Numerical simulations of ytterbium-doped fibre amplifiers utilising small scale parallelism

Contact ian.musgrave@stfc.ac.uk

P. N. Anderson, C. Wise and I. O. Musgrave

Central Laser Facility, STFC, Rutherford Appleton Laboratory, HSIC, Didcot, Oxon Ox11 0QX, UK

Introduction

A great deal of literature has been published regarding the design and development of the erbium-doped fibre amplifier (EDFA), and to a lesser extent the ytterbium-doped fibre amplifier (YDFA). Due to the huge commercial success of the EDFA in the telecommunications industry many simulations have been produced that model their behavior. These same simulations can, with a few minor adjustments be applied to the YDFA [1]. We are interested in the potential for the use of YDFAs as preamplifiers (of 1053 nm signals) in the Vulcan laser system and also utilising their very broad gain bandwidth as a potential new ASE source.

In simulations published elsewhere sequential numerical methods have been applied to solve systems of first order ordinary differential equations (ODEs), when these systems get very large it can take many hours to give full solutions. Here we develop a numerical simulation that takes advantage of small scale parallelism when solving large systems of ODEs reducing computation times significantly.

The model

The starting point for our work was the simple three level atomic system shown in figure 1a, which was further simplified by making the assumption that transitions into level three would be extremely short lived compared to the upper state lifetime of level two,

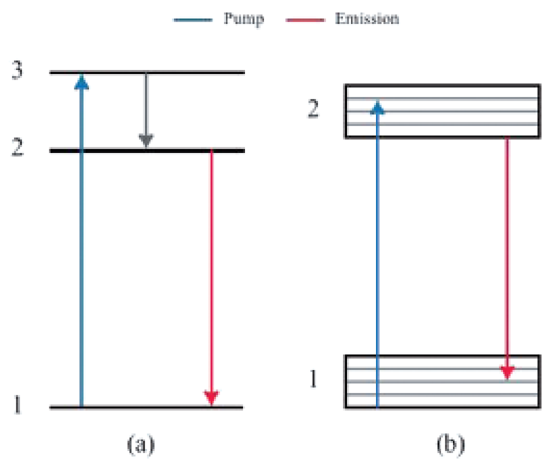

Figure 1. (a) The three level atomic system that is the starting point for our model. (b) The simplified atomic system comprising of a pair of multiplets.

hence the population of the third atomic level would essentially be negligible under steady state conditions. This allowed us to simplify the model into a system involving a pair of multiplets (Figure 1b), in which level three is now a higher-lying state of multiplet two. Contributions from both forward and backward ASE have been included in our model by dividing a continuous spectral region into discrete channels each of width Δf and central frequency f.

A pair of rate equations describing the relative populations (N_1 and N_2) of the two multiplets was set up [2] and solved analytically where $N_{1,2}'(t) = 0$, which resulted in

$$N_2 = \frac{\sum_{n=0}^{k} a_n P_n}{\sum_{n=0}^{k} b_n P_n + 1} \tag{1}$$

$$a_n = \frac{\tau\sigma_n^{abs}\Gamma_n}{Ahf_n}, b_n = \frac{\tau\left(\sigma_n^{abs}+\sigma_n^{ems}\right)\Gamma_n}{Ahf_n} \tag{2}$$

$$N_1 = 1 - N_2 \tag{3}$$

where k is the total number of Pump, Signal, and ASE components propagating within the fibre. P_n is the power of propagating component n, σ_n^{ems} and σ_n^{abs} are the emission and absorption cross sections of component n, Γ_n is the overlap factor between the optical mode of propagating component n and the Yb^{3+} distribution, A is the area of the Yb^{3+} ion distribution, and Ù is the upper state lifetime.

