THEORETICAL COMPARISON OF PR^{3+}-DOPED LA-GA-S AND FLUORIDE GLASS FIBRE AMPLIFIER

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Abstract

The performance and efficiency of a praseodymium-doped La-Ga-S chalcogenide glass fibre amplifier have been analyzed using a comprehensive large-signal numerical model. The four level laser model incorporates the LP_{01} mode radial field distribution in step-index single-mode fibre and experimentally obtained emission and absorption cross sections. The model has been used to optimize the fibre parameters for small-signal operation. The optimum cut-off wavelength of the LP_{11} mode has been found to be 700 nm. It follows from the analysis that at 1310 nm a small-signal gain of 36.7 dB can be expected from the Pr^{3+}-doped chalcogenide fibre amplifier for a pump power of 200 mW in contrast to 18.8 dB for the same pump power in the Pr^{3+}-doped fluoride fibre amplifier.

Keywords:
Optical communications, fibre optics, fibre lasers, fibre amplifiers

1. Introduction

The erbium-doped fibre amplifier has been thoroughly investigated and used in both laboratory and field applications in the 1550 nm band. The majority of installed optical communication systems operate, however, in the second window near 1300 nm. Praseodymium-doped fluoride fibres have been studied as active media in the 1300 nm wavelength range. The first demonstration of a Pr^{3+}-doped fibre amplifier (PDFA) showed a net gain of 5.2 dB at 1310 nm, a -3 dB bandwidth of 40 nm and pump efficiency of 0.03 dB/mW for a pump power of 180 mW at 1017 nm [1]. The maximum gross gain and the pump efficiency reported so far are 38.2 dB and 0.21 dB/mW, respectively [2]. Due to the short lifetime of the $^1G_4$ metastable level and low ground state absorption cross section at the 1017 nm pump wavelength, a pump power of several hundred mW was needed to achieve the above mentioned amplification.

Recently, Pr^{3+}-doped La-Ga-S chalcogenide glass has been reported to have metastable level lifetime and peak emission cross section values three times higher than those in fluoride glass [3]. Although the peak emission occurs at 1334 nm, the approximately eight times larger emission cross section-metastable level lifetime product promises significantly more efficient fibre amplification at 1300 nm.

To date, detailed numerical analysis of the chalcogenide PDFA has not been presented. A detailed large-signal model for a PDFA - which takes into account the LP_{01} mode field distribution in a step-index single-mode fibre and experimentally obtained emission and absorption cross section - has been used to perform an extensive analysis of a La-Ga-S PDFA. In this contribution we present the results of small-signal and large-signal analysis of a La-Ga-S PDFA and compare the properties of the chalcogenide PDFA with the fluoride PDFA.

2. Theory

Our model for the PDFA is based on a solution of both the rate equations describing the population of the $^3H_4$ ground level and the $^1G_4$ upper laser level and the equations describing the propagation of pump, signal and both the forward and backward amplified spontaneous emission (ASE) powers along the fibre [4]. The model considers only the LP_{01} modes of pump and signal waves in a step-index single-mode fibre. In the analysis of the fluoride PDFA the effect of the signal excited state absorption (ESA) due to the $^1G_4-^1D_2$ transition with the peak at $\approx$1375 nm and the signal ground state absorption (GSA) due to the $^3H_4-^3F_4$ transition which peaks at $\approx$1440 nm have been taken into account. These transitions affect the spectral gain of the PDFA at wavelengths longer than 1320 nm and have negligible influence at $\lambda < 1310$ nm. For the Pr^{3+}-doped La-Ga-S glass the appropriate signal ESA and GSA cross sections are not available. Relaxation of the $^1D_2$ and the $^3H_5$ levels is fast so that these levels can be assumed to be unpopulated.

It follows from the rate equations that the steady state population densities $\eta_3(r,z)$ of the $^1G_4$ upper laser level and $\eta_0(r,z)$ of the $^3H_4$ ground state level are

$$\eta_3(r,z) = \rho(r)\frac{W_{03}(r,z)}{W_{03}(r,z)+W_{31}(r,z)+W_{34}(r,z)+1/\tau}$$

$$\eta_0(r,z) = \rho(r) - \eta_3(r,z) \quad (1)$$

$\rho(r)$ is the praseodymium doping profile, τ is the spontaneous emission lifetime, W_{03}, W_{34} and W_{31} are the pump absorption, signal ESA and signal emission rates given by

$$W_{03}(r,z) = \sigma_{03}(\nu_p)\frac{P_p(z)}{h\nu_p}|E_p(r)|^2 \quad (2)$$

$$W_{34}(r,z) = |E_s(r)|^2\int_0^\infty \frac{\sigma_{34}(\nu)}{h\nu}[P_s^+(z,\nu)+P_s^-(z,\nu)]d\nu \quad (3)$$

$$W_{31}(r,z) = |E_s(r)|^2\int_0^\infty \frac{\sigma_{31}(\nu)}{h\nu}[P_s^+(z,\nu)+P_s^-(z,\nu)]d\nu \quad (4)$$

where $P_s^+(z,\nu)$, $P_s^-(z,\nu)$ are the forward and backward propagating optical powers at frequency ν in a frequency interval $\Delta\nu$ and at a longitudinal fibre coordinate z, h is Planck's constant. For signal frequency ν_s, $P_s(z,\nu)$ is the monochromatic signal power, for $\nu \neq \nu_s$ $P_s^\pm(z,\nu)$ represent the forward and backward propagating amplified spontaneous emission powers ASE$^+$, ASE$^-$. $P_p(z)$ is the pump power which is assumed to propagate in the forward direction, $E_s(r)$, $E_p(r)$ are the signal and pump field distribution of the LP_{01} mode and $\sigma_{31}(\nu)$, $\sigma_{34}(\nu)$ and $\sigma_{03}(\nu)$ are signal stimulated emission, signal excited state absorption and pump ground state absorption cross sections.

