Dual-functional Polymeric Waveguide with Optical Amplification and Electro-optic Modulation

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ABSTRACT

Optical amplification and electro-optic modulation have been observed simultaneously in one polymeric material photo-lime gel which has been used as a volume holographic material to produce dichromated gelatin (DCG) films. In this paper, the dual functions were achieved by doping neodymium chloride hexahydrate ($NdCl_3 \cdot 6H_2O$) and chlorophenol red ($C_{19}H_{12}Cl_2O_5S$). The optimized doping concentrations of Nd^{+3} and chlorophenol red were 6.7×10^{19} /cm^3 and 23% respectively. We observed a gain of 3.8 dB at 1.04 μm and an electro-optic coefficient of 30 pm/V at 633 nm. The experimental results confirms that the co-doping process does not degrade the respective functions of Nd^{+3} for optical amplification and chlorophenol red for electro-optic modulation.

Keywords: optical amplifier, electro-optic modulation, polymeric waveguide.

Dichromated gelatin (DCG) has been used widely as a volume hologram emulsion for many years[1]. A myriad of optical elements, such as wavelength division multiplexers, laser filters, cavity mirror for electro-optic modulation, and display holograms, has been demonstrated using this polymeric material[2-12]. 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 paper, we report a dual-functional polymeric waveguide using the same host polymeric material for DCG. The host material photo-lime gelatin is co-doped with neodymium chloride hexahydrate ($NdCl_3 \cdot 6H_2O$) and chlorophenol red ($C_{19}H_{12}Cl_2O_5S$). Neodymium chloride hexahydrate (NCH) is doped to provide Nd^{+3} ions for amplification, and chlorophenol red (CR) to provide electro-optic (EO) modulation.

Aqueous solution of photo-lime gel has a unique sol-gel ability to form a low loss waveguide[12]. However, the solubility of chlorophenol red in water is low (less than 30 mg/ml). Ethylene glycol (EG) can dissolve chlorophenol red very well, but partially dissolve gelatin. In order to get a higher doping concentration of chlorophenol red, so as to get a higher EO coefficient, we developed a fabrication procedure, as shown in Figure 1.

Gelatin and $NdCl_3 \cdot 6H_2O$ were dissolved in water, and kept in hot bath for 4 hours at 80°C, while chlorophenol red was dissolved in ethylene glycol ($HOCH_2CH_2OH$) and kept in hot bath for one hour at 80°C. The ratio of ethylene glycol and water was 2/3. The two solutions were mixed together and put in water 80°C bath for another 4 hours. A uniform solution containing Nd^{+3} ions and CR chromophore was thus formed. The quality of the solution is pivotal to make a high-performance waveguide. The concentration of photo-lime gel in the mixed solution was 100 mg/ml. Waveguide films were spin-coated on glass substrate, and dried in vacuum at 80°C. The thickness of the film was controlled within 3~5 µm by changing the spin speed.

