Compact Er^{3+}-Doped ZBLAN Green Upconversion Fibre Laser

Syed Sohail Abbas, Sergei Popov

Abstract**—**In this paper, a fibre laser at 546 nm has been studied for a signal power of -30 dB. Er^{3+}-doped ZBLAN fibre has been used by upconversion pumping of a 980 nm laser diode. Gain saturation effect has been investigated in detail. Laser performance has also been discussed. An efficiency of 35% has been calculated with a length of 5 mm fibre laser. Results show that Er^{3+}-doped ZBLAN is a promising candidate for optical amplification at 546 nm.

Keywords**—**Compact visible lasers, Erbium doped, Gain saturation, Green laser, Optical fibre lasers

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I. Introduction

Fibre lasers are widely used in telecommunication, material processing, spectroscopy and medicine. They can provide high optical gain because of several kilometer long active regions. They produce a high quality optical beam by reducing the thermal distortion of the optical path. Because light is already coupled into a fiber so it can be easily delivered to a focusing element for cutting, welding etc. They are compact as compared to gas lasers of the same efficiency because they can be bent/coiled to save the space.

A potential candidate for 546 nm gain medium is Er^{3+}-doped ZBLAN pumped at 980 nm [1]. The stimulated emission from $^4S_{3/2} \rightarrow {^4I_{15/2}}$ can produce an amplification of 546 nm. At high pump power, the strong gain saturation effects limit the further enhancement of signal gain at 546 nm. In this paper, we study a 20 dB fibre laser for a signal of -30 dBm.

II. Theoretical Models

Energy levels and upconversion mechanism in erbium-doped ZBLAN is shown in Fig. 1.

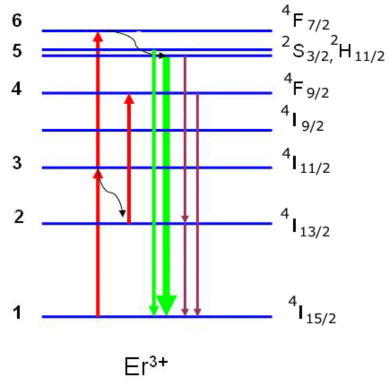

Fig. 1. Energy levels and upconversion mechanism in erbium-doped ZBLAN

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The population on different levels has been described by rate equations. The erbium concentration used for this model is of $1*10^{27}$ m^{-3}. A pump wavelength of 980 nm has been used for pumping the erbium ions in excited state and further.

The rate equations used are as follows:

$$\frac{dn_1}{dt} = -(R_{13} + W_{12})\, n_1 + (A_{21}+W_{21})\, n_2 + (A_{31} + R_{31})\, n_3 + A_{41}n_4 + (A_{51} + W_{15})\, n_5 \quad (1)$$

$$\frac{dn_2}{dt} = W_{12}\, n_1 - (R_{24} + A_{21} + W_{21} + W_{25})\, n_2 + (A_{32} + W_{nr32})\, n_3 + (A_{42} + R_{42})\, n_4 + (A_{52} + W_{52})\, n_5 \quad (2)$$

$$\frac{dn_3}{dt} = R_{13}\, n_1 - (R_{36} + A_{31} + A_{32} + W_{nr32} + R_{31})\, n_3 + A_{43}\, n_4 + A_{53}\, n_5 \quad (3)$$

$$\frac{dn_4}{dt} = R_{24}\, n_2 - (A_{43} + A_{42} + A_{41} + R_{42})\, n_4 + A_{54}\, n_5 \quad (4)$$

$$\frac{dn_5}{dt} = W_{15}\, n_1 + W_{25}\, n_2 + R_{36}\, n_3 - (W_{51} + W_{52} + A_{54} + A_{53} + A_{52} + A_{51})\, n_5 \quad (5)$$

$$n_1 + n_2 + n_3 + n_4 + n_5 \approx 1 \quad (6)$$

where n_1, n_2, n_3, n_4, n_5 are the fractions of erbium ions on different levels as shown in (Fig. 1).

The pump rates can be found using the formula

$$R_{ij} = \sigma_{ij} \text{ x } I_p / h\, \upsilon_p \quad (7)$$

where σ_{ij} is the pump cross section from i^{th} level to j^{th} level. I_p is the pump intensity, υ_p is the pump frequency.

The signal transition rates are given by

$$W_{ij} = \sigma_{ij} \text{ x } I_s / h\, \upsilon_s \quad (8)$$

where I_s is the signal intensity while υ_s is the signal frequency.

III. Results and Discussions

The schematic diagram of this model is shown (Fig. 2.). The core radius is 1 μm while the length of the fibre is 5 mm. If the amplifier length is greater than optimum length ($L > L_{opt}$), then signal is reabsorbed along the fibre.

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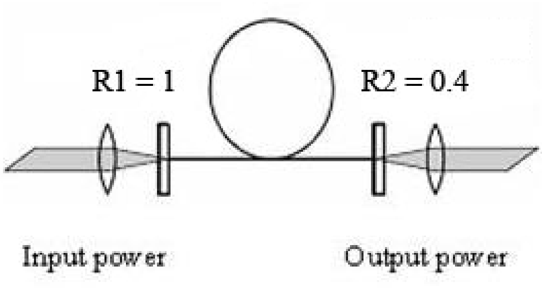

Fig. 2 Schematic diagram of the model

The pump power is 200 mW, it decreases along the fibre exponentially while signal power (1 µW) increases as a result.

$$\frac{\partial P_s}{\partial z} = \int_0^{2\pi}\int_0^{\infty} \sigma_s \left[N_5(r) - N_1(r)\right] I_s(z;r) r dr d\phi. \quad (9)$$

$$\frac{\partial P_p}{\partial z} = \int_0^{2\pi}\int_0^{\infty} \sigma_p N_1(r) I_p(z;r) r dr d\phi. \quad (10)$$

Fig. 3 shows the results of the above equations (9), (10) [2]. In the beginning, the pump power is max (0.2 W) which decreases along the fibre and as a result the signal power increases exponentially.

