Chapter 6: Instructions for the Simulation of Laser Transients and Spectral Evolution

The simulation of laser transients, such as build-up time, relaxation oscillations, intensity modulation and the spectral evolution of the laser output (with intra-cavity absorption spectroscopy) for a fibre loop laser, as illustrated in Chapter 6, Figure 6.8, is obtained by running the MATLAB program:

‘**Simulation_Ch6_Figures.m**’

The inputs to the program, which may be changed by the user, are as follows:

Absorption and emission coefficients for the rare-earth-doped fibre are stored in the csv files: ‘Data_absorption_coefficients.csv’ and ‘Data_emission_coefficients.csv’.

WL_FILTER	the centre wavelength of the filter in the loop, 1560nm
WI:	wavelength interval (0.2nm) in the data for absorption and emission coefficients
WL_PUMP	wavelength (nm) of the pump source, 980nm
ALPHA_P	the pump absorption coefficient, α_p, 4.5dB/m at 980nm
Ppmw	the pump power step applied at time zero, 25mW
TAU_21	lifetime of the upper state, τ_{21} ~10ms for erbium doped fibre
TAU	round-trip time of the fibre laser cavity, τ ~100ns
l	length of erbium-doped fibre, l ~10m
RHO	erbium ion density in doped fibre, ρ_e ~5x10^{24}ions.m^{-3}
S	effective area of erbium doping, S_e ~10^{-11}m^2
C_LOSS	the total fixed loss in the fibre cavity external to the fibre amplifier, and independent of wavelength (for example, from isolators, connectors, couplers and fibre), 5dB
ABSORB	the line centre absorbance, 0.01dB, of a gas absorption line within the cavity
HLW	the half linewidth, 0.02nm, of the gas absorption line
OFFSET	offset (in nm) of the gas absorption line centre from the filter centre wavelength
MODES	the number of modes, 25, in each mode group
Neqn	the number of mode groups and cavity rate equations, 200
END_TIME	the time span, 30ms, over which the laser output is modelled

The response of the wavelength filter and the gas absorption lines in an intra-cavity are defined within the subprogram: ‘**alphac.m**’

The various features of the simulation and the subprograms used are as follows:

1) Values for the absorption coefficient, $\alpha_a(\nu) = \Gamma\rho_e\sigma_a(\nu)$ and for the emission coefficient, $\gamma_e(\nu) = \Gamma\rho_e\sigma_e(\nu)$ in dB of the erbium doped fibre as a function of wavelength (nm) are stored in the xls (comma separated value) files, 'Data_absorption_coefficients.csv' and 'Data_emission_coefficients.csv'. This data is read into the main program by the statements:
```
A=dlmread('Data_absorption_coefficients.csv',',',0,0);
G=dlmread('Data_emission_coefficients.csv',',',0,0);
```
Other rare-earth-doped fibre amplifiers and lasers may be modelled by storing the appropriate data in these csv files.

2) The MATLAB subprogram '**alphac.m**' is used to define the total fibre cavity loss $\alpha_c(\nu)$ external to the fibre amplifier in a fibre loop laser as a function of the wavelength deviation from the centre wavelength of a filter within the loop. Referring to Figure 6.8 in Chapter 6, $\alpha_c(\nu)$ represents the total optical attenuation (as $e^{-\alpha_c(\nu)}$ or $4.34\alpha_c$ dB) experienced by the optical power from the amplifier output at point (2) back to the amplifier input at point (1) from the various optical components in the loop, including connectors, couplers, isolators, wavelength filter, intra-cavity gas cell, etc.

   The value used in the program is calculated from:
```
val = C_LOSS+Filter+Gas_Line
```
   where:

   `C_LOSS` represents the total fixed loss in the fibre cavity external to the fibre amplifier and independent of wavelength (for example, from isolators, connectors, couplers and fibre) with a typical value of 6dB/4.34

   `Filter` uses a polynomial function to describe the response of a wavelength filter in the loop as a function of the wavelength deviation, Wdev, from its centre wavelength, but any appropriate function may be used to specify the filter response. For example, a 1nm BW filter with 3dB insertion loss and parabolic response is modelled as:
```
Filter=(12*Wdev^2+3)/4.34
```
   (To model multi-wavelength operation, a periodic filter may be programmed here)

   `Gas_Line` represents a gas absorption line in an intra-cavity cell in the loop with a Lorentzian line shape of half-linewidth, HLW, gas absorbance of ABSORB at the line centre and line centre offset from the filter centre wavelength by OFFSET.

```
Gas_Line=ABSORB/(1+((Wdev-OFFSET)/HLW)^2);
```

Several absorption lines may be included by adding extra terms and an example is included of 3 gas lines with a broadband filter.

For convenience, the total cavity loss (in dB) is plotted (Figure 1 in the simulation output) and the data from this plot is stored in the excel file ‘Cavity Loss(dB).xlsx’. The net loss-gain at the steady-state condition is also plotted in Figure 2.

3) The MATLAB subprogram ‘**Rate_Eqns.m**’ defines the set of atomic rate and the cavity rate equations and is used in the MATLAB function ode15s in the subprogram ‘**Solver_Rate_Eqns.m**’ to solve the full set of coupled differential equations. There are Neqn cavity rate equations, listed as dy(1), dy(2), dy(3)........dy(Neqn), one for each mode group as defined by equation (6.18) in Chapter 6. The power in each mode group (in photons/s) at the output of the erbium fibre is normalised by the total steady-state output power, (PSS in photons/s) at this same point and represented as y(1), y(2), y(3).... y(Neqn). There is one atomic rate equation identified as dy(Neqn+1) and defined by equation (6.17) in Chapter 6. For programming, equation (6.17) is divided throughout by $\rho_e S_e l$ and normalised by the steady-state inversion level, NSS, so that y(Neqn+1) = $\overline{N_2}/NSS$.