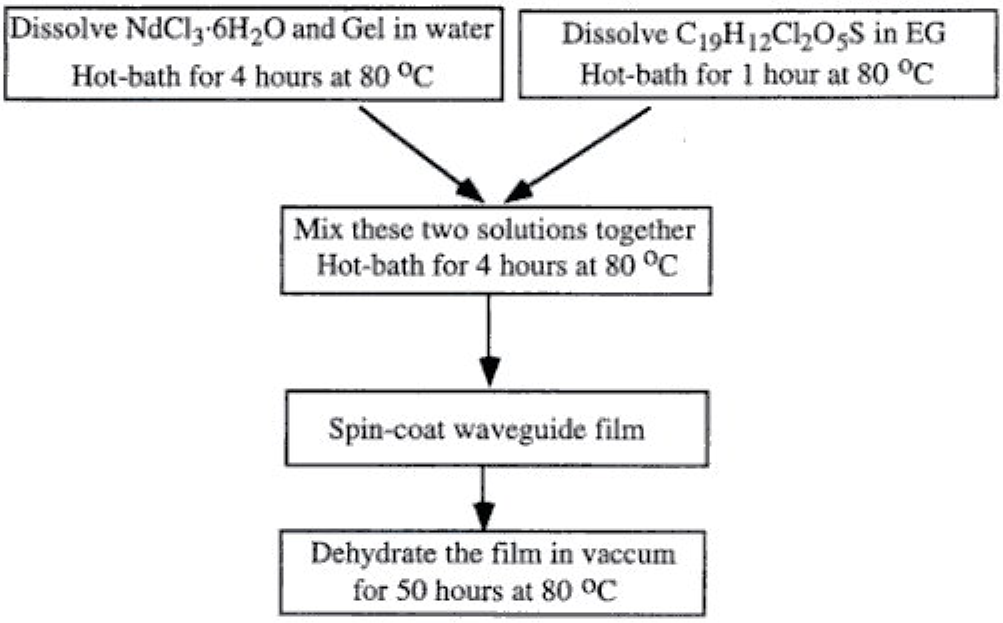


Fig. 1 Procedures to Make a Waveguide Film

The absorption spectra of three samples, a photo-lime gel (Gel) film, a chlorophenol red doped gel (CR/Gel) film, and an Nd^{+3} and chlorophenol red co-doped gel (Nd^{+3}/CR/Gel) film, shown in Figure 2, were measured with a Lambda spectrometer. Within the range of 400-1200 nm, four main absorption bands were observed, centered at 433nm, 578nm, 745nm, and 796nm. The first strong absorption band is due to chlorophenol red. The other three smaller bands of absorption correspond to the transitions of Nd^{+3} from ground state ($^4I_{9/2}$) to excited states of ($^2G_{7/2}$), ($^4F_{7/2}$), and ($^4F_{5/2}$), respectively. The absorption spectrum due to Nd^{3+} is very similar to that of Nd^{3+} doped silica fibers [13].

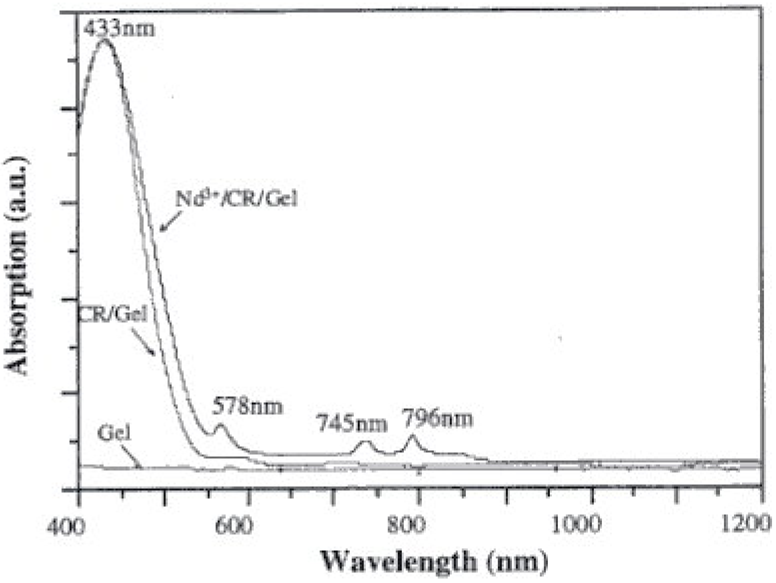


Fig. 2 The Absorption of Waveguide Films with Different Dopants
(1) No doping in **Gel** film; (2) CR is 23 wt. % in **CR/Gel** film;
(3) $NdCl_3$ and CR are 2.1% and 23% by weight in **Nd^{+3}/CR/Gel** film

Table 1 shows the propagation losses of waveguides of photo lime gelatin doped with Nd^{+3} and chlorophenol red at 796 nm (for pump beam) and 1064 nm (for signal beam). The thicknesses of the waveguides were ~3 μm, coated on BK-7 glass substrate (n=1.515 at 593 nm). The propagation losses at 1064 nm were in the neighborhood of 0.3-0.4 dB/cm for all of the waveguides. This shows that the simultaneous doing of $NdCl_3 \cdot 6H_2O$ and chlorophenol red has little effect on the absorption at 1064 nm. However, significant losses were observed in Nd^{+3}/CR/Gel films at 796nm. Apparently, the loss was caused by Nd^{+3} ion absorption.

