism coupling method. The input prism coupler for 790-nm pumping laser beam also functions as an output prism coupler for the amplified 1.06 μm laser beam [11]. An IR vidicon camera was employed in the alignment process. The Nd^{3+}:photolime gel thin film is a GRIN single-mode planar-waveguide without horizontal confinement. Therefore, the overlap between the pumping beam and the amplified laser beam (1.06 μm) plays an important role in achieving the maximum value of amplification. The measured gain for this demonstration shown in Fig. 3 is illustrated in Fig. 4. 3.8-mW throughput intensity at 1.06 μm corresponding to an 8.5-dB gain is observed. The output mode-dots corresponding to Fig. 4(a) and (b) are further displayed in Fig. 5(a) and (b). The throughput intensity enhancement is clearly indicated in Fig. 5(b).

Waveguide lasers have a number of plausible applications. These include amplification of high-speed modulated signals, optical generation, and manipulation of microwave signals (*e.g.*, injection locking for phased-array antennas), all-optical repeaters for long-distance communication, optical interconnection, and remote sensing. GRIN characteristic of the polymer waveguide allows us to implement an optical amplifier onto an array of substrates. Such universality greatly enhances system-integration capability of polymer-based photonic integrated circuits.

A paramount issue for guided-wave optical interconnect is the linear dimension of interconnection. Polymer-based waveguide is the best candidate for massively-parallel highly-distributed interconnect systems such as optical backplane and module-to-module interconnects. This is because of its unlimited linear dimension and device modability. We have recently reported a 45-cm long compression-molded optical bus based on the same polymeric material [12]. Availability of a waveguide amplifier based

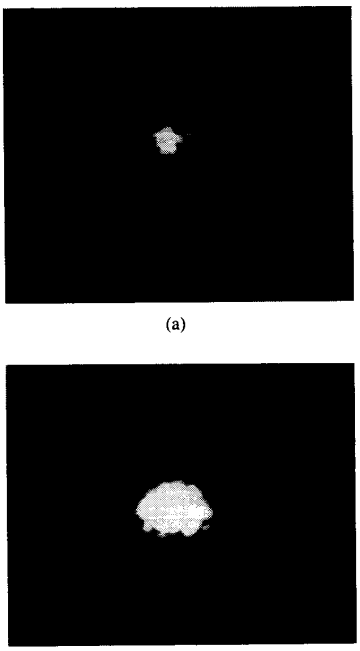

Fig. 5. Observed mode-dots (a) before and (b) after pumping.

on the same host material will further upgrade the power budget requirement and thus system reliability of the polymer-based optical interconnect system.

In summary, we report the first single-mode graded-index (GRIN) polymer waveguide amplifier working at 1.06 μm wavelength using Nd^{3+}:photolime gel material combination. 8.5-dB gain was observed using a 2.2-cm waveguide length with Nd^{3+} concentration of $1.03 \cdot 10^{20}/cm^3$. A tunable Ti:Sapphire laser was used as a pumping source. The success of this demonstration together with the previously-reported results on GRIN polymer passive and active guided-wave devices provide a full capability of integrating monolithic polymer-based photonic integrated circuits. Due to GRIN characteristic of the polymer thin film, the device reported herein can be made on any substrate of interest.

The authors wish to thank Dr. W. J. Miniscalco for helpful discussion.

REFERENCES

[1] W. J. Miniscalco, "Erbium-doped glasses for fiber amplifiers at 1500 nm," *IEEE J. Lightwave Technol.*, vol. 9, p. 234, 1991.

[2] E. Lallier, J. P. Pocholle, M. Papuchon, C. Greasiest-Besset, E. Pelletier, M. DeMicheli, M. J. Li, Q. He, and D. B. Ostrowsky, "Efficient Nd:MgO:$LiNbO_3$ waveguide laser," *Electron. Lett.*, vol. 26, no. 13, p. 927, 1990.

[3] E. Snitzer, "Neodymium glass laser," in *Proc. 3rd Int. Conf. Quantum Electron.*, Paris, France, 1963, pp. 999–1019.

[4] V. P. Gapontsev, S. M. Matitsin, A. A. Isineev, and V. B. Kravchenko, "Erbium glass laser and their applications," *Opt. Laser Technol.*, pp. 189–196, Aug. 1982.

[5] E. Snitzer and R. Woodcock, "Er^{3+}-glass laser: In silicate glass," *Appl. Phys. Lett.*, vol. 6, no. 45, 1965.