A system of coupled first order ordinary differential equations (equation 4) was set up to describe the simultaneous propagation of all k optical components along the length z of fibre.

$$\begin{aligned}
\frac{dP_n}{dz} &= \left(\left(N_2\sigma_n^{ems} - N_1\sigma_n^{abs}\right)\Gamma_n P_n + \right. \\
&\quad \left. \ldots N_2\sigma_n^{ems}\Gamma_n h f_n \Delta f\right) N, \\
\frac{dP_{n+1}}{dz} &= \left(\left(N_2\sigma_{n+1}^{ems} - N_1\sigma_{n+1}^{abs}\right)\Gamma_{n+1} P_{n+1} + \right. \\
&\quad \left. \ldots N_2\sigma_{n+1}^{ems}\Gamma_{n+1} h f_{n+1} \Delta f\right) N, \ldots, \\
\frac{dP_k}{dz} &= \left(\left(N_2\sigma_k^{ems} - N_1\sigma_k^{abs}\right)\Gamma_k P_k + \right. \\
&\quad \left. \ldots N_2\sigma_k^{ems}\Gamma_k h f_k \Delta f\right) N.
\end{aligned} \tag{4}$$

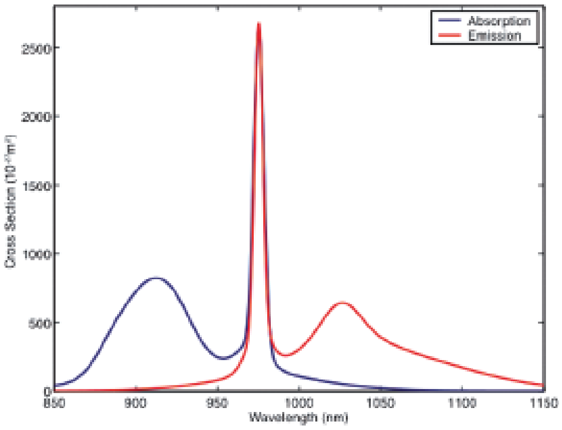

Figure 2. Absorption and emission cross sections of Yb, extrapolated from spectroscopy data.

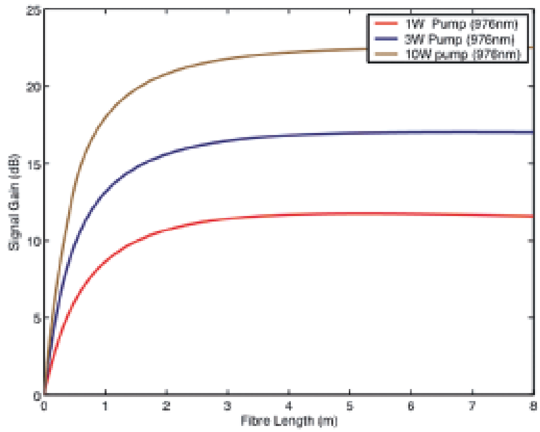

Figure 3. Signal Gain as a function of amplifier length for a co-propagating pump and signal. Signal wavelength 1053 nm.

Where N is the Yb^{3+} ion concentration and the one-dimensional unit vectors representing forward or backward propagation of each optical component have been omitted.

Numerical simulations

A program was written in the C programming language utilising the message passing interface (MPI) to solve the system of differential equations in (equation 4). Although the target architecture was to be a shared-memory environment, MPI was selected over alternatives such as openMP because of potential for future scalability to a distributed system. A basic "parallelism across the method" approach [3] was implemented that allowed the parallelism of large blocks of function evaluations within each Runge-Kutta step. Forward propagating ODEs were treated as initial value problems and solved using our Runge-kutta algorithm, whereas backward propagating ODEs had to be transformed into boundary value problems and a shooting method was used along with the Runge-kutta algorithm to give solutions.

A cladding pumped fibre amplifier was modeled using our program. The fibre modeled was a dual clad fibre with a 6 micron core. The inner cladding was pumped at 976 nm and a 50 mW 1053 nm signal was sent into the doped core. Forward- and backward propagating ASE was modeled between 850 nm and 1150 nm with an ASE channel width of 100 GHz. Absorption and emission cross section data (Figure 2) was obtained at all the required frequencies by the fitting of Gaussians to experimental spectroscopy data and then extrapolating.