Table 1 Propagation Loss of Light in Gelatin-based Waveguides

Waveguide Samples	Nd^{+3} ($10^{19}/cm^3$)	Composition (wt .%)			Propapation Loss (dB/cm)	
		$NdCl_3$	CR	Gelatin	796nm	1064nm
1. Gel	0	0	0	100	0.30	0.28
2. CR/Gel	0	0	23	77	0.39	0.37
3. Nd^{+3}/CR/Gel	6.7	2.1	23	74.9	1.94	0.40
4. Nd^{+3}/CR/Gel	11.2	3.5	23	73.5	5.13	0.40

Figure 3 shows the set-up 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, as indicated in Figure 3. The 1064nm signal beam was provided by an Nd:YAG laser, and coupled into the waveguide using the Prism P_2. Note that P_1 also functions as the output prism for the signal beam. The pumping beam and the signal beam were carefully aligned to ensure the overlap with each other to get the optimum amplification. A laser beam analyzer and an infrared CCD camera were employed for the alignment. The 1064 nm amplified signal was detected after passing through a wavelength-filtering system containing a rejection filter F_1, and a laser band-pass filter F_2 both working at 1064 nm.

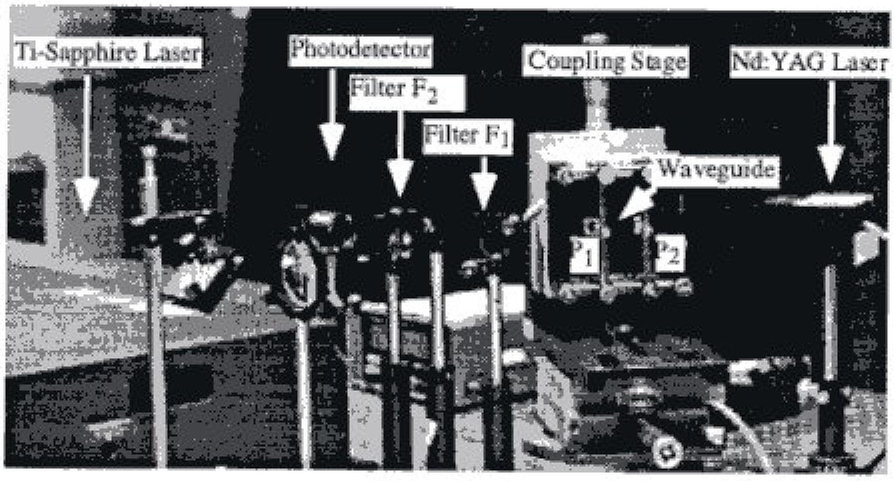


Fig. 3 Photograph of Amplification Measurement Setup

The optical amplification was experimentally confirmed to be dependent on the pumping power, the Nd^{+3}-doping concentration, and the interaction length of the signal and pump beams. Figure 4 shows the variation of optical gain versus the pumping power with Nd^{+3} doping concentration of $6.7x10^{19}/cm^3$ (sample 3 of Table 1). The interaction length of the signal and pumping beams in the waveguide was fixed to 1.8 cm. For this sample a saturated gain of 3.8 dB was observed, corresponding to a pump power of 49 mW.

The relationship between the gain and the concentration of Nd^{+3} is further illustrated in Figure 5. The concentration of chlorophenol red of all the waveguides was fixed at 23 wt. %. The optimized concentration of Nd^{+3} for amplification was $\sim 6.7x10^{19}$ /cm^3. Gain quenching occurred seriously when Nd^{+3} doping concentration was higher than $7.8x10^{19}$ /cm^3.

