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Analysis and design of a dye-doped polymer optical fiber amplifier

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ABSTRACT A rhodamine-B-doped polymer optical fiber amplifier (RBDPOFA) has been successfully fabricated and tested. In this paper, all parameters affecting the gain of the RBDPOFA are recognized. The time-dependent and time-independent rate equations are solved. By using Runge–Kutta and finite-element methods, different conditions are described and fluctuations of the fiber laser are analyzed. From the time-dependent rate equations, the gain and level-density variations with time can be predicted. These fiber amplifiers have unstable conditions. In experiments, the decay of dye dopants in the high pump power regime has been observed. For example, in a high pump power rhodamine-B is converted from the zwitterion isomer to the colorless lactone isomer [1]. Therefore, for complete coincidence of theoretical and experimental results, this effect must be included in the analysis, which is however beyond the scope of this paper and will be discussed in the near future.

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1 Introduction

Work on polymer optical fiber amplifiers started by successful fabrication of a rhodamine-B-doped polymer optical fiber amplifier in Kieo University [2]. In this kind of amplifier, organic dyes and also rare-earth ions are used. Many research groups have carried out experiments on these amplifiers [2–5]. A theoretical analysis of these amplifiers is necessary to approve the experimental results. In this paper, a simulation of the amplifier is made, relating its gain to all fiber parameters, such as signal and pump wavelengths, power, dopant density and distribution, optimum fiber length, etc. By gain simulation, we have specified that, contrary to Er^{+3}-doped glass optical fiber amplifiers, the gain of an organic dye-doped polymer optical fiber amplifier is independent of the input signal power, due to its higher saturation power. Also, the necessary time for the amplifier to reach the equilibrium condition is in the order of the steady-state lifetime of the dye. There are several procedures to study the absorption and emission of light in materials. In one of the methods, the system's density matrix is reduced to rate equations for incoherent light. In another method, rate equations can be extracted from the charge and energy stability that gives the equations relating the charge-density variations of the levels with the pump and the signal power variations. To analyze the optical fiber amplifiers, we have numerically solved the time-dependent rate equations to predict the results.

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2 Rate equations in dye-doped polymer optical fiber amplifiers

It is assumed that this kind of amplifier is a three-level system and that the third level decays fast. Due to this fast decay, the time-dependent rate equations in dye-doped optical fiber amplifiers can be expressed as a two-level system [2, 3]:

$$\frac{\partial N_2(t,z,r)}{\partial t} = \frac{2\pi\,\sigma_{\mathrm{p}}^{\mathrm{a}}\,N_1(t,z)\,I_{\mathrm{p}}(t,z)}{h\upsilon_{\mathrm{p}}}\eta - \frac{N_2(t,z)}{\tau} - \frac{2\pi(\sigma_{\mathrm{s}}^{\mathrm{e}}N_2(t,z) - \sigma_{\mathrm{s}}^{\mathrm{a}}\,N_1(t,z))I_{\mathrm{s}}(t,z)}{h\upsilon_{\mathrm{s}}}\,\eta\,, \tag{1}$$

$$\frac{\partial I_{\mathrm{s}}(t,z,r)}{\partial z} = 2\,\pi\,(\sigma_{\mathrm{s}}^{\mathrm{e}}\,N_2(t,z) - \sigma_{\mathrm{s}}^{\mathrm{a}}\,N_1(t,z))\,I_{\mathrm{s}}(t,z)\eta\,, \tag{2}$$

$$\frac{\partial I_{\mathrm{p}}(t,z,r)}{\partial z} = -2\,\pi\,\sigma_{\mathrm{p}}^{\mathrm{a}}\,N_1(t,z)\,I_{\mathrm{p}}(t,z)\eta\,, \tag{3}$$

$$N_t = N_1(t,z) + N_2(t,z)\,, \tag{4}$$

where N_1, N_2, and N_{t} are the ground, metastable, and total charge densities, respectively, I_{p} and I_{s} are the pump and signal intensities, respectively, $\sigma_{\mathrm{a}}^{\mathrm{p}}$, $\sigma_{\mathrm{a}}^{\mathrm{s}}$, and $\sigma_{\mathrm{e}}^{\mathrm{s}}$ are cross sections of the pump, signal absorption, and signal emission, respectively, h is Planck's constant, τ is the steady-state lifetime of the dye in the metastable level, z is the direction of propagation of light in the fiber, η is the overlap integral: $\eta = \int_0^{a_0} \theta(r)\bar{\Psi}(r)\,r\;\mathrm{d}r$, where $\theta(r)$ and $\bar{\Psi}(r)$ are the dye and the pump distributions, respectively, and a_0 is the dopant radius.

In the steady state, the electron density of the second level can be assumed to be constant ($\partial N_2/\partial t = 0$). The time-independent signal and pump evolutions can be expressed

Parameter	Notation	Value
Signal wavelength	λ_s	591 nm
Pump wavelength	λ_p	532 nm
Core diameter	a_0	0.5 mm
Signal attenuation	k_s	10 dB m^{-1}
Pump attenuation	k_p	10 dB m^{-1}
Steady-state lifetime of RB	τ	2.85 ns
Steady-state lifetime of rhodamine-6G	τ	4.8 ns
Steady-state lifetime of DCM	τ	1.31 ns
Steady-state lifetime of rhodamine-110	τ	2.85 ns
Dye concentration	N_t	3 ppm
Pump absorption cross section at 532 nm	σ_p^a	2.2×10^{-16} cm^2
Signal emission cross section at 591 nm	σ_s^e	2.3×10^{-16} cm^2
Input signal power	P_s	1 W

TABLE 1 Parameters for simulation of dye-doped POF [4]

as [3]:

$$\frac{\partial I_s(z,r)}{\partial z} = \eta \frac{\left(\frac{\sigma_s^e \sigma_p^a}{h\upsilon_p}\right) I_p(z) + \frac{\sigma_s^a}{\tau}}{\left(\frac{\sigma_p^a}{h\upsilon_p}\right) I_p(z) + \left(\frac{\sigma_s^e + \sigma_s^a}{h\upsilon_s}\right) I_s(z) + \frac{1}{\tau\eta}} I_s(z)\, N_t - k_s\, I_s(z)\,, \quad (5)$$

$$\frac{\partial I_p(z,r)}{\partial z} = -\eta \frac{\left(\frac{\sigma_s^e \sigma_p^a}{h\upsilon_s}\right) I_s(z) + \frac{\sigma_p^a}{\tau}}{\left(\frac{\sigma_p^a}{h\upsilon_p}\right) I_p(z) + \left(\frac{\sigma_s^e + \sigma_s^a}{h\upsilon_s}\right) I_s(z) + \frac{1}{\tau\eta}} \times I_p(z)\, N_t - k_p\, I_p(z)\,, \quad (6)$$

where υ_s and υ_p are the signal and pump frequencies, respectively, and k_s and k_p are the fiber loss at the signal and pump wavelengths, respectively. Due to the selected wavelengths for the signal and pump, the same fiber background loss has been assumed for both of them, as given in Table 1.

The absorption and emission cross sections of some dopants in polymer optical fiber amplifiers are shown in Fig. 1, which have been used in the simulation [4].

3 Effects of different parameters on performance of the optical fiber amplifiers

The local signal gain is defined by $g(z) = 10 \log (I_s(z))/(I_s(0))$. The time-independent rate equations were solved by the Runge–Kutta method, to derive the gain evolution of the amplifier. The fiber amplifier parameters used in the simulations are constant, as shown in Table 1, except when other values are specified, or the effects of variations of a parameter are under study.

The evolutions of amplifier gain vs. fiber length and pump power are shown in Fig. 2.

The gain of the fiber amplifier is maximized at the optimum length. With an increment of the pump power, the maximum gain and its relevant optimum length increase. Gain variation with pump power for various fiber lengths is shown in Fig. 3. The fiber amplifier parameters and the simulation results are the same as those shown in [3].