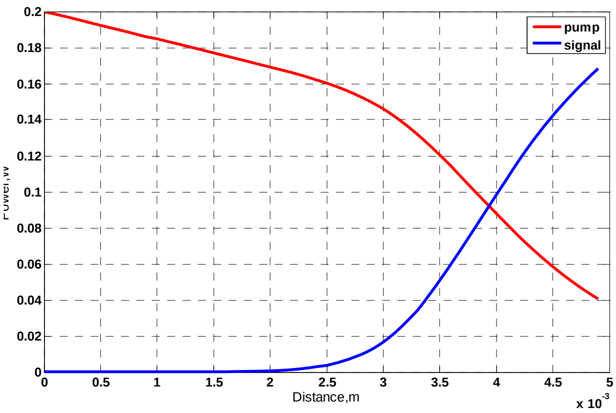

Fig. 3 Signal and pump power behavior along the fibre

Fig. 4 shows the population inversion (erbium ions) on different levels along the fibre. Because pump power decreases along the fibre, the erbium ions on level-5 also deceases but increases on level-1 (ground level).

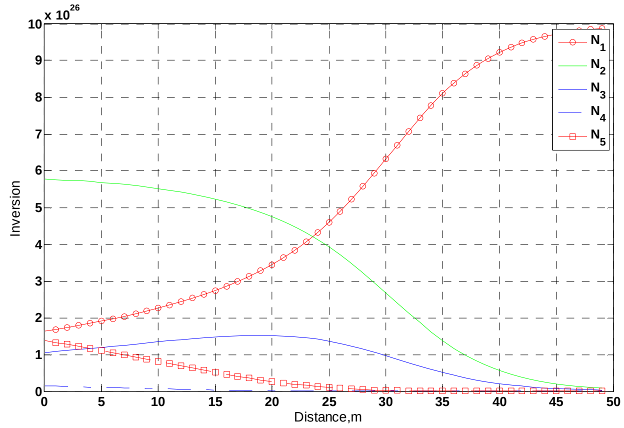

Fig. 4 Population inversion on different levels along the fibre

Fig. 5 shows gain as a function of pump power. A signal gain of 20 dB is calculated for a pump power of 200 mW with 5 mm fibre laser as shown in fig. 5 . [3]

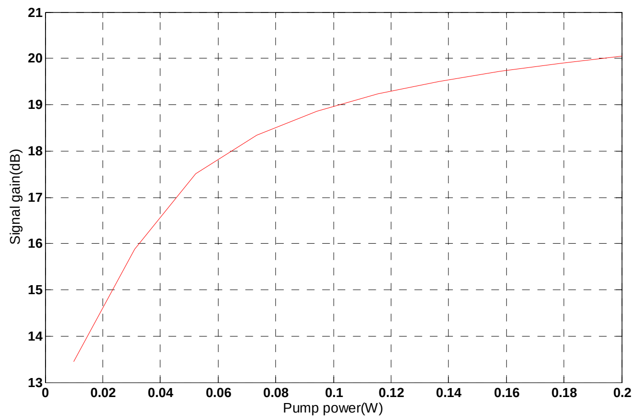

Fig. 5 Gain versus pump power

As signal gain is directly proportional to the length of the fibre and this would increase indefinitely if near-complete inversion is maintained along the fibre. This inversion in some region of the fibre is decreased so that unlimited signal growth is not possible. The four factors affecting the inversion are [4]

1. Pump power is absorbed along the fibre
2. Amplified signal saturates the gain
3. Gain is also saturated by the ASE (noise power)
4. Laser oscillations are also one of the reasons of gain saturation

Fig. 6 shows a graph between output power and the pump power [5]. An efficiency of 35% is achieved from this laser.

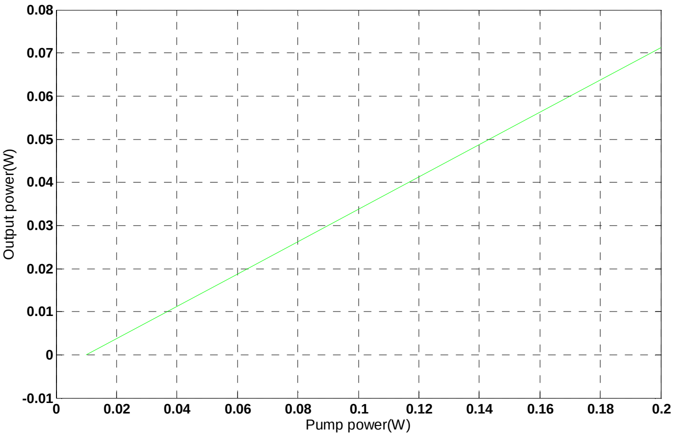

Fig. 6 Output power versus input power

IV. CONCLUSIONS

Rare-earth-doped ZBLAN upconversion fibre laser has been studied theoretically. Using the above mentioned formulae, one can decrease the length of a fibre laser up to 5 mm with $1*10^{27}$ m^{-3} erbium ion concentration. This laser has an efficiency of 35%. The calculated gain is 20 dB for 200 mW of pump power which is almost the same (22 dB) as previously calculated [1].

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