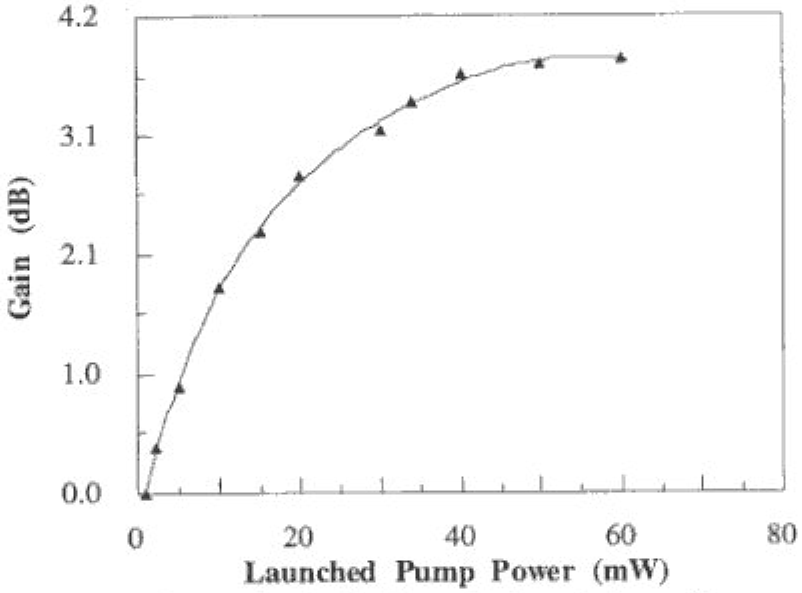


Fig. 4 Dependence of optical gain on the launched pumping power Signal: 1 mW at 1064 nm; Pumping at 796nm (Sample 3 of Table 1)

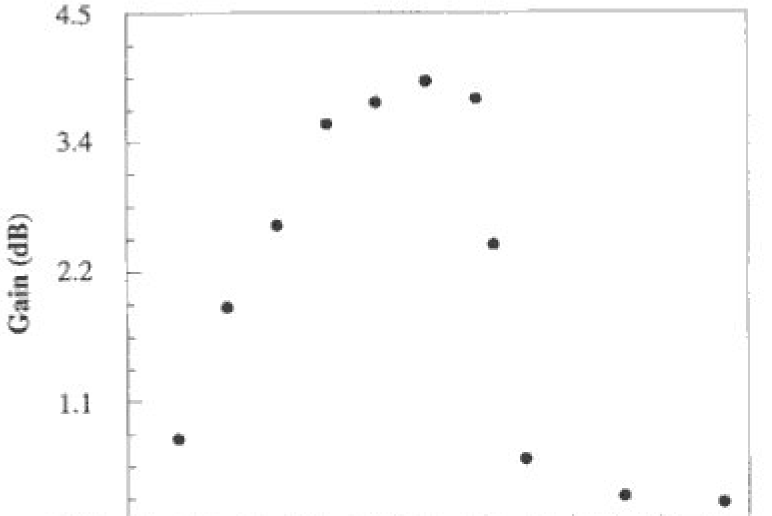


Fig. 5 Dependence of Optical Gain on Nd^{+3} Concentration Signal: 1mW at 1064 nm; Pump: 50 mW at 796nm. The CR concentrations of the waveguides are all the same, 23 wt. %

Nd^{3+} has two broad absorption bands centered at 745 nm and 796 nm, as indicated in Fig. 2. These absorption bands were further confirmed by the measurement of gain versus pumping wavelength, shown in Figure 6. The pumping efficiency reached maximum around 745 nm and 796nm and decreased slowly when the pump wavelength was detuned away from the peaks.