It is experimentally shown that the dyes decrease with pump power in excess of 800 W [1]. It seems that if the dye molecules of the fiber increase, the amplifier gain will increase. The amplifier gain spectrum for different dye densities is shown in Fig. 4. It is shown that, for a constant pump power, when the dye density increases from 0 to 3 ppm, the maximum

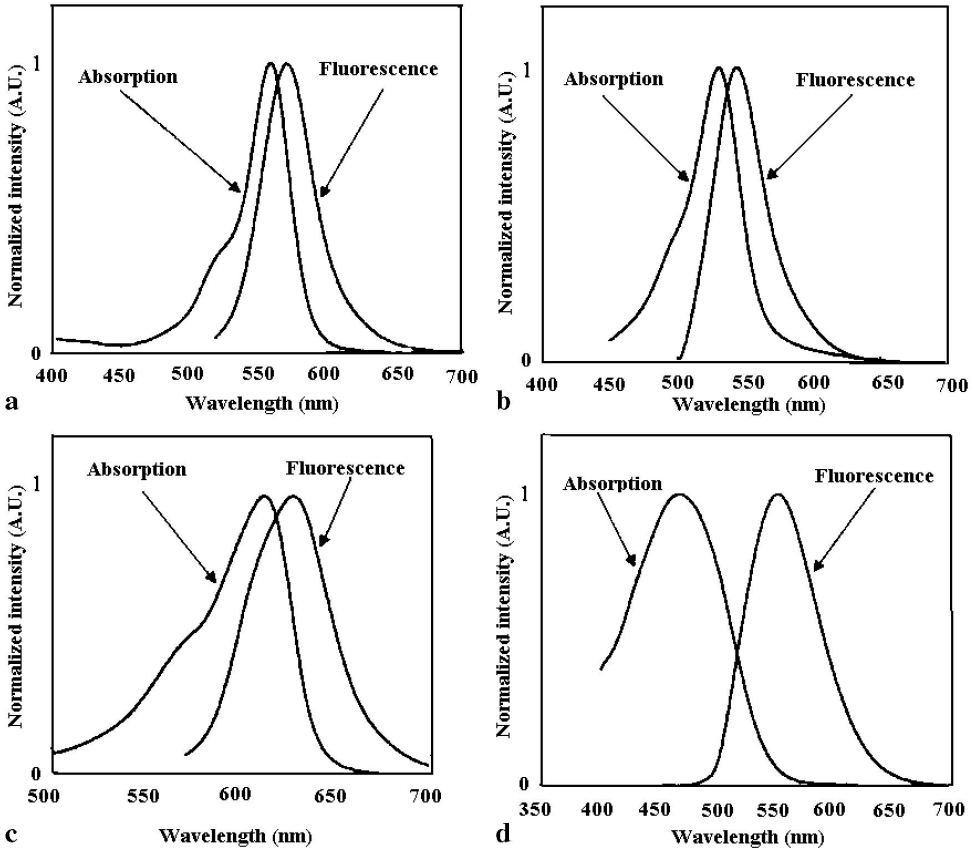

FIGURE 1 Absorption and emission cross sections of organic dopants in polymer optical fiber amplifiers. **a** Rhodamine-B, **b** Rhodamine-6G, **c** 04PC, and **d** DiChloroMethane [4]

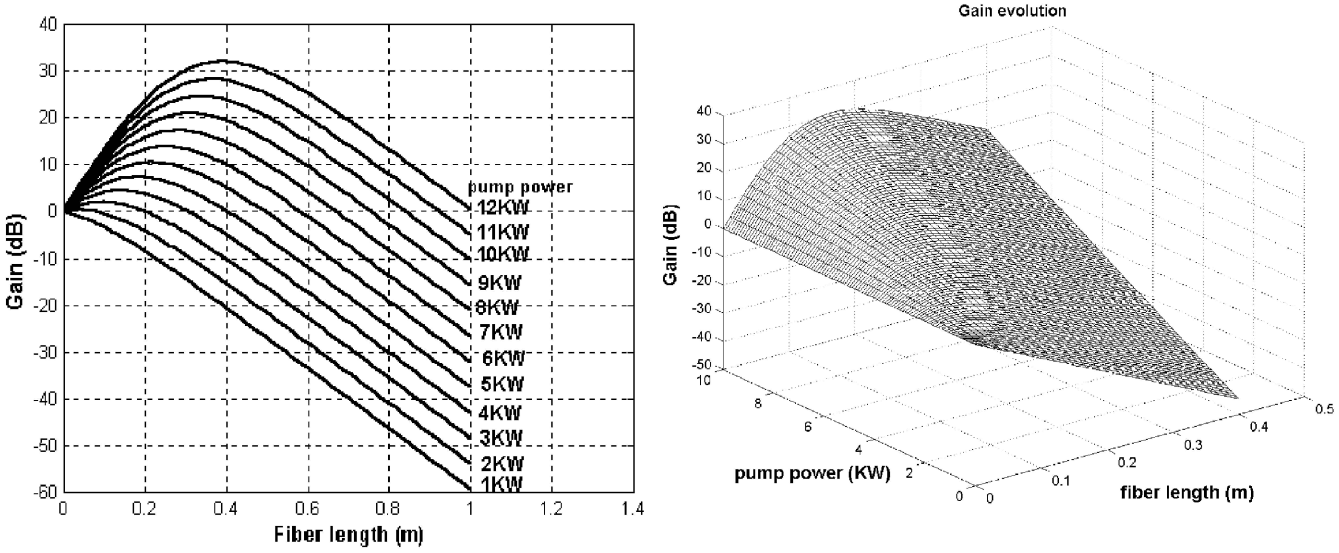

FIGURE 2 Evolution of fiber amplifier gain vs. fiber length and pump power

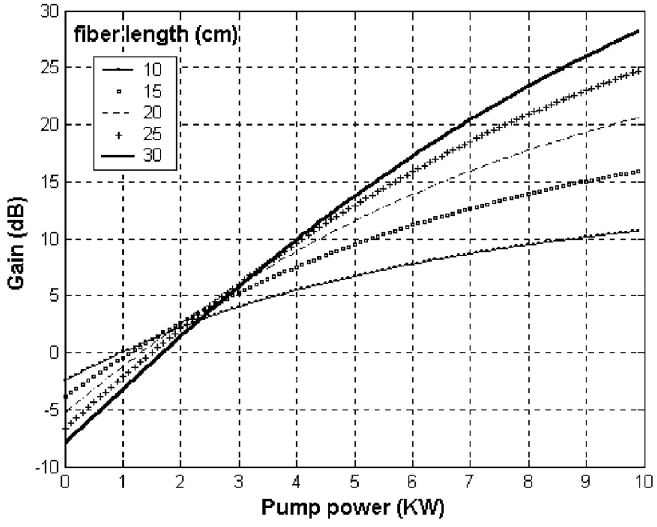

FIGURE 3 Signal gain variation of fiber amplifier vs. input pump power for several fiber amplifier lengths

gain increases, while for higher densities, the gain is almost fixed.

With increase in dye density, the optimum length of the amplifier becomes shorter. Actually, the dye concentration cannot be increased to the desired density in methyl methacrylate (MMA) background molecules [1].

The distributions of pump power and dye density affect the value of the factor η. First, suppose that the dye density of the fiber core is monotonic, i.e. $\theta(r) = \text{cte}$. Therefore, η will have a fixed value:

$$\eta = \text{cte}\int_0^{a_0} \bar{\psi}(r) r\mathrm{d}r = \text{cte}\int_0^{a_0} \frac{\Psi(r) r\mathrm{d}r}{\int_0^{a_0} \Psi(r) r\mathrm{d}r} = \text{cte}\frac{\int_0^{a_0} \Psi(r) r\mathrm{d}r}{\int_0^{a_0} \Psi(r) r\mathrm{d}r} = \text{cte}.$$

This means that, with a monotonic dye density, η does not depend on the pump distribution. Therefore, the gain of the fiber with a monotonic dye density is independent of the pump distribution, and is dependent on the fixed density distribution N_t. Now, suppose the dye density distribution not to be monotonic; therefore, η varies. From (1) and (2) it is observed that when η decreases, the dye density or the pump power distribution is narrowed.

