Design of erbium doped double clad ZBLAN Fibre laser

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Abstract. A high powered octagonal double clad ZBLAN (33 µm/330 µm, NA=0.13) glass fibre for mid-infrared light generation is studied using a one dimensional rate equation model. The fibre laser design employs the concept of cascade lasing and includes up-conversion phenomena. The results obtained demonstrate that efficient cascade lasing may be achieved in practice without the need for fibre grating fabrication, as a sufficient level of feedback for laser action is provided by Fresnel light reflection at ZBLAN glass fibre air interfaces. Further enhancement of the laser efficiency can be achieved by terminating one of the fibre ends with a mirror. Simulation results show that the laser operation with 20 W of pump power at 0.98 µm wavelength can be achieved at 2.75 µm operating wavelength with Er³⁺ ion concentrations of 60,000 ppm.

1. Introduction

Fibre lasers are the subject of considerable research interest. Erbium-doped silica fibre lasers with output power levels around 297 W [1] have been demonstrated under continuous wave (CW) operation. The natural minimum loss at 1.5 µm possesses significant challenge in extending the emission wavelengths of silica based fibre lasers. At longer wavelengths, the emission efficiency of erbium in silica is limited by the high phonon energy of the glass matrix which introduces competing multi-phonon relaxation paths. ZBLAN on the other hand, is a heavy metal fluoride glass with a wide transmission window of 0.3 – 5 µm and a good rare earth ion solubility. Compared with silicate glasses, ZBLAN glass has a lower maximum phonon energy (of ~565 cm⁻¹[2]) because the bond strength is weaker while atoms forming the glass are heavier [3].

Double clad Fibre provides opportunities for realisation of high power lasers with improved confinement when compared with the traditional step index single clad Fibres. In this work, we focus on two geometries of the double-clad Fibre with different doping levels of the erbium ions. In the model employed we include up-conversion processes that produce the green photoluminescence in ZBLAN fibre laser. Under a continuous wave (CW) pump an investigation of the influence of the fibre length, input pump power and facet reflectivity on the laser operating characteristics are studied. Finally, the modelling results are compared with experimental ones.
2. Fibre laser Modelling

The measured absorption cross section spectra used in this study have been taken from [4] and were fitted using Gaussian functions: \( a \exp \left( -\ln(2) \left( \frac{\lambda - \lambda_0}{d_\lambda} \right)^2 \right) \), where \( a \) is the amplitude, \( \lambda_0 \) is the wavelength position of the peak and \( d_\lambda \) is the half width at half maximum. The corresponding emission cross sections were calculated using McCumber [5] and Judd-Ofelt [6] theory. Figures 1a, 1b, and 1c show cross sections for the pump (~0.98 µm), idler (~1.55 µm and signal (~2.7 µm) waves that were used in the calculations.

(a) \hspace{1cm} (b) \hspace{1cm} (c)

Figure 1 Emission and absorption cross sections for: (a) – pump, (b) - idler and (c) - signal

Two double-clad fibre geometries that are referred to as ‘Fibre 1’ and ‘Fibre 2’ are investigated in this work. Fibre 1 is a 5000 ppm erbium doped ZBLAN fibre with 4.7 µm core diameter and 124 µm circular inner cladding diameter. Fibre 2 is a 60000 ppm erbium doped ZBLAN fibre with a 33 µm core diameter and a 330 µm octagonal inner cladding diameter. We note that both fibres are commercially available. Their schematic diagrams of cross sectional refractive index distributions are presented in figures 2a and 2b.

(a) \hspace{1cm} (b)

Figure 2 Refractive index distribution for: (a) – ‘Fibre 1’, i.e. circular double clad fibre – doped with erbium ions at 5000ppm and (b) – ‘Fibre 2’, i.e. octagonal double clad fibre - doped with erbium ions at 60,000ppm

The properties of the erbium doped ZBLAN fibre laser are investigated theoretically using the rate equations (1). Figure 3 shows the corresponding energy-level diagram for the erbium ion doped ZBLAN glass. In Fibre 1, the interactions of ion-ion energy transfer up-conversions are labelled as \( W_{2206} \), \( W_{1103} \). The cross relaxation process which in Fig.3 is labelled as \( C_{0513} \) was ignored given the relatively low level of erbium doping.

Fibre 2 on the other hand, is highly doped which makes ion-ion interactions highly probable. In our experimental setup, we observed a visible green-glow when using this fibre. This confirms an emission from the thermal levels \( ^4\text{H}_{11/2}/^4\text{S}_{3/2} \) which can only be populated by energy transfer from lower lying energy states. Excited ions at the \( ^4\text{F}_{7/2} \) levels are rapidly depleted by multi-phonon transition to the thermal levels \( ^4\text{H}_{11/2}/^4\text{S}_{3/2} \) as the energy gap can be bridged by 2 phonons. This effectively makes the 3 levels: \( ^4\text{F}_{7/2}, ^4\text{H}_{11/2} \) and \( ^4\text{S}_{3/2} \) to act as a single band. The energy level \( ^4\text{F}_{9/2} \) is not
directly populated by any of the energy transfer processes or indirectly by multi-phonon relaxations. This is because of the relatively large energy gap that separates level \( ^4F_{9/2} \) from the upper lying level \( ^4S_{3/2} \). As a result of this, the contribution of \( ^4F_{9/2} \) to the system at equilibrium is negligible. The energy diagram is therefore represented by 5 levels: \( ^4I_{15/2}, ^4I_{13/2}, ^4I_{11/2}, ^4I_{9/2} \) and \( ^4S_{3/2} \). In simulations the coefficients for energy transfer up-conversion and cross relaxation processes were taken from the available literature \([7–9]\) and are listed in Table 1.