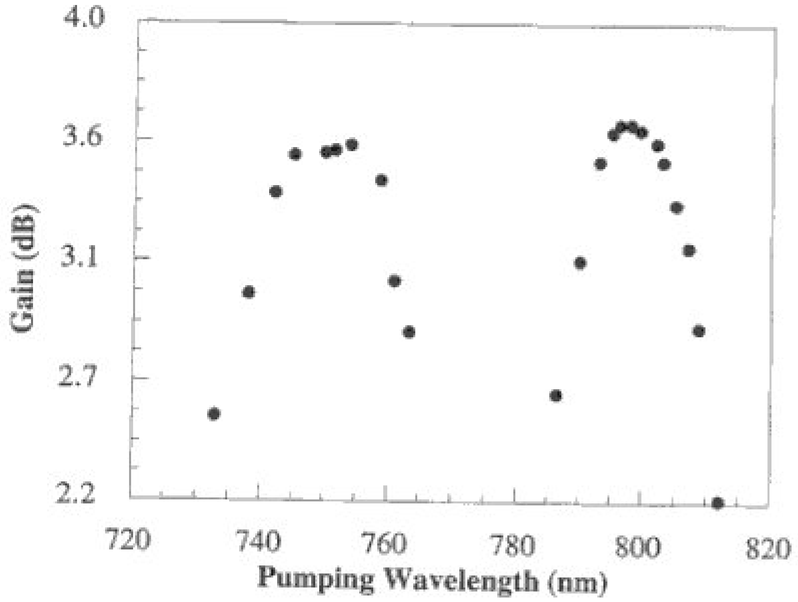
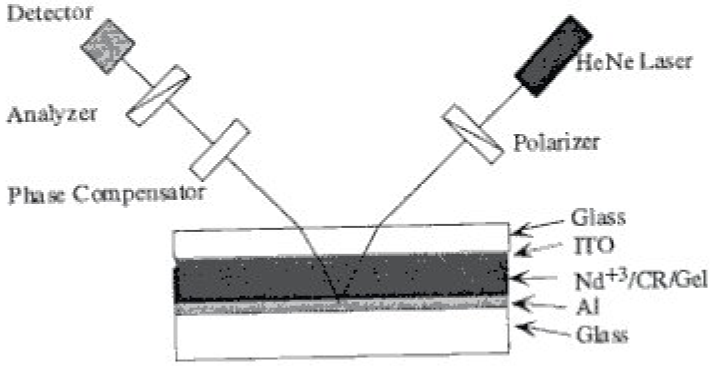
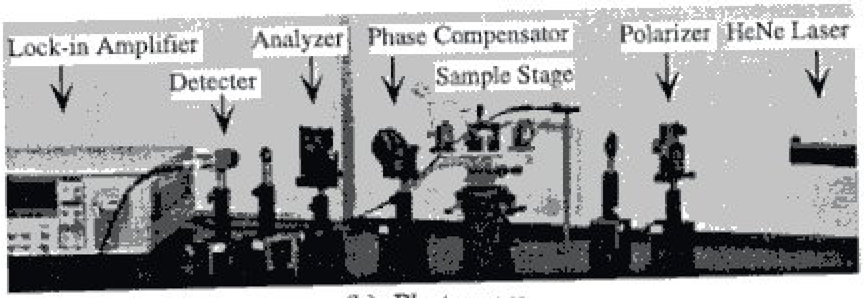


Fig. 6 Dependence of gain on pumping wavelength for Sample 3 in Table1
Signal: 1 mW at 1064 nm; Pump: 50 mW

To further evaluate the EO effect of the same Nd^{+3}/CR/Gel film, upon which the amplification phenomena was observed, contact poling was performed at the glass transition temperature. A 0.2μm-thick aluminum layer was deposited on a glass substrate by E-beam evaporation, to fabricate an electrode for poling and modulation. An Nd^{+3}/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^{+3}/CR/Gel film to serve as the second electrode. Figure 7 shows the setup for the electro-optic coefficient measurement using the optical retardation method. A 10mW HeNe laser beam was coupled from the back of the glass substrate. It propagates through the substrate, the transparent ITO layer, and the Nd^{+3}/CR/Gel film , and then is reflected back by the Al electrode. In our experiment, the polarization of the incident 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 beam reflected from the Al coating propagated through a Soleil-Babinet phase compensator, an analyzer, and into a photodiode. 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.