Another factor that can influence the amplifier gain is the pump and signal wavelengths. Actually, there are limitations for these two parameters. It is desirable that the optimum signal wavelength be located at one of the optical communication windows but, unfortunately, it is not possible. Variation of the gain of the Rhodamine-B (RB)-doped polymer optical fiber amplifier vs. pump wavelength is demonstrated in Fig. 5.

It is shown that the maximum gain can be derived in the wavelength range of 510 to 590 nm. Due to the requirement of high pump power, a Nd–YAG laser is a suitable choice to be used in this range of wavelengths, because its second harmonic, 532 nm, is suitable. The input pump power is $P_\mathrm{p} = 5$ kW. Gain variations vs. fiber length and signal wavelength are shown in Fig. 6. It is demonstrated that the 500–550-nm wavelength range has the worst amplification condition, in which the optical signal is attenuated. Meanwhile, the wavelength range of 550–600 nm is the best region for signal amplification. In this low-loss window of the polymer fiber, a dye laser or an optical parametric oscillator (OPO) can be used as a signal light source. Frequently, the signal laser used in the experiments has a wavelength of 591 nm.

The small-signal gain factor given by

$$g(z) = \eta \frac{\left(\frac{\sigma_\mathrm{s}^\mathrm{e}\,\sigma_\mathrm{p}^\mathrm{a}}{h\upsilon_\mathrm{p}}\right) I_\mathrm{p}(z) + \frac{\sigma_\mathrm{s}^\mathrm{a}}{\tau}}{\left(\frac{\sigma_\mathrm{p}^\mathrm{a}}{h\upsilon_\mathrm{p}}\right) I_\mathrm{p}(z) + \left(\frac{\sigma_\mathrm{s}^\mathrm{e}+\sigma_\mathrm{s}^\mathrm{a}}{h\upsilon_\mathrm{s}}\right) I_\mathrm{s}(z) + \frac{1}{\eta\tau}} N_\mathrm{t} - k_\mathrm{s}\,. \tag{7}$$

Since the pump power must be high in this kind of amplifier, the signal power can be ignored:

$$g_0 = \eta \frac{\left(\frac{\sigma_\mathrm{s}^\mathrm{e}\,\sigma_\mathrm{p}^\mathrm{a}}{h\upsilon_\mathrm{p}}\right) I_\mathrm{p}(z) + \frac{\sigma_\mathrm{s}^\mathrm{a}}{\tau}}{\left(\frac{\sigma_\mathrm{p}^\mathrm{a}}{h\upsilon_\mathrm{p}}\right) I_\mathrm{p}(z) + \frac{1}{\eta\tau}} N_\mathrm{t} - k_\mathrm{s}\,. \tag{8}$$

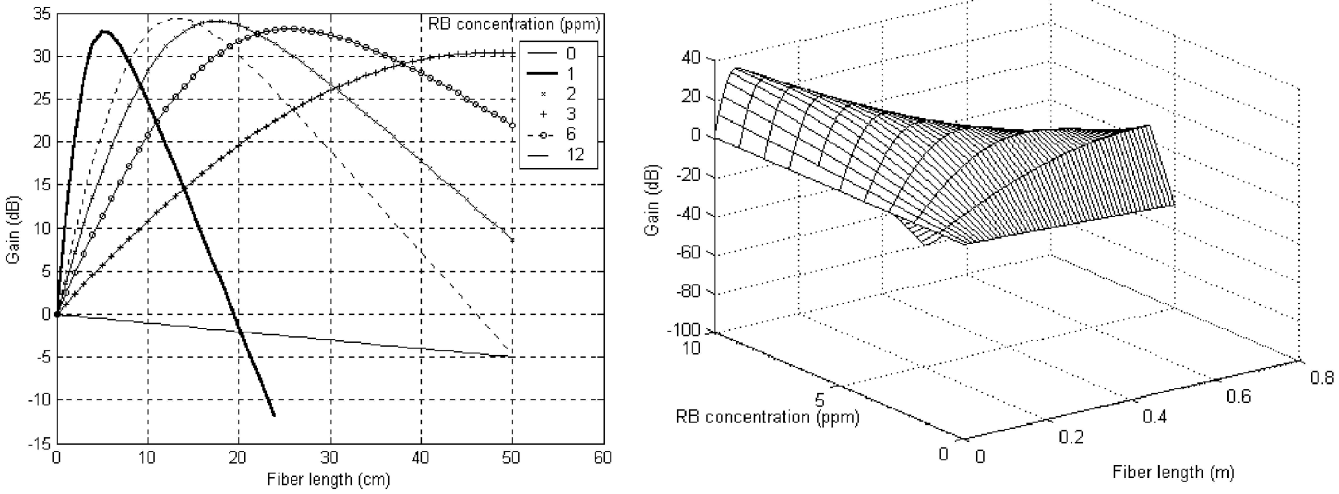

FIGURE 4 Gain variations vs. fiber length and dopants

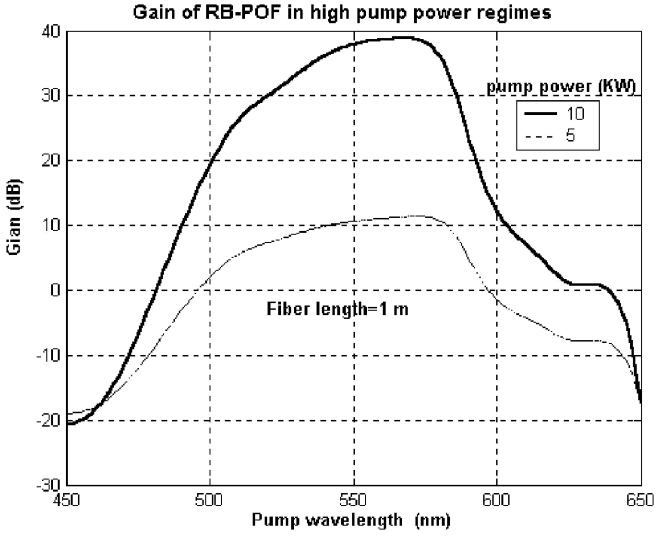

FIGURE 5 Fiber gain variation vs. pump wavelength for two different pump powers

Then, the signal variation is assumed to be

$$I_s(z) = I_0 \exp(g_0 z) \ . \tag{9}$$

With a pump increment in (7), the gain saturates, as illustrated in Fig. 7. The gain variation agrees with that of an Er-doped fiber amplifier [8].

For a pump power lower than 600 W, the amplifier operates as an attenuator. Therefore, this kind of amplifier needs high pump powers. From Fig. 7b, it can be seen that the increment of the pump power from a certain amount saturates the gain.

Since the metastable lifetime in rhodamine dyes is much lower than that of Er, both signal and pump saturation powers are higher than that of Er. The Er metastable lifetime is in the order of 10 ms, while the rhodamine one is in the order of nanoseconds [3]. The pump saturation power is given by [8]

$$P_{\text{sat}}(\upsilon_{s,p}) = \frac{h\upsilon_{s,p}\,\pi\, W_{s,p}^2}{[\sigma_a(\upsilon_{s,p}) + \sigma_e(\upsilon_{s,p})]\tau} \ . \tag{10}$$

From this equation, it can be shown that the saturation power of the RB-doped fiber amplifier is almost 1000 times higher than that of Er [8]. An increase in saturation signal power is desirable, but not the pump power, because an increase in the pump power destroys the fiber dyes. Gain spectra of several fiber amplifiers with various dye dopants are shown in Fig. 8. The best dye for a polymer fiber amplifier is RB. A RB-doped polymer fiber has a higher and wider output gain, which agrees with results in [4].

