

# Dual-functional polymeric waveguide with optical amplification and electro-optic modulation

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Optical amplification and first-order electro-optic effect have been observed simultaneously in one polymeric material photolime gel which has been used widely as a volume holographic material to produce dichromated gelatin films. In this letter, the dual functions were achieved by doping neodymium chloride hexahydrate and chlorophenol red. The optimized doping concentration of  $\text{Nd}^{+3}$  is  $6.7 \times 10^{19} \text{ cm}^{-3}$ . The weight percentage of chlorophenol red is 23%. We observed a 3.8 dB of optical gain at  $1.06 \mu\text{m}$  and an electro-optic coefficient of 22 pm/V at 633 nm. © 1998 American Institute of Physics. [S0003-6951(98)03622-5]

Dichromated gelatin (DCG) has been used widely as a volume hologram emulsion for many years.<sup>1</sup> A myriad of optical elements, such as wavelength division multiplexers, waveguide amplifiers, laser filters, cavity mirrors for electro-optic modulation, and display holograms, has been demonstrated using this polymeric material.<sup>2-13</sup> In order to realize a monolithically-integrated polymer-based optical circuit, active devices such as waveguide modulators, switches, amplifiers, and lasers are needed. In this letter we report a dual-functional polymeric waveguide using the same host polymeric material for dichromated gelatin, aimed at providing not only holographic optical elements but also amplification and electro-optic (EO) switching. The host material photolime gelatin is codoped with neodymium chloride hexahydrate ( $\text{NdCl}_3 \cdot 6\text{H}_2\text{O}$ ) and chlorophenol red ( $\text{C}_{19}\text{H}_{12}\text{Cl}_2\text{O}_5\text{S}$ ). Neodymium chloride hexahydrate is doped to provide  $\text{Nd}^{+3}$  ions for optical amplification, and chlorophenol red to provide electro-optic modulation.

Low-loss waveguides were obtained through a novel method dissolving all active dopants completely in mixed solvents.<sup>14</sup> No aggregation was observed in the waveguide even when the concentrations of  $\text{NdCl}_3$  and chlorophenol red reached as high as 10% and 35% by weight, respectively. The absorption spectra of three samples, a photolime gel (Gel) film, a chlorophenol red doped gel (CR/Gel) film, and an  $\text{Nd}^{+3}$  and chlorophenol red codoped gel ( $\text{Nd}^{+3}/\text{CR}/\text{Gel}$ ) film, are shown in Fig. 1. Within the range of 400–1200 nm, four main absorption bands were observed, centered at 433, 578, 745, and 796 nm. The first strong absorption band is due to chlorophenol red. The other three smaller bands of absorption correspond to the transitions of  $\text{Nd}^{+3}$  from ground state ( $^4I_{9/2}$ ) to excited states of ( $^2G_{7/2}$ ), ( $^4F_{7/2}$ ), and ( $^4F_{5/2}$ ), respectively.

Figure 2 shows the setup for amplification measurement. The waveguide under test was mounted on a prism coupling stage. The pumping beam, from a tunable Ti:Sapphire laser, was coupled into the waveguide using the prism  $P_1$ . The  $1.06 \mu\text{m}$  signal beam was provided by an Nd:YAG laser, and coupled into the waveguide from the opposite direction using the prism  $P_2$ . Note that  $P_1$  also functioned as the output prism for the  $1.06 \mu\text{m}$  signal beam. The pumping beam and the signal beam were carefully aligned to ensure the overlap

with each other to get the optimal amplification. A laser beam analyzer and an infrared CCD camera were employed for the alignment. The  $1.06 \mu\text{m}$  amplified signal was detected after passing through a wavelength-filtering system containing a rejection filter  $F_1$  and a band-pass filter  $F_2$  both working at  $1.06 \mu\text{m}$ .