Figure 3. Energy level diagram of Er:ZBLAN showing pump, signal and idler transitions.

Thus we obtain the rate equations (1) which are complemented by the conservation law, equation (2), where \( R_\lambda = P_\lambda/h\nu_\lambda A_{core} \) is the photon flux rate, \( P_\lambda \) denotes the power, \( h \) is the Planck’s constant, \( A_{core} \) is the area of the fibre core. \( \sigma_{a\lambda} \) and \( \sigma_{e\lambda} \) are the absorption and emission cross sections respectively. The subscript \( \lambda \) represents the pump(p), signal(s) and idler(id) wavelengths. \( \tau \) is the total lifetime which includes both radiative (\( \tau_r \)) and non-radiative (\( \tau_{nr} \)) processes. \( \beta_{ij} \) is the branching ratio from level \( i \) to \( j \). The second order interactions are represented by \( W_{in} \) while the number of ions involved in the interactions between levels \( i \) and \( j \) are represented by \( m \).

\[
\frac{dn_k}{dt} = \pm(n_x\sigma_{a\lambda}-n_y\sigma_{e\lambda})R_\lambda \pm mW_{in}n_in_{k+1} + \sum_{i=1}^{l} \frac{n_{i-1}m}{\tau_{ir}+\tau_{nr_{i-1}}} - n_{k}n_{i-1} \left( \frac{1}{\tau_{ir}} + \frac{1}{\tau_{nr_{i-1}}} \right) - n_{k+1} \left( \frac{1}{\tau_{ir}} + \frac{1}{\tau_{nr_{i+1}}} \right) + \frac{n_{k-1}}{\tau_{ir}} + \frac{n_{k}}{\tau_{nr_{i-1}}} - \frac{n_{k+1}}{\tau_{nr_{i+1}}} \right)
\]

(1)

\[
N_{Er} = n_0 + n_1 + n_2 + n_3 + n_4
\]

(2)

The evolution of the pump, signal and idler powers can be calculated by solving a set of ordinary differential equations \([10]\):

\[
\frac{dP_\lambda}{dz} = \pm\Gamma_{\lambda} P_\lambda^\pm(n_x\sigma_{a\lambda}-n_y\sigma_{e\lambda})\pm\sigma_{a\lambda} P_\lambda^\pm
\]

(3)

The symbol ‘\( \pm \)’ represents the direction of the travelling waves. The total power \( P_w \) at any point along the fibre is the sum of the forward (\( P^+_3 \)) and backward (\( P^-_3 \)) travelling waves. At the ends of the fibre, \( (z=0, z=L) \), the forward and backward propagating photon fluxes are partially reflected. If we denote the reflectivity of the input and output mirror by \( R_{in} \) and \( R_{out} \), respectively, we obtain the boundary conditions for equations (3):

\[
\phi^+_3(z=0) = R_{in} \phi^+_3(z=0) + (1 - R_{in}) P_p \quad \text{and} \quad \phi^-_3(z=L) = R_{out} \phi^-_3(z=L)
\]

The fibre ends were either terminated by air-glass interface or a mirror. The equations (1)-(3) were solved using coupled solution method \([10]\). The simulation parameters are \( \tau_{rk} = 0.73-8.52\text{ms}[8], \tau_{nr2} = 11, \tau_{nr3} = 0.58 \text{ms}[8][11], W_{2204} = 2.8e^{-17}, W_{1103} = 1.0e^{-17}, C_{0413} = 2.7e^{-17} \text{ cm}^2/\text{s}[7], \) Pump overlap factor = 0.14% (circular), 1.11% (octagonal).

3. Results

In the simulations we assume that our pump laser module delivers 60 W of power. In Figure 4a,b we show the dependence of the signal and idler power on the fibre length for the pump power equal 60 W. These results show that the optimal length of the fibre for Fibre 1 is 17.3 m for the laser configuration that relies on Fresnel reflections only while for the configuration that uses a mirror, it is 13.2 m. Fibre 2 has an optimum length of 2.8 m for the laser configurations that relies on Fresnel reflections only and 1.8m for the configuration that uses a mirror. Figure 4c,d shows the dependence of the idler and signal powers on the pump power. Fibre 1 produced a slope efficiency of 2.1% (Signal) and 3.7%
(Idler) for the laser configuration that relies on Fresnel reflections only while the one that uses mirror has slope efficiencies of 4.9% (Signal) and 8.4% (Idler). Fibre 2 produced a slope efficiency of 13.0% (Signal) and 22.8% (Idler) for the laser configuration that relies on Fresnel reflections only while the one that uses mirror produced slope efficiencies of 27.8% (Signal) and 48.2% (Idler).

Figure 4. Calculated dependence of idler & output signal powers on length and pump power.

4. Conclusions

In this paper, two double-clad fibres have been considered for the realisation of a mid-infrared fibre laser. The proposed device uses either Fresnel reflections at both ZBLAN glass-air interfaces or the Fresnel reflection on one side and a fully reflective mirror on the other one. The results obtained show that the device that uses a mirror is more efficient. Further, the highly doped, double-clad octagonal geometry with the larger core allows achieving higher optical efficiency than the circular clad fibre with a comparatively lower concentration of erbium.

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