Gain variation vs. input signal power for different fiber lengths is displayed in Fig. 9. The signal gain does not depend strongly on the input signal power, except when it is comparable with the pump power, as shown in Fig. 9. So, the actual signal power is regularly less than the pump power. This is desirable because in optical communication intensity modulation is being used. Therefore, by signal amplification, the information carried does not change.

Since the steady-state lifetime of rhodamine dyes is low, the fiber saturation power is much higher than that of an Er-doped fiber amplifier. Pump power variation vs. fiber length for several initial pump powers is illustrated in Fig. 10.

4 Noise figure in rhodamine-B-doped polymer optical fiber amplifier

The spontaneous emission factor in a RB-doped polymer optical fiber amplifier is given by [8]

$$n_{\text{sp}} = \frac{N_2}{N_2 - N_1} = \frac{\left(\frac{\sigma_s^e \sigma_p^a}{h\upsilon_p}\right) I_p(z) + \frac{\sigma_s^a}{\tau}}{\left(\frac{\sigma_p^a}{h\upsilon_p}\right) I_p(z) - \left(\frac{\sigma_s^e - \sigma_s^a}{h\upsilon_s}\right) I_s(z) - \frac{1}{\eta\tau}} \ , \tag{11}$$

where the parameters are defined in (1)–(4). The spontaneous emission factor depends on the fiber length. The noise variation can be expressed as [6]

$$P_{\text{ASE}}^{\pm\text{out}} = G(l)\, P_{\text{ASE}}^{\pm\text{in}} \ , \tag{12}$$

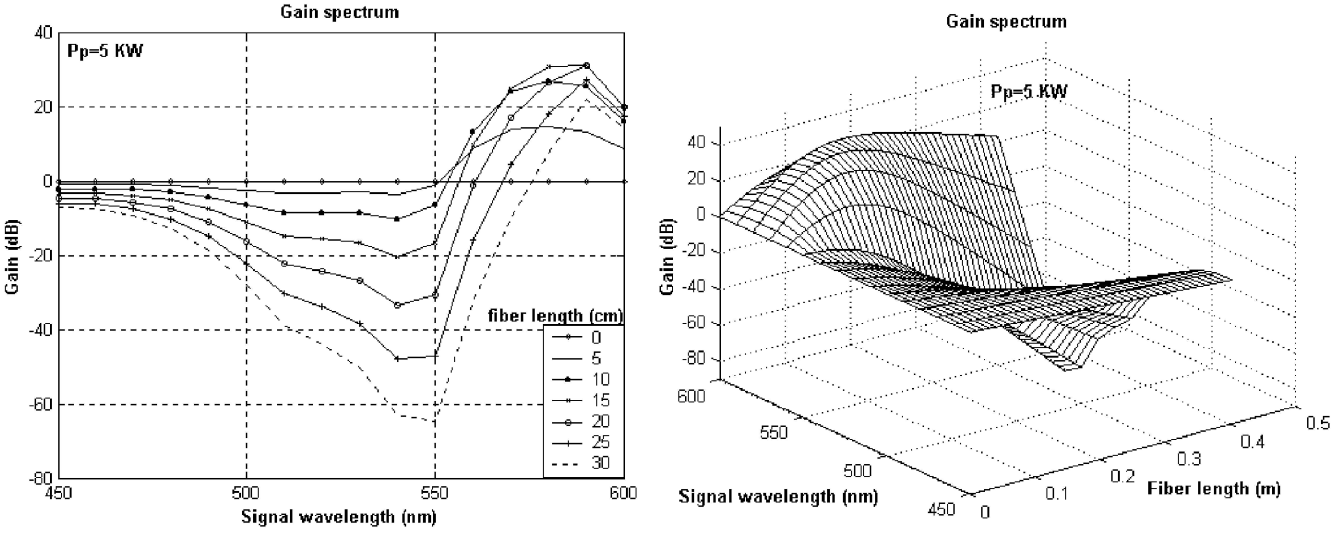

FIGURE 6 Gain variation vs. fiber length and signal wavelength

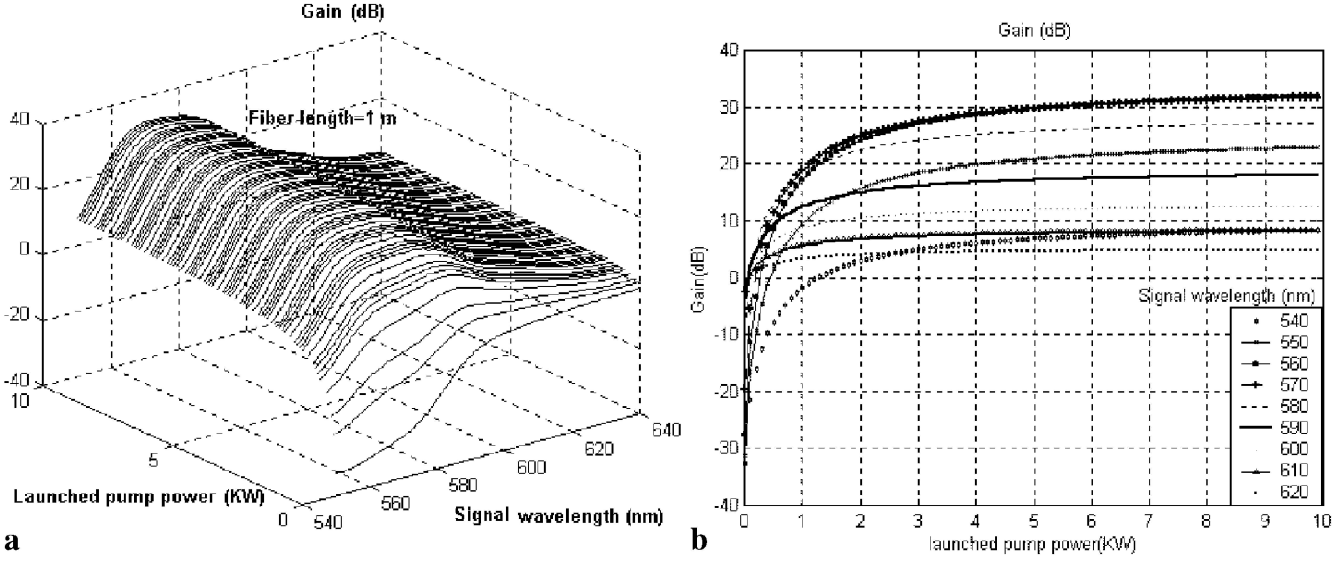

FIGURE 7 **a** Gain variation vs. input pump power and signal wavelength in a 1-m length of rhodamine-B-doped optical fiber amplifier. **b** Saturation condition

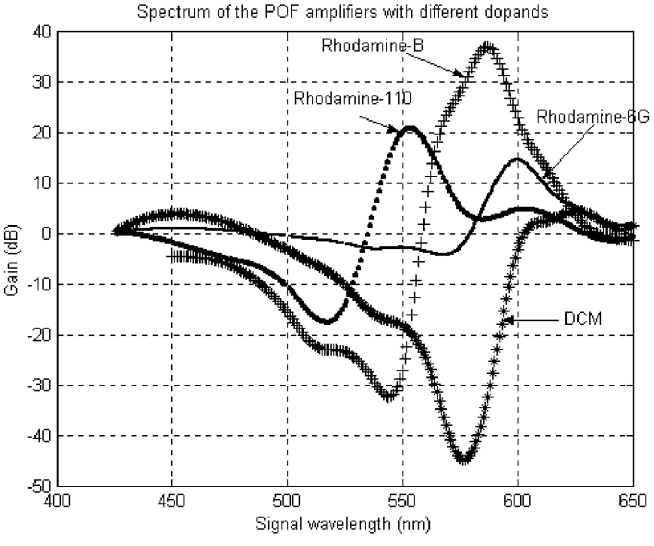

FIGURE 8 Gain spectra of several dye-doped polymer optical fiber amplifiers

$$G(l) = \exp \int_0^l g(z)\mathrm{d}z\,, \tag{13}$$

where $g(z)$ is the small-signal gain factor. In (11), n_{sp} is given as follows [6]:

$$n_{\mathrm{sp}} = \int_0^l \frac{g(z)\, n_{\mathrm{sp}}(z)}{G(z)}\,\mathrm{d}z\,. \tag{14}$$