(a) Schematic Diagram



(b) Photogram

Fig. 7. Setup for Electro-optic Coefficient Measurement

The electro-optic coefficient r_{33} was calculated using the following equation[14]:

$$r_{33} = \frac{3\lambda I_m}{4\pi V_m I_c n^2} \frac{(n^2 - \sin^2\theta)^{3/2}}{(n^2 - 2\sin^2\theta)} \frac{1}{\sin^2\theta}$$

where λ is wavelength, θ is incident angle, V_m is the amplitude of the electrical modulating signal, I_m is the peak intensity of the detected ac optical signal, and I_c is the half intensity of the dc optical signal. For Sample 3 in Table 1, prepared with 6.7×10^{19} /cm^3 of Nd^{+3} and 23 wt. % of chlorophenol red, its electro-optic coefficient r_{33} at the wavelength of 633 nm was experimentally confirmed to be 30 pm/V with a poling strength of 200V/µm. Figure 8 shows the modulation characteristics of this device on an oscilloscope. The upper curve is the electrical modulating signal. The bottom curve is the corresponding modulated optical signal from a HeNe laser. Note that the amplification of 3.8 dB and the EO coefficient of 30 pm/V at 633 nm were observed at the same device after the poling experiment.

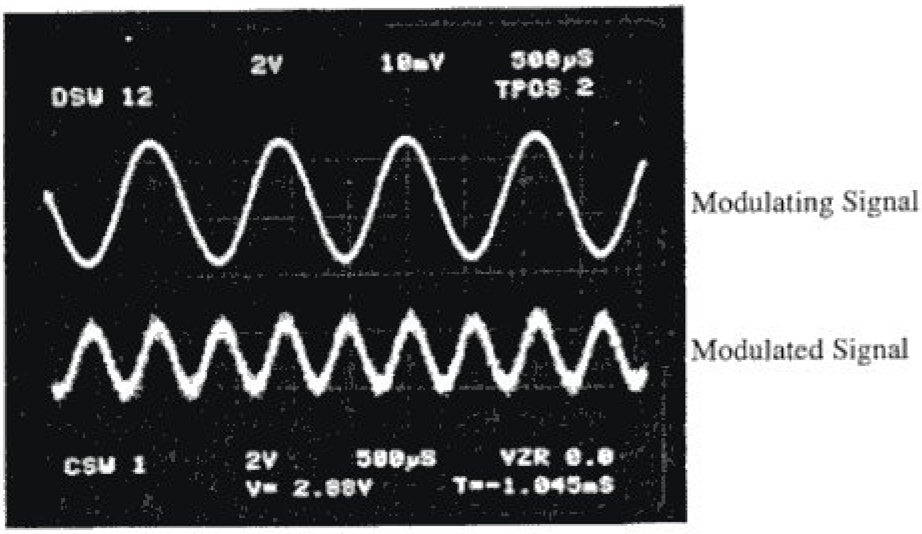


Fig. 8 Modulation characteristics of Sample 3 in Table 1

In summary, an active dual-functional polymeric waveguide was fabricated through simultaneously doping $NdCl_3 \cdot H_2O$ and chlorophenol red in photo-lime gel polymer matrix. Optical amplification and electro-optic effect were observed in the waveguide simultaneously. The doping concentrations of Nd^{+3} and chlorophenol red were investigated to get the optimum amplification and EO modulation. The optimized doping concentrations of Nd^{+3} and chlorophenol red in gelatin were 6.7×10^{19} /cm^3 and 23%, respectively. A 3.8 dB of amplification gain and 30 pm/V of electro-optic coefficient were demonstrated.

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