Numerical Simulation of Optical Amplifiers based on Eu-doped Polymer Optical Fibers

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***Abstract*—We model the light amplification in Eu-doped PMMA polymer optical fibers by solving our own rate equations that describe the physical system. These equations are firstly solved in stationary state, for a constant pump power. In this case, we determine the optimum fiber length for maximum output power. We also solve the time-dependent equations to be able to launch a pulse of signal power at the input end, together with pulsed or constant pump power. The results are useful to determine the influence of some important design parameters, such as the temporal pump width or the fiber concentration.**

I. Introduction

A numerical simulation of Eu^{3+}-doped polymer optical fibers (POFs) made of poly(methyl methacrylate) PMMA working as light amplifiers is carried out in order to determine the influence of some important design parameters of current interest. This work allows us to clarify the best choice of the width and peak power of the pump pulses, and the influence of the concentration of europium. Although this is not directly soluble in PMMA, each europium ion may be surrounded by a set of four ligands that makes it soluble. The employed europium complex is called AC46 [1-4]. It has the added advantage that its absorption cross section, which peaks at 345 nm, is much higher than that of the Eu^{3+} ion.

II. Modeling of the System

We model the system by means of four rate equations that describe the temporal and spatial evolution of the generated power P at the peak wavelength of the emission, of the pump power P_p, and of the number of molecules per unit volume in the excited state corresponding to the europium ion, or N_D, and to the set of ligands, or N_T.

$$\frac{\partial P_p}{\partial z} = \underbrace{-\sigma^a (N - N_T) P_p}_{\text{absorption}} - \underbrace{\frac{1}{v_z}\frac{\partial P_p}{\partial t}}_{\text{propagation}} \quad (1)$$

$$\frac{\partial N_T}{\partial t} = \underbrace{-N_T \cdot 1/\tau_{T-S_0}}_{\text{spontaneous decay}} + \underbrace{\frac{\sigma^a}{h\left(\frac{c}{\lambda_p}\right) A_{core}}}_{\text{absorption}} \underbrace{-1/\tau_{T-D}\frac{(N-N_D)}{N} N_T}_{\text{intercrossing}} \quad (2)$$

$$\frac{\partial N_D}{\partial t} = \underbrace{-N_D \cdot 1/\tau_{D-F}}_{\text{spontaneous decay}} \underbrace{-\frac{\sigma^e}{h\left(\frac{c}{\lambda_s}\right) A_{core}} N_D P}_{\text{stimulated decay}} + \underbrace{1/\tau_{T-D}\frac{(N-N_D)}{N} N_T}_{\text{intercrossing}} \quad (3)$$

$$\frac{\partial P}{\partial z} = \underbrace{\sigma^e N_D P}_{\text{stimulated emission}} + \underbrace{\frac{N_D}{\tau_{D-F}} h\left(\frac{c}{\lambda_s}\right)\beta A_{core}}_{\text{spontaneous emission}} - \underbrace{\frac{1}{v_z}\frac{\partial P_p}{\partial t}}_{\text{propagation}} \quad (4)$$

The processes involved in these rate equations and the meaning of the variables are explained in [3]. Notice that the model does not take the attenuation of the host material into account. The doped fiber is pumped longitudinally from the input end.

A. Resolution in Stationary State

When the pump power is constant, after the stationary state has been reached, the partial derivatives with respect to time become zero. As a consequence, the first members of equations (2) and (3) vanish, which allows us to isolate N_T and N_D in terms of P and P_p. By substituting these expressions into (1) and (4), we obtain a set of two ordinary differential equations, which can be solved using a Runge-Kutta method. The boundary condition is the constant value of $P_p(z = 0)$.

B. Resolution of the Time-Dependent Equations

The four rate equations have been solved by means of finite - differences. Specifically, we have employed the following approximations:

$$\frac{\partial P_p}{\partial t}(i+1,j) \approx \frac{P_p(i+1,j)-P_p(i,j)}{dt}, \qquad \frac{\partial P_p}{\partial z}(i+1,j) \approx \frac{P_p(i+1,j+1)-P_p(i+1,j)}{dz}$$

$$\frac{\partial N_T}{\partial t}(i,j+1) \approx \frac{N_T(i+1,j+1)-N_T(i,j+1)}{dt}, \frac{\partial N_D}{\partial t}(i,j+1) \approx \frac{N_D(i+1,j+1)-N_D(i,j+1)}{dt}$$

$$\frac{\partial P}{\partial z}(i+1,j) \approx \frac{P_p(i+1,j+1)-P(i+1,j)}{dz}$$

In this way, we can calculate the four variables P, P_p, N_T and N_D at the point (i+1, j+1) in terms of the values at the points (i, j), (i, j+1) and (i+1, j). The initial conditions are that $P_p(t, z = 0) \equiv P_p(i, 1)$ is either a Gaussian pulse or a constant value , and that $P(t, z = 0) \equiv P(i, 1)$ is a Gaussian signal, usually centered around the same time as the pump pulse.