The optical amplification was experimentally confirmed to be dependent on the pumping power, the  $\text{Nd}^{+3}$  and chlorophenol red doping concentrations, the intensity of the  $1.06 \mu\text{m}$  signal light, and the interaction length of the signal and pumping beams.<sup>14</sup> In the measurement below, the concentration of chlorophenol red of all the waveguides was fixed at 23 wt. % with a interaction length of 1.8 cm. For a signal of 1 mW at  $1.06 \mu\text{m}$ , optical gain was saturated when the pumping intensity launched into the waveguide was over 50 mW. The relationship between the gain and the concentration of  $\text{Nd}^{+3}$  is illustrated in Fig. 3. The optimized concentration of  $\text{Nd}^{+3}$  for amplification was determined to be  $6.7 \times 10^{19}/\text{cm}^3$ . The gain quenching effect occurred seriously when  $\text{Nd}^{+3}$  doping concentration was higher than  $7.8 \times 10^{19}/\text{cm}^3$ .

$\text{Nd}^{+3}$  has two broad absorption bands centered at 745

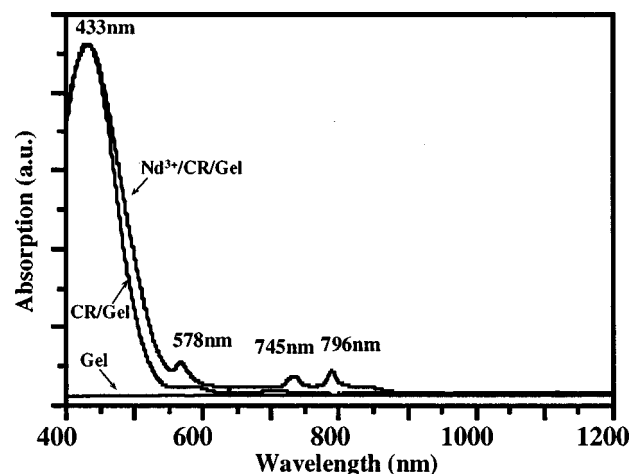


FIG. 1. The absorption spectra of photolime gel (Gel) film, chlorophenol red doped (CR/Gel 23 wt. %) film, and  $\text{NdCl}_3$  (2.1 wt. %) and chlorophenol red (23 wt. %) codoped ( $\text{Nd}^{+3}/\text{CR}/\text{Gel}$ ) film. The thickness of the three samples are 5, 4.7, and  $4.8 \mu\text{m}$ , respectively.

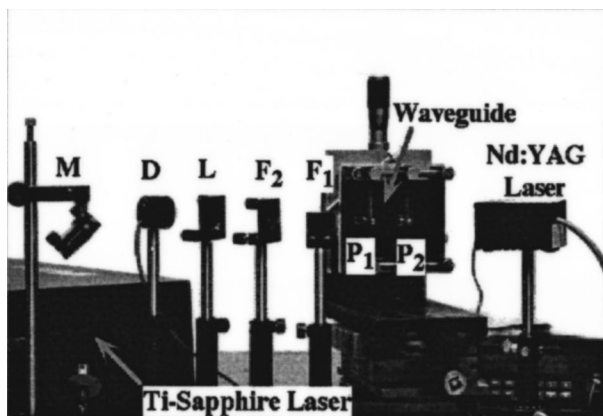


FIG. 2. Photograph of amplification measurement setup. M: Beam steering device. D: detector. L: lens. F<sub>1</sub>: rejection filter. F<sub>2</sub>: band-pass filter at 1.06 μm. P<sub>1</sub> and P<sub>2</sub>: coupling prisms.

and 796 nm, as indicated in Fig. 1. The pumping efficiency reached maximum around 745 nm and 796 nm, respectively, and decreased slowly when the pump wavelengths were detuned away from the peaks.