Then, we have [6]

$$P_{\mathrm{ASE}}^{\mathrm{out}} = n_{\mathrm{sp}}(l)\, h\upsilon\, \Delta\upsilon \frac{G(l)-1}{G(l)^{\pm}} \approx n_{\mathrm{sp}}(l)\, h\upsilon\, \Delta\upsilon\,, \tag{15}$$

$$F = 2\,\frac{P_{\mathrm{ASE}}}{h\upsilon\, \Delta\upsilon\, G(l)} = 2\, n_{\mathrm{sp}}(l)\, h\upsilon\, \Delta\upsilon \frac{G(l)-1}{G(l)^{\pm}} \approx 2\, n_{\mathrm{sp}}(l)\, h\upsilon\, \Delta\upsilon\,, \tag{16}$$

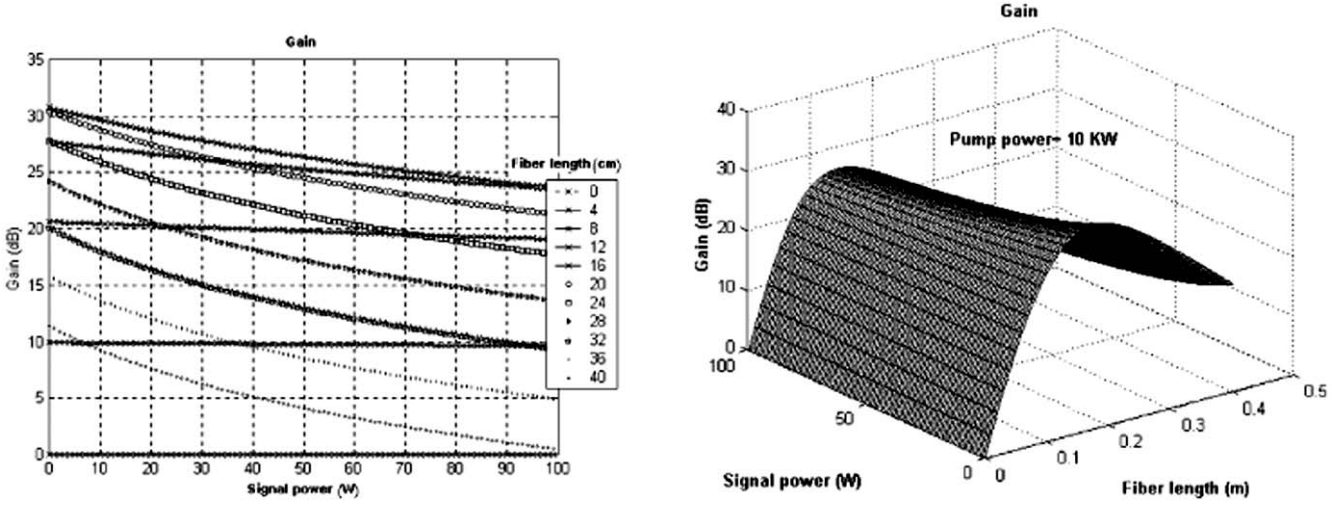

FIGURE 9 Gain variation vs. input signal power for different fiber lengths

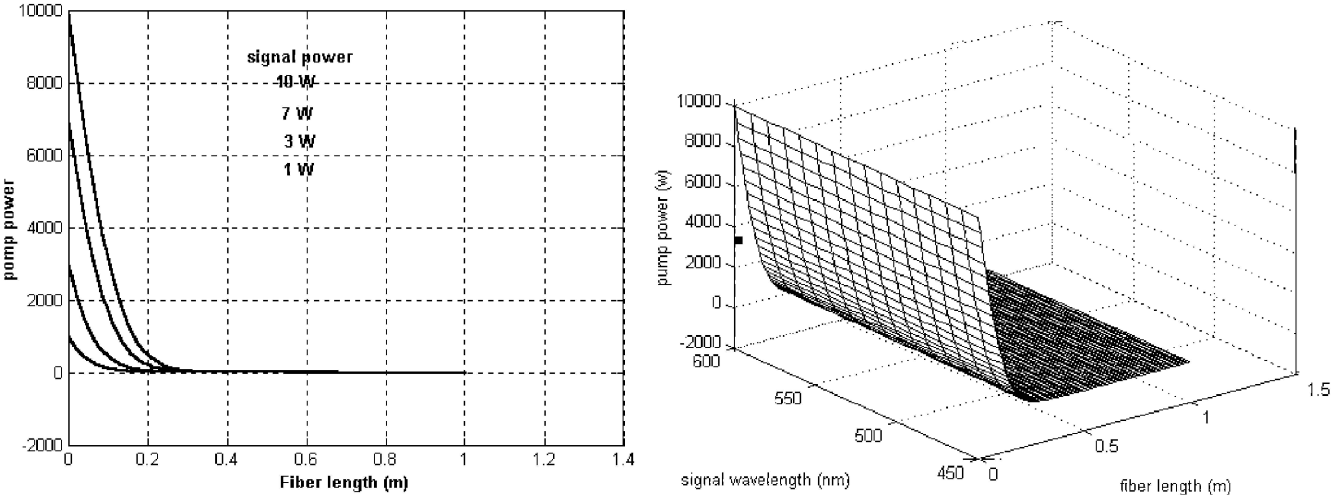

FIGURE 10 Pump variation vs. fiber length, for **a** one signal wavelength and **b** various signal wavelengths

where F is the noise figure. The noise-figure variation vs. fiber length is shown in Fig. 11. The amplifier noise figure is fixed at higher fiber lengths. Variation of the first and the second level densities, N_1 and N_2, is illustrated in Fig. 12.

Metastable and ground-state level densities near the maximum gain have their lowest and highest values, respectively, because the pump power in the fiber near the maximum gain becomes zero. From Figs. 11 and 12 it is seen that a noise peak occurs when N_1 and N_2 are equal. Here, some questions are raised as to why, where, and when this occurs. Does it occur at the fiber optimum length? To find the answer, we differentiate (16), giving

$$\frac{\mathrm{d}F}{\mathrm{d}z} = 2h\upsilon\,\Delta\upsilon\frac{\mathrm{d}n_{\mathrm{sp}}}{\mathrm{d}z} = 2h\upsilon\,\Delta\upsilon\frac{(N_2+N_1)}{(N_2-N_1)^2}\frac{\mathrm{d}N_2}{\mathrm{d}z}\,, \qquad (17)$$

where $\mathrm{d}n_{\mathrm{sp}}/\mathrm{d}z$ is derived from (11) and the variations of N_1 and N_2 with z are assumed to be the same, but with opposite signs. The noise figure is constant with z if

$$\frac{\mathrm{d}N_2}{\mathrm{d}z} = 0 \rightarrow N_2 = \mathrm{cte}\,.$$

It is shown in Fig. 12 that, in the selected amplifier for fiber lengths longer than 60 cm, N_2 is practically zero. Therefore, the noise in fibers with lengths longer than 60 cm must be constant, as shown in Fig. 11. From (17) the noise figure approaches infinity for $N_2 = N_1$, which is displayed in Figs. 11 and 12. When the amplifier gain is maximum, the length of the amplifier is optimum or the variation of gain with z is zero. From (2) this occurs when $\sigma_{\mathrm{s}}^{\mathrm{a}}\ N_1 = \sigma_{\mathrm{s}}^{\mathrm{e}} N_2$, and the noise peak occurs at the optimum gain when $\sigma_{\mathrm{s}}^{\mathrm{a}} = \sigma_{\mathrm{s}}^{\mathrm{e}}$. From Fig. 1, this occurs at the intersection of the absorption and emission cross-section spectra. If the pump and signal wavelengths are equal, at the optimum length the noise becomes maximum. In our simulation, the signal wavelength differs from the pump wavelength. It can be seen from Figs. 5 and 6 that the optimum pump and signal wavelengths are 532 nm and 591 nm, respectively, as given in Table 1. It is important that the pump wavelength be at the maximum of the absorption cross section. It is shown in Figs. 2 and 4 that there are two lengths of fiber with the same gain but, due to the lower noise and gain variation, the shorter length is preferred.