4) The pump waveform for the fibre laser is specified by the user in the MATLAB subprogram: ‘**Pump_Waveform.m**’ The pump waveform may be a simple step at *t* = 0 or may include a sinusoidal modulation of the pump to simulate an intensity modulated output from the fibre laser.

5) The MATLAB subprograms ‘**alphaq.m’** and ‘**gammaq.m’** assign wavelengths to each mode group and calculate the appropriate absorption and emission coefficients for each mode group by extrapolation from the input data.

6) The MATLAB subprogram ‘**Solver_Rate_Eqns.m**’ is the core of the simulation process. It first reads off the appropriate values for the absorption and emission coefficients and the cavity loss for each mode group from the subprograms ‘**alphaq.m**’, ‘**gammaq.m’** and ‘**alphac.m**’ and determines the steady-state values of the inversion level and laser power.

It then uses the MATLAB function ode15s to solve the complete set of rate equations defined in the subprogram '**Rate_Eqns.m**'.

The output from ode15s a column vector, T, of time and an array, Y for the normalised power, $y_1, y_2, y_3, \ldots y_n$ in each mode group as a function of time, with y_{n+1} as the normalised inversion level as a function of time:

$$T = \begin{bmatrix} t_1 \\ t_2 \\ t_3 \\ . \\ . \\ etc. \end{bmatrix} \qquad Y = \begin{bmatrix} y_1(t_1) & y_2(t_1) & y_3(t_1) & . & . & . & . & . & . & . & y_{n+1}(t_1) \\ y_1(t_2) & y_2(t_2) & y_3(t_2) & . & . & . & . & . & . & . & y_{n+1}(t_2) \\ y_1(t_3) & y_2(t_3) & y_3(t_3) & . & . & . & . & . & . & . & y_{n+1}(t_3) \\ . & . & . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & . & . \\ etc. & . & . & . & . & . & . & . & . & . & etc. \end{bmatrix}$$

Various outputs are generated from [T, Y] as follows:

(i) The normalised power output of a particular mode group may be plotted in time.

(ii) By summing the elements in each row of Y, the total normalised power output as a function of time may be plotted. This is shown in Figure 3 in the simulation and the data from this plot is stored in the excel file, 'Figure 6_11.xlsx', corresponding to Figure 6.11 in Chapter 6.

(iii) Since each cavity rate equation and mode group, y_n, corresponds to a particular output wavelength, the spectral distribution of the laser output a particular time, t_k, corresponding to the k^{th} row in [T, Y], may be obtained by plotting the values of $y_1(t_k)$, $y_2(t_k)$, $y_3(t_k)$,….$y_n(t_k)$ against the corresponding wavelength of each mode group. The simulation outputs several examples of this (Figures 4-11) to show the spectral evolution in time and the data from these plots are stored in the excel file 'Figure 6_12.xlsx', corresponding to Figure 6.12 in Chapter 6.

7) The global parameters shared by the various subprograms are defined as follows:

```
global WL_FILTER A G WI ALPHA GAMMA ALPHAC ALPHA_C WL_PUMP ALPHA_P Pp;
global TAU_21 TAU RHO S l RHOSL C_LOSS;
global ABSORB HLW OFFSET;
global MODES Y T Neqn Ncentral DL;
global NSS PSS END_TIME;
```

WL_FILTER	the centre wavelength of the filter in the loop
A	absorption coefficient data for erbium-doped fibre as function of wavelength
G	emission coefficient data for erbium-doped fibre as a function of wavelength
WI	wavelength interval (nm) of the data for absorption and emission coefficients
ALPHA	the value of the absorption coefficient for each mode group
GAMMA	the value of the emission coefficient for each mode group
ALPHAC	the cavity loss value for each mode group
ALPHA_C	the minimum cavity loss value at steady-state operation
WL_PUMP	wavelength (nm) of the pump source
ALPHA_P	the pump absorption coefficient
Pp	the pump power (photons/s) applied as a step input from 0 to P_p
TAU_21	lifetime of the upper state, τ_{21}
TAU	round-trip time of fibre laser cavity, τ
RHO	erbium ion density in doped fibre, ρ_e
S	effective area of erbium doping, S_e
l	length of erbium-doped fibre, l
RHOSL	the product, $\rho_e S_e l$
C_LOSS	the total fixed loss in the fibre cavity external to the fibre amplifier, and independent of wavelength (for example, from isolators, connectors, couplers and fibre)
ABSORB	the line centre absorbance of a gas absorption line within the fibre laser cavity
HLW	the half linewidth (in nm) of the gas absorption line
OFFSET	offset (in nm) of the gas absorption line centre from the filter centre wavelength
MODES	the number of modes in each mode group, each group being represented by one cavity rate equation.
Y	output array from ode15s giving solution to the set of rate equations
T	output column vector of time from ode15s
Neqn	the number of mode groups and cavity rate equations
Ncentral	the number assigned to the central group; `Ncentral = floor(Neqn/2) + 1`
DL	the wavelength spacing of the mode groups i.e. the number of modes in each group multiplied by the longitudinal mode spacing, MODES x ($\lambda^2/c\tau$)

NSS	the steady-state inversion level
PSS	the steady state power in photon/s at the output of the erbium fibre
END_TIME	the time span over which the laser output is modelled