Investigations on europium aluminum incorporated polymer composite optical waveguide amplifier

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Abstract. The gain performance of 50-µm core diameter graded-index (GI) multimode europium aluminum benzyl methacrylate (Eu-Al/BzMA) waveguide was investigated by numerically solving rate and propagation equations using MATLAB. At a fixed waveguide length of 10 cm and gain medium concentration of 13 wt.%, optical gain was found to be dependent on pump power and input signal power. This paper utilized a 532 nm wavelength pump with power varied from 100 mW to 500 mW, together with low (-30 dBm) and high (0 dBm) input signal powers, within the amplification range of 580 to 640 nm wavelength. With the highest pumping power of 500 mW and the lowest input signal power of -30 dBm, a 29-dB optical gain with wavelength of 617 nm was observed from forward pumping amplification. For comparison, an identical waveguide in terms of properties was fabricated through an innovative fabrication method for polymer waveguide—the Mosquito method. The fabricated waveguide was then experimentally tested for -30 dBm input signal power with 200 mW pump power in the attempt to realize future real-world applications of short reach networks such as in Local Area Network (LAN) and in-vehicle optical interconnects.

1. Introduction

Visible light wavelength technology has been developing rapidly until now, with applications seen in products such as high-end routers, high-performance computers (HPCs) [1], medical imaging devices [2], automotive applications [3-5], board-level interconnects [6] and home local area network (LAN). Additionally, for short-distance optical reach applications like in-vehicle optical networks, optical amplifiers are deemed necessary to fulfill the demand for data rates, not only in connecting vehicular infotainment systems but also the control systems and other safety systems such as airbags [5, 7]. Apart from that, optical amplifiers are a requisite for LAN. It is important to compensate for the losses that accumulate throughout the polymer optical fiber (POF) transmission by enhancing the optical signal through optical amplifiers. To date, rare earth metal-doped material amplifiers like europium (Eu^{3+}) to polymer bases have developed such that they can operate in the region of visible wavelength. Some examples include, europium thenoyltrifluoroacetonate ($Eu(TTFA)_3$) doped polymethyl methacrylate (PMMA) [8], europium di-benzoyl methane (Eu(DBM)3-phen) doped PMMA [9], $Eu(TTFA)_3$ doped di-dodecyl dimethyl ammonium ($(C_{12}H_{25})_2(CH_3)_2N^+$) [10], deoxyribonucleic acid-cetyltrimethylammonium (DNA-CTMA) biopolymers [11], Norland optical adhesive (NOA) polymers

[12] and Eu-doped ultraviolet (UV)-curable epoxy-based negative photoresist (SU8) polymers [13]. As a matter of fact, polymeric materials are a promising candidate for optical amplifiers since the materials exhibit low absorption losses in the visible light wavelength region [14-16].

It is known that in order to attain a highly efficient signal amplification, the concentration of the gain medium should be higher; achievable by increasing the RE ions. However, such high concentration of RE ions from doping may result in *concentration quenching*. Hence, obtaining a high-concentration gain medium by the addition of RE ions is rather unfeasible. To address this problem, amplifiers with RE metals (RE-M) incorporated in polymer composites came into development; for instance, europium aluminum benzyl methacrylate (Eu-Al/BzMA), whereby Eu^{3+} and Al^{3+} were selected as the RE metal and metal ions, respectively. It was previously tested and had recorded a satisfactory result in optical gains [17-20]. Although many experimental results on such waveguide amplifiers had been reported before, numerical analysis for the optical gain performance has yet to be attempted. Therefore, in this study, parameter optimizations were conducted on various pump powers and input signal powers to investigate the dependency of the optical gain of the Eu-Al/BzMA optical waveguide amplifier on these parameters. Apart from that, an exact waveguide was fabricated by using the Mosquito method, which is one of the fabrication methods for polymer waveguides. An optical gain experiment was then carried out to assess the measured optical gain results, which was to be compared with the preliminary results from numerical analysis. This is for the purpose of designing the waveguide with desired behaviors.

2. The amplifier models

Since in this work, Eu^{3+} was chosen as the rare earth (RE) dopant, it is paramount to scrutinize the properties and energy transfers of Eu^{3+}. It has an atomic number of 63 and electronic configuration of [Xe] $4f^7 5s^2 5s^6 6s^2$. The general amplification mechanism of this waveguide can be understood from the energy level of Eu^{3+} as illustrated in Figure 1. There are several stages in the energy transfer of Eu3+. First, the absorption of ultraviolet energy (~350 nm wavelength) by Eu^{3+} ions is due to the ground state to the excited state absorption of the organic ligand as the gain medium is pumped. The excitation of the ligand from the singlet ground state (S_0) to the singlet upper state (S_1) only occurs after the absorption of energy. Next, the photon undergoes the intersystem, crossing to the triplet state (T_1) after vibrational relaxation. Both processes take place by radiationless transition.