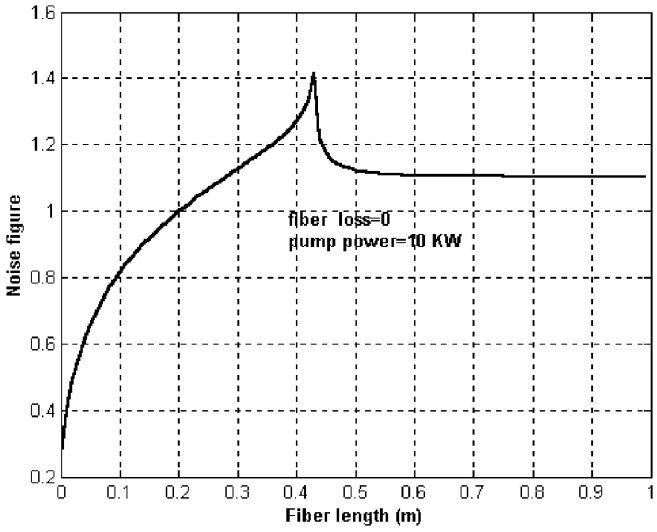

FIGURE 11 Noise figure vs. fiber length

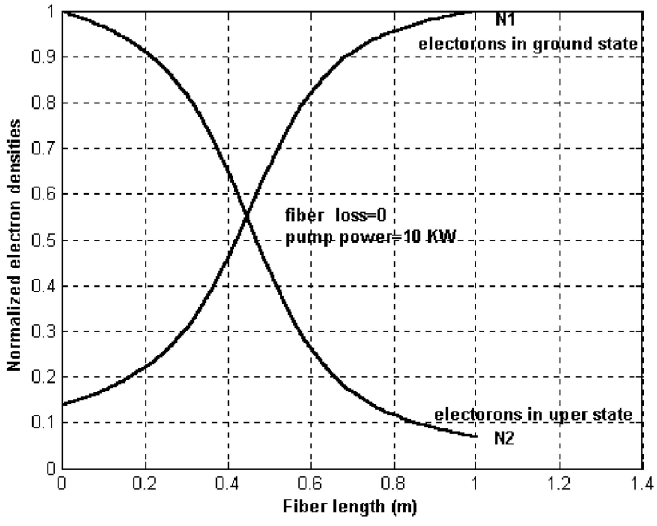

FIGURE 12 Density variation of levels 1 and 2 vs. fiber length

5 Solution of the time-dependent rate equations

To predict the transient behavior of the polymer optical fiber amplifier, the time-dependent rate equations must be solved. The finite-element method was used to solve these rate equations. N_2, I_p, and I_s can be expressed as

$$\begin{aligned} N_2(t+\Delta t, z) &= N_2(t, z) + F(N_2(t, z)\,, I_\mathrm{p}(t, z)\,, I_\mathrm{s}(t, z))\,\Delta t \\ I_\mathrm{p}(t, z+\Delta z) &= I_\mathrm{p}(t, z) + G(N_2(t, z)\,, I_\mathrm{p}(t, z))\,\Delta z \\ I_\mathrm{s}(t, z+\Delta z) &= I_\mathrm{s}(t, z) + H(N_2(t, z)\,, I_\mathrm{s}(t, z))\,\Delta z\,, \end{aligned} \tag{18}$$

where F, G, and H are the nonlinear relations of N_2, I_p, and I_s. The boundary conditions are shown in Fig. 13 and can be expressed as

$$\begin{cases} I_\mathrm{p}(z=0\,, t) = I_\mathrm{p}(i=1\,, j) = I_{0\mathrm{p}} & j = 1,\ 2,\ \ldots,\ N, \\ I_\mathrm{s}(z=0, t) = \begin{cases} I_\mathrm{s}(i=1\,, j) = I_{0\mathrm{s}} & j = 2k, \\ I_\mathrm{s}(i=1\,, j) = 0 & j = 2k+1\,, \end{cases} \end{cases} \tag{19}$$

where j is the fiber length, k is a real number, and $I_{0\mathrm{p}}$ and $I_{0\mathrm{s}}$ are the input pump and signal intensities, respectively.

To determine the boundary conditions, we have assumed that the pump is switched on at $t < 0$, while $I_\mathrm{s} = 0$. Since the pump power is continuous, due to the complete population inversion the fiber reaches the equilibrium condition, which we can assume to be $\partial N_2/\partial t = 0$. Therefore, in the high pump power regime the rate equations are time independent:

$$\begin{aligned} N_2 &= \frac{\sigma_\mathrm{p}^\mathrm{a}\, I_\mathrm{p} N_\mathrm{t}/h\upsilon_\mathrm{p}}{\sigma_\mathrm{p}^\mathrm{a}\, I_\mathrm{p} N_\mathrm{t}/h\upsilon_\mathrm{p} + 1/\eta\tau}\,, \\ \frac{\mathrm{d}I_\mathrm{p}}{\mathrm{d}z} &= -\frac{\sigma_\mathrm{p}^\mathrm{a}/\tau}{\sigma_\mathrm{p}^\mathrm{a}\, I_\mathrm{p} N_\mathrm{t}/h\upsilon_\mathrm{p} + 1/\eta\tau} N_\mathrm{t} I_\mathrm{p} - k I_\mathrm{p}\,. \end{aligned} \tag{20}$$

The analytical solution of these equations yields

$$\begin{aligned} z = {} & \frac{1}{k + \eta\sigma_\mathrm{p}^\mathrm{a} N_\mathrm{t}} \ln\left| \frac{I_\mathrm{p} + \frac{h\upsilon_\mathrm{p}}{\eta\tau\sigma_\mathrm{p}^\mathrm{a}} + \frac{\sigma_\mathrm{p}^\mathrm{a} N_\mathrm{t}}{\tau}}{I_\mathrm{p}} \right| \\ & - \frac{1}{k} \ln\left| I_\mathrm{p} \frac{k\sigma_\mathrm{p}^\mathrm{a}}{h\upsilon_\mathrm{p}} + \frac{k}{\eta\tau} + \frac{\sigma_\mathrm{p}^\mathrm{a} N_\mathrm{t}}{\tau} \right|. \end{aligned} \tag{21}$$

The numerical solution yields a pump power variation similar to that of the steady state, as shown in Fig. 10a, but here I_p tends to zero at shorter lengths.

To solve the rate equations, we let $\Delta t = 10^{-11}$ and $\Delta z = 0.0025$. Gains for a continuous signal beam are shown in Fig. 14. It is obvious that in the high pump regime the gain approaches a fixed value, and Fig. 15 shows that this does not differ for continuous or pulsed signals.