[6] S. N. Tabr, "The economics and technology of integrated optical modulators: 1969–1999," *Critical Review on Integrated Optics and Optoelectronics*, SPIE CR-45, pp. 180–197, 1992.
[7] R. T. Chen, W. Phillips, T. Jannson, and D. Pelka, "Integration of holographic optical elements with polymer gelatin waveguides on GaAs, $LiNO_3$, glass, and aluminum," *Opt. Lett.*, vol. 14, no. 16, Aug. 15, 1989.
[8] R. T. Chen, "Graded index linear and curved polymer channel waveguide arrays for massively parallel optical interconnects," *Appl. Phys. Lett.*, vol. 61, p. 2278, 1992.
[9] C. B. Layne and M. J. Weber, "Multiphonon relaxation of rare-earth ions in beryllium-fluoride glass," *Phys. Rev. B*, vol. 16, pp. 3259–3261, 1977.
[10] R. T. Chen, "Polymer-based passive & active guided wave devices & their application," *Critical Review on Integrated Optics and Optoelectronics*, SPIE CR-45, pp. 198–235, 1992.
[11] R. T. Chen, C. Lin, Z. Z. Ho, and D. Robinson, "Graded index polymer waveguide amplifier," *1993 OSA Top. Meet. Integrated Photonics Res.*, Palm Springs, PD-9, 1993.
[12] R. T. Chen and S. Tang, "45 cm long compression-molded polymer-based optical bus," *Appl. Phys. Lett.*, 1993.

Thermal Hysteresis of Bragg Wavelengths of Intra-core Fiber Gratings

M. Douay, E. Fertein, W. X. Xie, P. Bernage, P. Niay, J. F. Bayon, and T. Georges

Abstract—**Bragg gratings written within GeO_2 doped-silica-glass fibers were submitted to increasing temperature steps. Bragg wavelength permanent shifts induced by heating were measured at room temperature after each step using a tunable laser (accuracy of the measurement $\pm 3\ 10^{-3}$ nm). Thus, hysteresis could be observed even after a temperature step as low as 80°C from room temperature. Through other experiments, the temperatures of various gratings were progressively increased in stages. During each stage, the Bragg wavelength was measured as a function of the grating temperature. The thermal evolutions of the Bragg wavelength were shown to depend slightly upon the experimental conditions used for the photoinscription of the gratings. These two effects were minimized through a curing process.**

I. Introduction

BRAGG gratings written in Germania-doped fibers [1], [2] act as compact, narrow-band tunable filters or reflectors. Thus, Bragg gratings are now commonly used in research for applications in various fields such as telecommunication or sensing. The Bragg wavelength of a grating is approximately a linear function of the fiber temperature [3] because the refractive index of silica varies linearly with temperature via the thermal expansion and the thermooptic effects. However, small non-linearities may occur as a result of erasure of the refractive index changes which were induced during the photoinscription. Thus, an important point concerns the checking of the reproducibility of the Bragg wavelength for temperature-sensing applications or for a technical point of view. In this paper, we present experimental results about the thermal evolutions of the Bragg wavelengths of the grating written under various experimental conditions within fibers.

Manuscript received May 7, 1993; revised September 9, 1993. This work was supported by C.N.E.T. under Contract 9386006 and by D.R.E.T. under Contract 92147.

M. Douay, E. Fertein, W. X. Xie, P. Bernage, and P. Niay are with Laboratoire de Dynamique Moléculaire et Photonique, Unité de Recherche Associee au C.N.R.S. n° 779, Université des Sciences et Technologies de Lille, UFR de Physique-Batiment P5, 59655 Villeneuve d'Ascq Cedex, France.
J. F. Bayon and T. Georges are with LAB/OCM/FOG-C.N.E.T.-Lannion BP 40, 22301-Lannion Cedex, France.

IEEE Log Number 9213375.

II. Experimental Setup and Methodology

All the Bragg gratings were produced following the method described first by Meltz *et al.* [1]. A pulsed UV-laser beam, tuned near 243 nm, impinged on the hypotenuse face of a prism interferometer. The prism split the UV beam into two equal intensity halves which were subsequently combined to interfere on one face of the prism. The germanium-doped fiber leaned against this face. The UV-beam was focused onto the core of the fiber with a cylindrical lens. For each experiment, three gratings were written in the fiber (I or II or III): two gratings were used for probing the wavelength shifts. The distance between these two gratings were 1 cm. They were written at a distance of 0.8 m to the third grating used for referencing the wavelengths of the two other gratings. The three gratings were written using the same fluence but with a different number of pulses; thus, their transmittances were different. The Bragg wavelengths were chosen so that the spectral profiles of the three gratings did not overlap one with each other. The part of the fiber around where the gratings were written was held in a quartz tube of 5 mm in diameter and 1.1 m in length. Polymer coating of this part of the fiber was removed and