Concurrently, competing ligand fluorescence and radiationless deactivation of the excited singlet are released as thermal energy. Afterwards, the radiationless energy transfers from T_1 and couples with the ^5D energy levels of Eu^{3+} ions. The population inversion occurs from upper to lower levels of ^5D. The most intense emission line appears at 617 nm and is due to the transition of $^5D_0$ to $^7F_2$. This strong emission from $^5D_0$ to $^7F_2$ of the Eu^{3+} ion is a result of highly polarized ligand fields surrounding the Eu^{3+} ion. In short, it can be concluded that optical amplification occurs when stimulated emissions happen, which is due to population inversion resulting from the excitation of ions at ground energy level to an upper energy level.

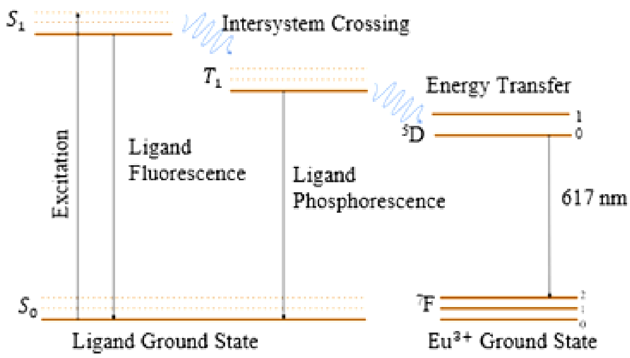


Figure 1. Schematic diagram of Eu^{3+} energy levels

However, for amplifier modelling purposes, the three-level system can be approximated by a two-level system by implementing the propagation and rate equations into Desurvire erbium-doped fiber amplifier (EDFA) model [21]. Since the waveguide core in this research is circular, it can be simulated by using a two-level system model with uniform spread. The procedures to run the computational model are almost similar to that of other RE material amplifiers. Hence, this study assumed the MATLAB coding function by Baskar [22], which adopted the Fourth Order Runge-Kutta method with modifications on pump power; besides the adjustments on the parameters from the propagation equation with negligible spontaneous emission factor.

3. Numerical calculation and results

In this section, the gain performance of Eu-Al/BzMA optical waveguide amplifier was numerically calculated by using MATLAB for various pump powers with low (-30 dBm) and high (0 dBm) input-signal powers. These calculations were based on the rate and propagation equations with the parameters tabulated in Table 1.

Table 1. Parameters of Eu-Al/BzMA waveguide amplifier

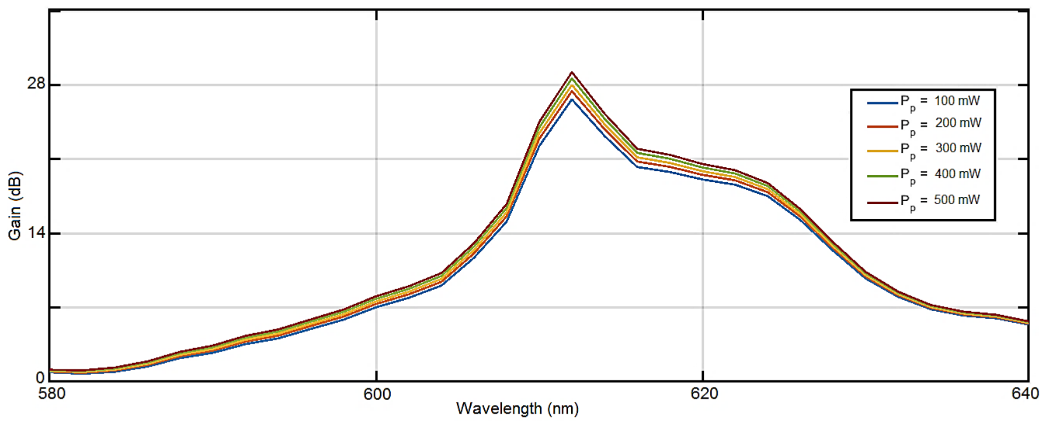
Parameters	Symbol	Unit	Values
Index core radius	a	m	25×10^{-6}
Core radius	b	m	25×10^{-6}
Index step	Δn	-	0.007
Excitation length	L	m	1×10^{-3}
Core refractive index	n	-	1.51
Cladding refractive index	n	-	1.501
The fluorescence lifetime of metastable level	τ	s	4.92×10^{-4} [23]
Signal wavelength	λs	m	617×10^{-9}
Pump wavelength	λp	m	532×10^{-9}
Signal absorption cross-section	α_{as}	cm^2	5.62×10^{-22}
Signal emission cross-section	α_{es}	cm^2	1.33×10^{-20}
Pump absorption cross-section	α_{ap}	cm^2	6.10×10^{-22}
Pump emission cross-section	α_{ep}	cm^2	0
Total population density	N_t	-	2.84×10^{-23}