The same gain variations have been shown in Er-doped fiber amplifiers [8], except that the time needed to reach the fixed gain is in the range of nanoseconds. This means that

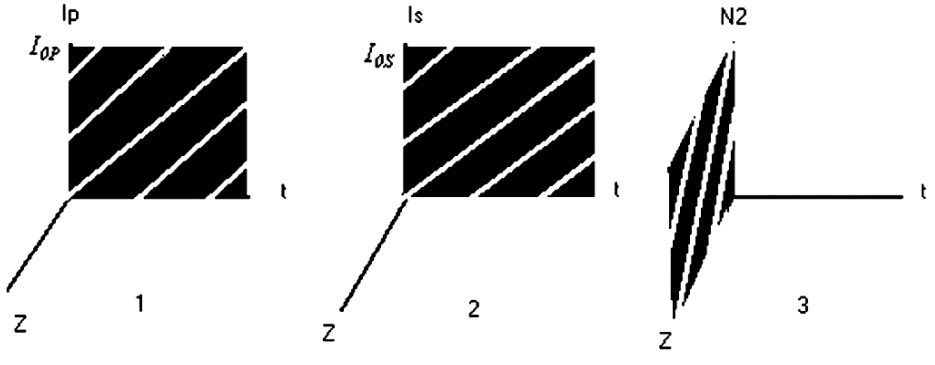

FIGURE 13 Boundary conditions of I_p, I_s, and N_2 for solution of the rate equations

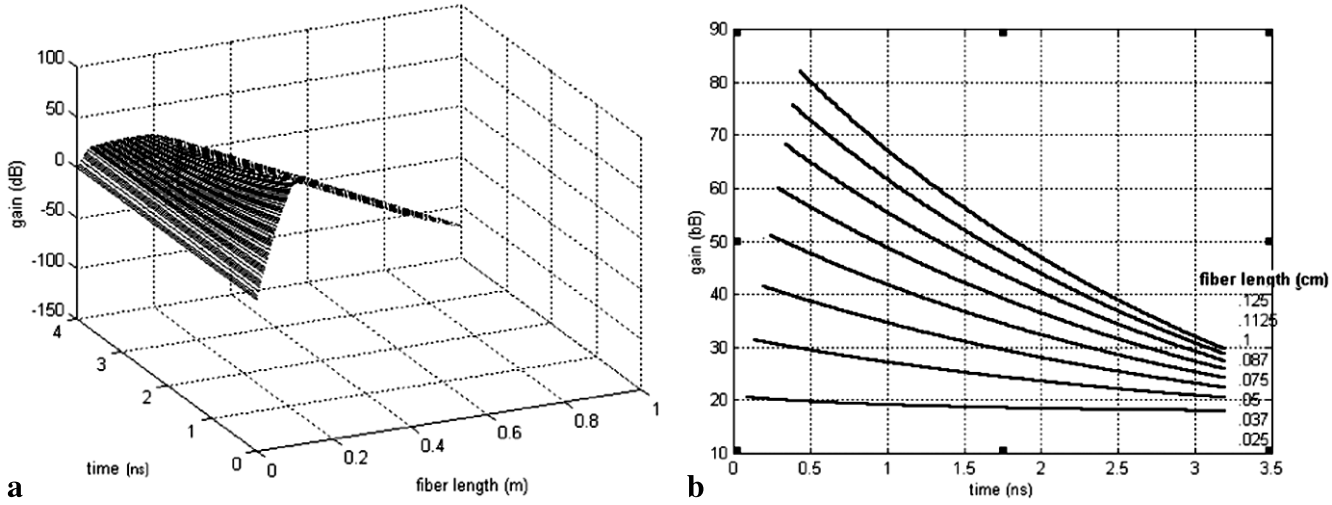

FIGURE 14 Gain variation of continuous-wave signal vs. **a** fiber length and time and **b** time for different fiber lengths

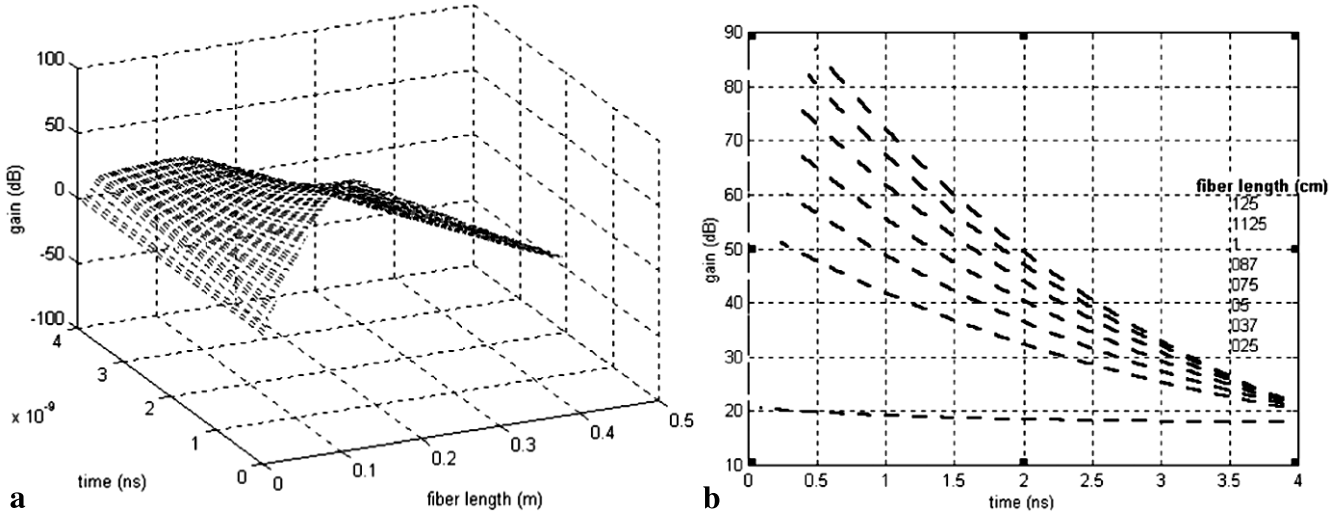

FIGURE 15 Gain variation of input pulse signal vs. **a** fiber length and time and **b** time for several fiber lengths

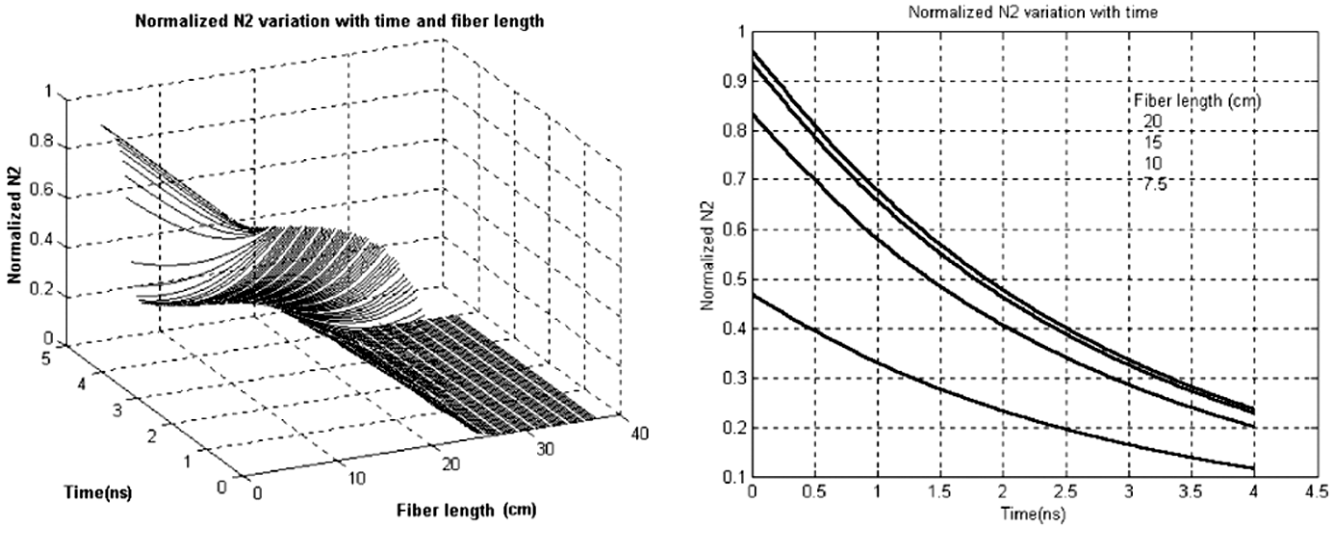

FIGURE 16 Variations of metastable charge density, N_2, vs. time and fiber length

in both cases this scale is in the range of the steady-state metastable lifetime.