To further evaluate the EO effect of the same Nd<sup>3+</sup>/CR/Gel film, upon which the amplification phenomena was observed, contact poling was performed at its glass transition temperature (185 °C). A 0.2-μm-thick aluminum layer was deposited on a glass substrate by e-beam evaporation, to fabricate an electrode for poling and electro-optic modulation. The Nd<sup>3+</sup>/CR/Gel film was spin coated directly on the Al electrode. An optically transparent indium tin oxide (ITO) layer was made on top of the Nd<sup>3+</sup>/CR/Gel film to serve as the second electrode. Figure 4 shows the setup for the electro-optic coefficient measurement using the optical retardation method.<sup>15,16</sup> A 10 mW HeNe laser beam was coupled from the back of the glass substrate. It propagates through the substrate, the transparent ITO layer, the Nd<sup>3+</sup>/CR/Gel film, and then was reflected back by the Al electrode. The beam reflected from the Al coating propagated through a Soleil-Babinet phase compensator, an analyzer, and into a photodiode. In the experiment, the polarization of the inci-

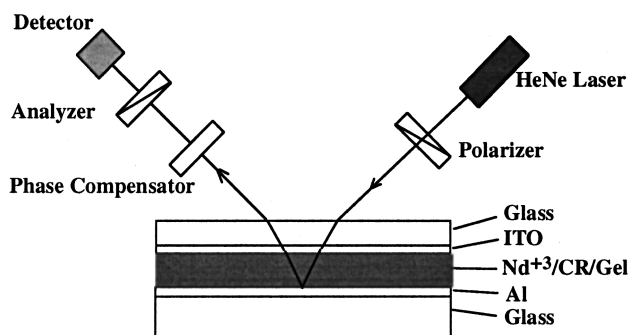


FIG. 4. Schematic diagram for electro-optic coefficient measurement.

dent beam was set at 45° to the incident plane, so that the parallel and perpendicular components of the optical field were equal in amplitude. The analyzer was set at a cross-polarization angle with respect to the polarizer. The EO modulation in the beam was measured through a lock-in amplifier. For a sample prepared with 6.7×10<sup>19</sup>/cm<sup>3</sup> of Nd<sup>3+</sup> and 23 wt. % of chlorophenol red, its electro-optic coefficient *r*<sub>33</sub> at the wavelength of 633 nm was experimentally confirmed to be 22 pm/V with a poling strength of 200 V/μm. Note that the optical gain and electro-optic coefficient were observed at the same device after the poling experiment.

In summary, an active dual-functional polymeric waveguide was fabricated through simultaneously doping NdCl<sub>3</sub>·H<sub>2</sub>O and chlorophenol red in photolime gel polymer matrix. Both optical amplification and electro-optic effect were observed in the waveguide simultaneously. The doping concentrations of Nd<sup>3+</sup> and chlorophenol red were investigated to get the optimum amplification and EO modulation. The optimized doping concentrations of Nd<sup>3+</sup> and chlorophenol red in gelatin were 6.7×10<sup>19</sup>/cm<sup>3</sup> and 23%, respectively. A 3.8 dB of amplification gain and 22 pm/V of electro-optic coefficient were demonstrated.

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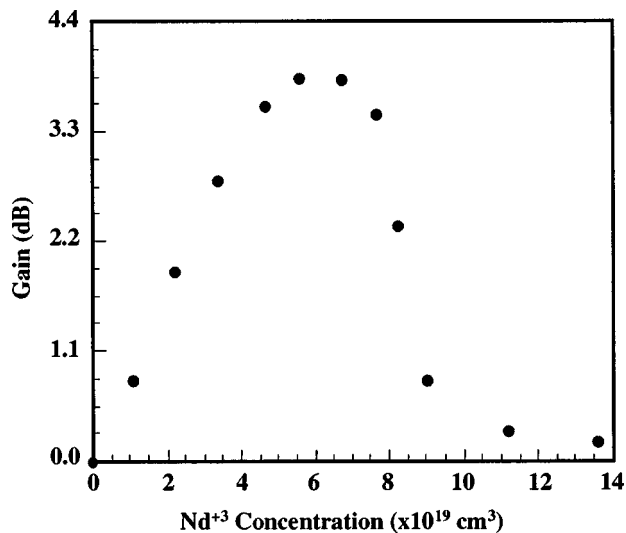


FIG. 3. Dependence of optical gain on Nd<sup>3+</sup> concentration, for a signal of 1 mW at 1.06 μm, pumped by 50 mW laser at 796 nm. The doping concentration of chlorophenol red was 23 wt. %.

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