In this research, the pump powers were varied from 100 to 500 mW within the wavelength range of 580 to 640 nm for both input signal powers as shown in Figure 2(a) and Figure 2(b). Here, the gain amplification performance was analyzed for a fixed-length waveguide of 10 cm to attain the preliminary results. From the results, the optical trends were somewhat similar for all pump powers and both input signal powers. The highest amplification can be seen from the peak at the wavelength of 617 nm. This is because the 617-nm wavelength was deemed to be at a high excitation level. Besides that, the amplification was also due to higher absorption as well as weaker Eu^{3+} emission level for wavelengths less than 617 nm. Hence, the optical gain focused on the wavelength of 617 nm.

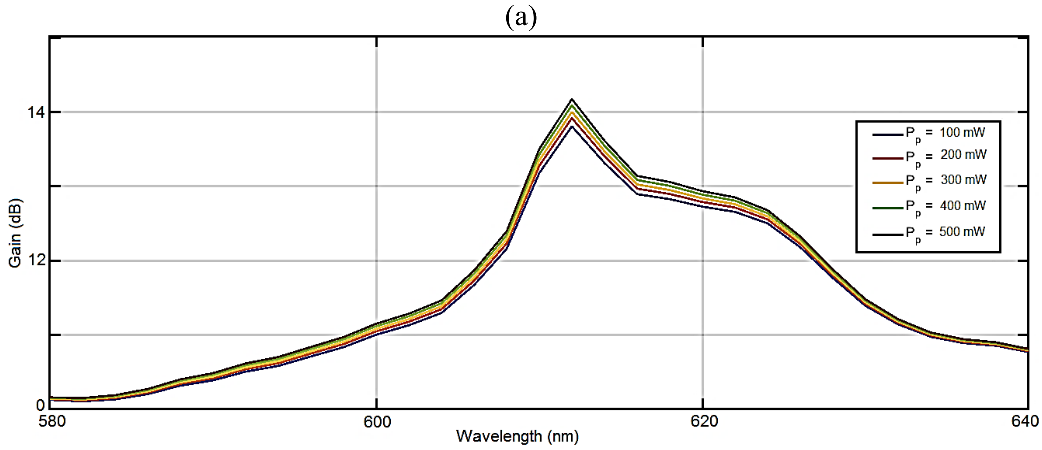
At the wavelength of 617 nm, the highest pump power of 500 mW recorded the highest optical gains, which were 29 dB for input signal power of -30 dBm and 14.2 dB for input signal power of 0 dBm. This was followed by the 400-mW pump power, with the optical gain of 28.5 dB for input signal power of -30 dBm and 14.1 dB for input signal power of 0 dBm. Meanwhile, the lowest optical gains were documented from the lowest pump power of 100 mW; with 25-dB and 13.8-dB optical gains for the input signal power of -30 dBm and 0 dBm, respectively. In short, the decrease in optical gain with decreasing pump power is mainly due to the decrease in total power coupled to the waveguide core, which reduces the emissions that result in a lower amplification of gain. Similar findings have been observed from other studies that investigated the relation between optical gain of the polymer waveguide amplifier based on Eu^{3+} and the pump power [12, 24].

Apart from that, correspondingly, the optical gain depicted a decreasing trend with increasing input signal power. For instance, at 300 mW pump power the optical gain of -30 dBm input signal power was 28 dB, which was double in comparison to that of the input signal power of 0 dBm. This was believed to occur due to the depletion of energy by a high-rate stimulated emission as the input signal power was larger. The rate of Eu^{3+} ions to be excited for population inversion is constant for a fixed pump power. Therefore, when the input signal power is increased over the small-signal region, more photons are entering the gain medium to stimulate emission and thus deplete the energy faster than it can be filled. Hence, the output power may reduce or saturate with increasing input signal power once it reaches a particular limit.

Overall, the -30 dBm input signal power with 500 mW pump power was found to give the highest optical gain about 29 dB, whereas the lowest optical gain was 13.8 dB from the 0 dBm input signal power with 100 mW pump power.