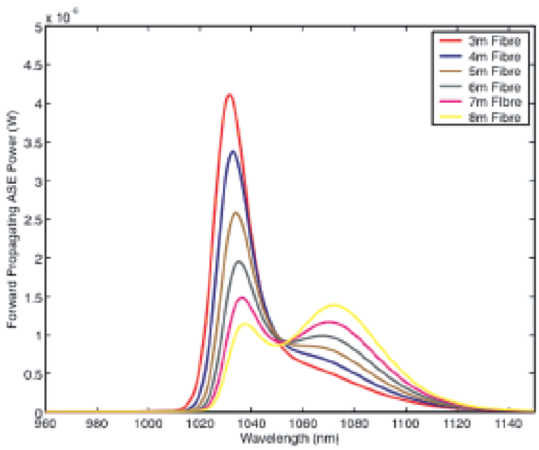

Figure 4. Forward propagating ASE spectrum simulated as a function of fibre length, with an initial pump power of 1 W.

The first computation was performed using a machine with a quad core processor and 4 GB of RAM. Outputting signal gain (figure 3), and a full forward ASE spectrum (figure 4) both at intervals of 1E-4 m along the fibre. Subsequent computations were then performed for a series of different pump powers so that a comparison could be made of the signal gain achievable in the amplifier and any variations in the ASE spectrum. It can be seen in figure 3 that the amount of pump power coupled correctly into the fibres inner cladding dramatically changes the maximum achievable gain from the amplifier. This is due to the majority of the pump power being absorbed before it had propagated a significant distance along the fibre, allowing the rate of signal absorption to dominate that of emission lowering the gain.

The simulated ASE spectrum in figure 4 could be very useful when aligning the fibre: When aligning the pump into the cladding a spectrometer could be placed at the output of the fibre and the spectral shape and position can be matched to that of the simulation. Difficulties arising from coupling the signal into the very small core could be combated with this ASE profile matching approach, by sending the pump along the signals optical path and into the core; the spectral profile could then once again be matched to that of the simulation. The pump can then be returned to its own channel leaving good alignment between the optical path of the signal and the doped core.

The shift in the ASE Spectrum as a function of fibre length comes about due to a significantly higher absorption cross section at 1030 nm than at 1080 nm (figure 2), and as fibre length increases there will be a point at which absorption will dominate emission at some ASE wavelengths. Although the ASE spectral broadening is much less apparent when using higher pump powers the shift does still occur (Figure 5). It was thought this somewhat tunable spectral profile could be useful for the development of a new superluminesant source.

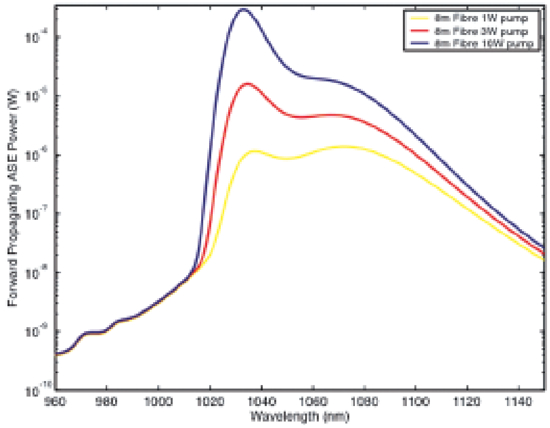

Figure 5. Forward propagating ASE spectrum output from an 8 m fibre for a series of different pump powers (plotted on a logarithmic scale).

Conclusions

A new numerical simulation utilising a "parallelism across the method" approach to model Ytterbium doped fibre amplifiers has been developed. This method allowed us to quickly solve the very large systems of coupled ordinary differential equations present in the mathematical model of the amplifier. A simulation was then performed of a cladding pumped ytterbium doped fibre amplifier outputting data describing amplifier gain dynamics and forward ASE spectral shift, the latter of which has been observed experimentally in [4].

References

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3. K. Burrage, *Adv. Comput. Math.*, **7**, 1 (1997).
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