The finite-element method's error is related to the calculation steps. Therefore, the convergence of this method is very slow. Variations of N_2 with time and fiber length are shown in Fig. 16.

6 Amplification conditions for lasing wavelength

Organic dyes such as rhodamine have absorption, emission, and lasing spectra in bulk or doped fiber, as shown in Fig. 17 for Rhodamine-6G (R6G) in a polymer fiber.

From the Einstein relation we know that in the lasing condition the signal absorption and emission cross sections are equal; therefore, (2) will change [7]:

$$\frac{\partial I_s(t,z)}{\partial z} = 2\pi\sigma_1 \left(N_2(t,z) - \frac{g_1}{g_2} N_1(t,z) \right) I_s(t,z) \int_0^{a_0} \theta(r)\, \bar{\Psi}(r)\, r\,\mathrm{d}r, \qquad (22)$$

where g_1 and g_2 are the degenerate sublevels of levels 1 and 2, respectively, and σ_1 is the value of the lasing cross section. From (22) it can be seen that the amplifier gain depends on the level degeneracies. There is no information about the levels of dyes in doped Polymer Optical Fibers (POFs); therefore, we have assumed a suitable fixed value for the lasing cross section. The amplifier gain rises by increasing g_2. This continues until g_2 becomes 10 times g_1; for a higher amount of g_2, the gain approaches a fixed amount.

If the signal wavelength is equal to the lasing wavelength, the output light will be a mixture of coherent and incoherent light. To enter this effect into our calculation, the exact spectrum of lasing must be known. In the POF amplifiers, setting the signal wavelength on the lasing wavelength is not appropriate, because the absorption and emission cross sections are equal at this wavelength, and the amplifier gain reduces. But, in the fiber lasers, the signal has the lasing wavelength, and reflection surfaces at the end facets of the fiber cause higher gain and coherent output light.

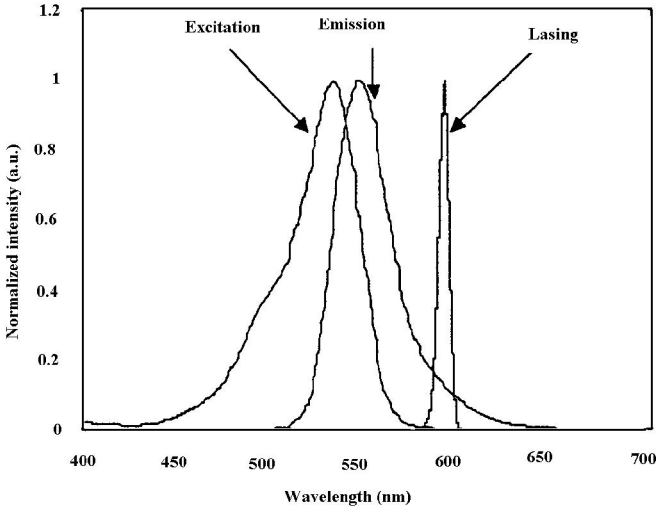

FIGURE 17 Absorption, emission, and lasing spectra of R6G in PMMA polymer fiber [5]

In experiments, when the signal wavelength is equal to the lasing wavelength, the time-dependent signal and pump intensities have alternations, as shown in Fig. 18.

When laser light is coherent, the atom density matrix will be replaced by the Schrödinger equation. In the simplest case this equation shows that the output signal must have some alternations [7]. The study of time-dependent performance of polymer laser fibers is a new and attractive field of research, to be discussed in the near future.

7 Conclusion

From the simulation results, it was shown that rhodamine-B is one of the best organic dyes to be used for polymer optical fiber amplifiers.

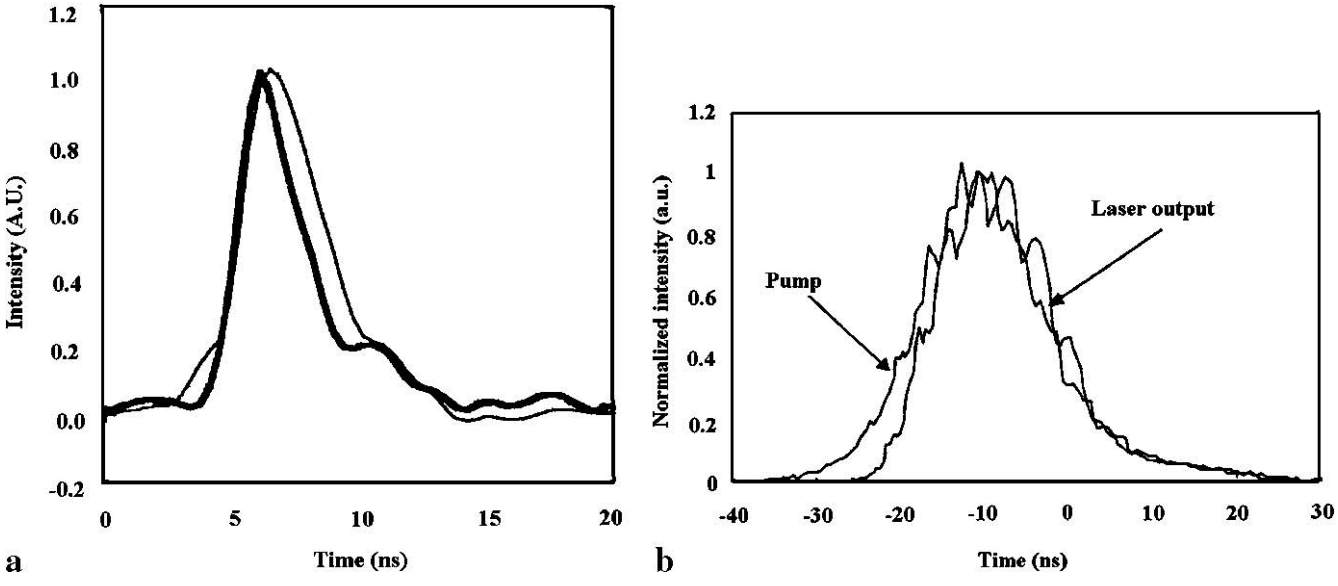

FIGURE 18 Temporal profile variation **a** in RB-doped fiber [9] and **b** in R6G-doped fiber laser [5]

Suitable signal and pump wavelengths used in this kind of amplifier are 591 nm and 532 nm, respectively.

Since the metastable lifetime in organic dyes is very low, this kind of amplifier needs a high pump power. A high-power Nd–YAG laser can be used to pump these amplifiers.

Since the loss in polymer optical fiber amplifiers is high, the optimum length of this type of amplifier is about 0.5 m. The absorption and emission cross sections of organic dyes are very high; therefore, regardless of the short lifetime and high loss, high gain can be achieved from these amplifiers. The gain of the amplifier with optimum length and sufficient pump power is about 30 dB.

Since the signal power is low compared to the pump power, the signal intensity distribution has no effect on the amplifier gain. Therefore, the overlap coefficient, η, is constant, independent of the dye and pump power distribution.

Increasing the concentration of the dye dopants shifts the optimum length of the fiber amplifier to shorter lengths. From the simulation, 1–3 ppm dye density is proper for amplification.

The noise in a polymer optical fiber amplifier has a peak when $N_2 = N_1$.

From two lengths of fiber with the same gain, the shorter length is preferable due to its lower noise and lower gain variation with signal power.

In any fiber amplifier (glass or polymer), the required time to reach the steady-state condition is in the order of the dye's lifetime.

The time required for the amplifier to reach equilibrium is independent of the type of the input signal (digital or analogue).

If the signal wavelength is equal to the dye's lasing wavelength, the output signal is a combination of coherent and incoherent light, and the signal gain reduces with some fluctuations. This quantum mechanical effect can be simulated by numerical solution of density matrix equations.

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