(a)



(b)

Figure 2. Gain performance for Eu-Al incorporated polymer optical waveguide amplifier by varying pump power at input signal power of (a) -30 dBm and (b) 0 dBm

4. Fabrication

To realize the gain performance of the Eu-Al/BzMA optical waveguide amplifier, a waveguide with similar dimensions (length of 10 cm and circular core diameter of 50 µm) was fabricated by using the Mosquito method; an innovative method to fabricate polymer waveguides [17, 18, 25-30]. In the initial stage of the Mosquito method—the cladding coating—a 17 × 2.5 cm silicon sheet with a thickness of 500 µm was placed on a 21 × 3 cm glass substrate, of which a 15 × 1 cm frame was cut away from the silicon sheet by using a razor. Afterwards, the surface of the substrate was cleaned with ethanol to circumvent the presence of dust, dirt particles and also grease. The cladding monomer, XCL01 with 5000 cPs viscosity was filled in the frame cavity of the prepared silicon sheet as illustrated in Figure 3(a). At this point, a cover glass was used to make the height of the liquid on the upper surface as uniform as possible. The process of cladding coating was completed in a clean chamber space under the exposure of yellow light to avoid photodegradation that can affect physical, mechanical and chemical properties of the polymers.

Next, the core monomer, Eu-Al/BzMA with 13 wt.% concentration and 2000 cPs viscosity was inserted into a syringe attached to the tube of a dispenser for the core dispensing process. Core dispensing was based on the parameters appropriate for the fabrication of a 50-μm core diameter waveguide. After dispensing the core monomer into the cladding monomer, as shown in Figure 3(b), the core and cladding monomers were diffused into each other for a suitable interim time since both monomers were miscible for concentration distribution. The interim time here refers to the time delay or gap between the exposure standby time until the ultraviolet exposure is finished. By optimizing the interim time, the waveguide with an ideally parabolic graded index profile is formed in the circular cores. Then, ultraviolet rays were slightly irradiated from ultraviolet light emitting diodes (UV-LED) connected adjacent to the holder of the dispenser machine, whereby the cladding monomer was completely cured through photopolymerization as shown in Figure 3(c). This process is known as UV curing. Consecutively, the waveguide was kept in a thermal incubator (Eye land ND 500) with temperature set at 70 °C for about 90 minutes to allow the core monomer to be completely cured as in Figure 3(e) through thermal polymerization as shown in Figure 3(d).

As soon as the thermal polymerization was complete, the silicon sheet frame on the glass substrate was removed and the cured waveguide was peeled gently from the glass substrate using a razor. The razor was put in a cross-section, orthogonal to the longitudinal direction of the waveguide to obtain a 10 cm length of the peeled waveguide. Then, the end-facet was polished by using different sandpaper roughness to obtain a smoother facet surface so that the core could be observed and with that, the waveguide was ready to be tested.

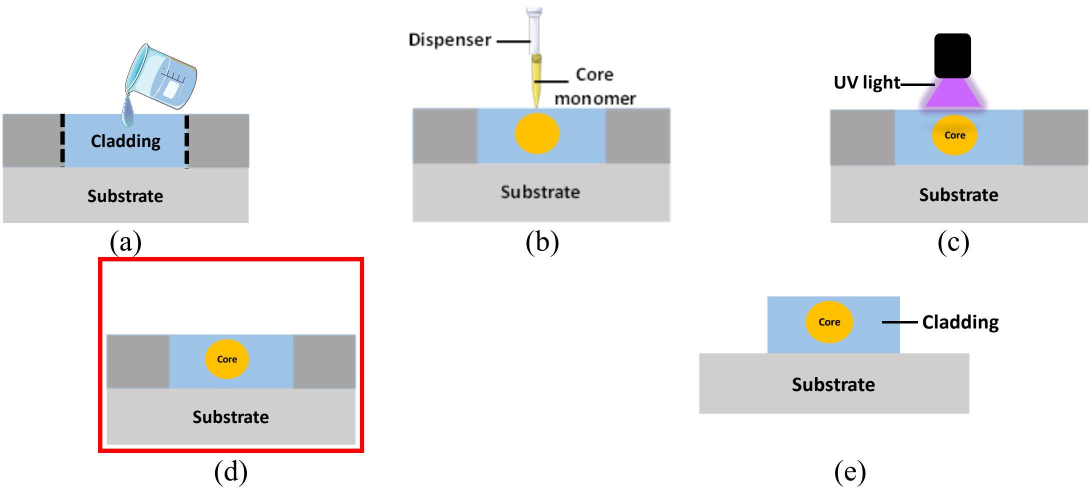


Figure 3. Overview of a fabrication technique for Eu-Al incorporated polymer optical waveguide amplifier (a) cladding coating; (b) core dispensing; (c) UV curing; (d) thermal polymerization and (e) fabricated waveguide

5. Experimental results

The optical gain of the fabricated waveguide was measured in a similar manner to Saris et al. [20] by using a 50-μm core GI-MMF coupler. The measurement of signals, the pumping signal and the coupled signal of input and light pump, were made separately. Consequently, the gain without any noise such as the amplified spontaneous emission could be obtained by using mathematical subtraction.