The optimum fiber length for a constant pump power is defined as that for which both the amplified spontaneous emission (ASE) and the signal gain just reach their maximum values (see Figs. 1 and 2), since the attenuation of PMMA would tend to reduce the obtained power if longer fibers were employed.

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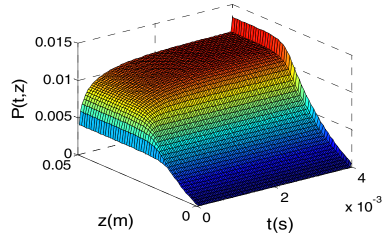

Fig. 1: Example illustrating that, for a constant pump power, the ASE power for each *z* reaches a stationary value after a transient time. In this example, the signal is launched at $t = 4$ ms. The optimum fiber length corresponds to the *z* from which no further power increase is achieved by increasing *z*.

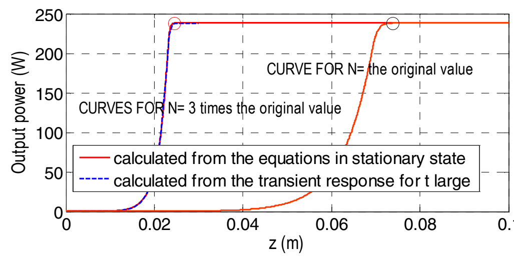

Fig. 2: Example illustrating that, for a constant pump power and without input signal, the curve of the evolution of the ASE power with *z*, for any *t* that is large enough, reaches a stationary shape that coincides with that obtained by solving the simplified equations in stationary state. In the case of low attenuation of the host material, the optimum fiber length is inversely proportional to the dopant concentration *N*.

Figs. 1 and 2 also show that the gain that is obtainable in the case of low attenuation of the PMMA host is independent of the dopant concentration.

C. Memory-Saving Optimization Algorithm

Memory and computation time can be saved if we only use two values of *i* (1 and 2) for the calculations, since only a pair of *i* need to be considered in each step. More values can be saved for analysis and post-processing.

III. Post-processing

The numerical results so obtained consist of four matrices $\mathbf{P}$, $\mathbf{P_P}$, $\mathbf{N_D}$, and $\mathbf{N_T}$ expressed as functions of time *t* (rows) and position *z* (columns). The matrix $\mathbf{P}$ represents the generated light power at 614 nm. The main objective of the post-processing stage is to calculate the area, or energy, of the amplified output signal appearing in the last column of $\mathbf{P}$ and compare it with the area of the input signal in order to calculate the energy gain obtained in the fiber. The input signal is typically Gaussian. Owing to the nature of the numerical resolution, $\mathbf{P}$ has very little noise (due to the rounding errors of the numerical process only), so the automatic location of the output peak can be done based on looking for its left and right inflection points by means of second-order finite differences. The output signal pokes out of an ASE baseline, which is not straight (see Fig. 3). Therefore, it is necessary to model it as a polynomial (e.g. a third-degree one near the peak) prior to the calculation of the area of the detectable signal. For this purpose, the distances of each of the signal's inflection points from the signal's maximum can serve as a guide to determine the necessary four nearby points on the ASE baseline. The next step is to calculate the signal energy as the yellow area above the baseline (Fig. 3).

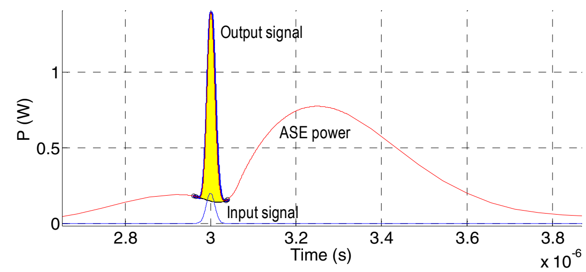

Fig. 3: Calculation of the signal energy for a pulsed pump power, which should be broader than the signal pulse and synchronized with it.

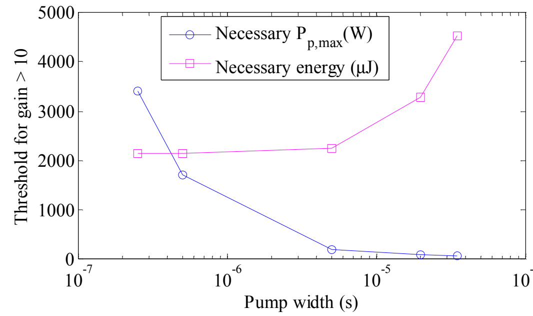

Fig. 4: Example illustrating that a constant gain (e.g. 10) corresponds to constant pump energies for small pump widths, whereas this constant gain corresponds to constant peak powers for sufficiently large pump widths.

As an example of application of these numerical methods, Fig. 4 shows the influence of the pump widths on the pump energies and peak powers necessary to obtain a certain signal gain (e.g. 10).

Conclusion

We have written equations to model and clarify Eu-doped POF amplifiers, and we have solved them both in stationary state, using a Runge-Kutta method, and in non-stationary state including the variable time, using a finite-difference scheme.

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