For this research, forward pumping was applied. The amplification occurred within the wavelength range of 580 to 640 nm under the 532-nm laser pump excitation of a diode-pumped solid-state (DPSS) laser diode with -30 dBm input signal power. In this case, only the -30 dBm and 200 mW were selected as the input signal power and pump power, respectively, for instrument safety reasons and practicality in real-world applications. The result of the optical gain amplification was collected by utilizing Optical Spectrum Analyzer (OSA). Three measurement steps were involved and each step is explained as follows:

Step 1:

- Only the signal light was made incident to the waveguide using a fiber coupler and the light emitted from the waveguide was received by the OSA using the light receiving probe.

Step 2:

- The signal was kept switched on the same way as in Step 1. Then, the pump was turned on to supply the excitation light to the waveguide. Then, the light emitted from the waveguide was measured.

Step 3:

- The signal source was switched off. Only the excitation light was made incident to the waveguide. The outgoing light from the waveguide was measured.

The output from each step is illustrated in Figure 4 (a), (b) and (c). Step 1 and Step 3 indicated the measured output of the Signal (s) and Pumping (p) from the waveguide, respectively. Step 2 indicated that (p) is coupled with (s) resulting in (s and p coupled). For calculating the optical gain, the algebraically added spectrum of (s) and (p) were also plotted and resulted in (s and p added). The difference between (s and p coupled) and (s and p added) was calculated by using Microsoft Excel, which corresponded to the optical gain.

Figure 4(a) Output of switching on the 617 nm LED signal only (Step 1)

Figure 4(b) Output of switching on both 617 nm LED signal and 532 nm pump (Step 2)

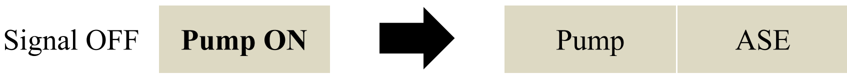


Figure 4(c) Output of switching on 532 nm pump only (Step 3)

For experimental purposes, several measurements were made to acquire better results for the optical gain. Table 2 shows the results of the measured optical gain for the 10-cm Eu-Al/BzMA waveguide amplifier. Contrary to expectation, the average measured optical gain was found to be 12.19 dB. It differed by 53.12% from the simulation result, which documented an optical gain of 26 dB for 200 mW pump power and -30 dBm input signal power. This contradictory result was believed to be due to errors during fabrication and measurement of the waveguide, which led to optical loss that affected the waveguide gain performance. However, the measured result was still acceptable, since the gap was not so huge.

Table 2. The optical gain for 10-cm Eu-Al/ BzMA waveguide amplifier (200 mW pump power and -30 dBm input signal power)

Measurement Attempt	**1st**	**2nd**	**3rd**	**4th**	**5th**
Optical Gain (dB)	12.13	11.23	10.82	10.44	16.27

6. Conclusion

In summary, a theoretical study on the effect of pump power and input signal power on the optical gain of 10-cm Eu-Al/ BzMA optical waveguide amplifier was presented in this research. It has been shown that the optical gain can be amplified by maximizing the total pump power injected into the system. The highest optical gain was observed at 617 nm wavelength through forward pumping of the 10 cm waveguide, by which the signal gain of 29 dB was obtained with 500 mW pump power and -30 dBm input signal power. Therefore, the optical gain of the Eu-Al/BzMA amplifier is strongly dependent on pump power and input signal power.

Apart from that, a waveguide with similar properties as the simulation was fabricated in the attempt to realize the gain performance of the waveguide with the pump power of 200 mW for practical uses. The average measured optical gain was found to be 12.19 dB, whereas that of the simulation was 26 dB. In short, more detailed work needs to be carried out so that more accurate measurements can be attained, e.g. enhancement of pump power density by decreasing the diameter of the fiber coupler core for pumping light without increasing pump power intensity (fixes the pump power value). Overall, the simulation result suggests the indicators that may act as guidelines in designing an ideal waveguide amplifier based on the rate and propagation equations.

Acknowledgment

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