In our PDFA model, propagation of pump power is described by the following propagation equation

$$\frac{dP_p(z)}{dz} = -g_p(z)P_p(z) \quad (5)$$

where $g_p(z)$ is the pump loss factor defined as

$$g_p(z) = 2\pi\sigma_{03}(\nu_p)\int_0^B \eta_0(r,z)|E_p(r)|^2\, r\,dr \quad (6)$$

In the above equation, B is the radius of the praseodymium - doped part of fibre core. For the propagation of signal and ASE powers we can write

$$\frac{dP_s^\pm(z,\nu)}{dz} = \pm 2h\nu\Delta\nu g_e(z,\nu) \pm$$

$$\pm[g_e(z,\nu) - g_a(z,\nu) - \alpha(\nu)]P_s^\pm(z,\nu) \quad (7)$$

where $\alpha(\nu)$ describes the wavelength dependent fibre internal loss due to the signal GSA by the $^3H_4 - ^3F_4$ transition. The signal emission and absorption factors $g_e(z,\nu)$, $g_a(z,\nu)$ are determined as follows

$$g_e(z,\nu) = 2\pi\sigma_{31}(\nu)\int_0^B \eta_3(r,z)|E_s(r)|^2\, r\,dr \quad (8)$$

$$g_a(z,\nu) = 2\pi\sigma_{34}(\nu)\int_0^B \eta_3(r,z)|E_s(r)|^2\, r\,dr \quad (9)$$

Boundary conditions for the signal, pump and ASE$^+$ powers are defined at $z = 0$ and for ASE$^-$ powers at $z = L$ (L is the length of the PDFA)

$$P_p(z=0) = P_{p0}$$

$$P_s^+(z=0, \nu=\nu_s) = P_{s0}$$

$$P_s^+(z=0, \nu\neq\nu_s) = P_s^-(z=L, \nu\neq\nu_s) = 0 \quad (10)$$

The above equations describe the evolution of pump, signal and ASE powers along the praseodymium-doped fibre. The spectral dependence of signal emission and signal ESA cross-sections, $\sigma_{31}(\lambda)$, $\sigma_{34}(\lambda)$ in m^2, for Pr^{3+} ions in ZBLAN glass were simulated in the model by the superposition of three Gaussian curves,

$$\sigma(\lambda) = \sum_{i=1}^{3} a_i \exp\left(-((\lambda-\lambda_i)/b_i)^2\right) \quad (11)$$

derived from least-square fits to the experimental spectral data [5]. The coefficients a_i, λ_i and b_i are summarized in Table 1. The wavelength dependent fibre internal loss from the signal GSA due to the Pr^{3+} $^3H_4 - ^3F_4$ transition in ZBLAN glass, $\alpha(\lambda)$ in Np/m, is a function of Pr^{3+} doping. It was simulated in the model by a single Gaussian curve,

$$\alpha(\lambda) = 8.942\cdot 10^{-4}\exp\left(-((\lambda-1430)/84.08)^2\right)\cdot PPM \quad (12)$$

	σ_{31}	σ_{34}
a_1	$0.8352\cdot 10^{-25}$	$1.019\cdot 10^{-25}$
a_2	$0.1745\cdot 10^{-25}$	$0.729\cdot 10^{-25}$
a_3	$0.1722\cdot 10^{-25}$	$2.019\cdot 10^{-25}$
λ_1	1 318	1 345
λ_2	1 340	1 380
λ_3	1 385	1 400
b_1	48	33.6
b_2	72.1	38.4
b_3	36	66.1

Table 1
Coefficients for the least-square fit of σ_{31}, σ_{34} in Pr^{3+}-doped ZBLAN

derived from a least-square fit to the experimental spectral data [1]. PPM is the concentration of Pr^{3+} ions in ppm (weight). The pump absorption cross-section, σ_{03}, given in [5] was used.

The spectral dependence of emission cross section for the Pr^{3+}-doped La-Ga-S glass was simulated by the superposition of three Gaussian curves fitted to the experimental data, the peak emission cross section was taken as $10.5 \cdot 10^{-25}\,m^2$, [3]. The appropriate coefficients are given in Table 2. Using the Judd-Ofelt parameters given in [3], the pump absorption cross section at 1015 nm was calculated to be $\sigma_{03} = 8.80 \cdot 10^{-26}\,m^2$ under the assumption that the $^1G_4$ level effective linewidth is 60nm. This value is about twice as high as that for the Pr^{3+}-doped fluoride glass.

	σ_{31}
a_1	$8.1700 \cdot 10^{-25}$
a_2	$3.1820 \cdot 10^{-25}$
a_3	$-7.378 \cdot 10^{-25}$
λ_1	1 334
λ_2	1 355
λ_3	1 360
b_1	48
b_2	75.7
b_3	96.1

Table 1
Coefficients for the least-square fit of σ_{31} in Pr^{3+}-doped La-Ga-S

The spectral region from 1200 nm to 1550 nm has been subdivided into 175 sections of $\Delta\lambda = 2\,nm$. Thus 351 coupled differential equations describing the propagation of pump, signal, co-propagating and counter-propagating amplified spontaneous emission must be integrated simultaneously. The modified Euler method has been used for forward and backward integration.

In the analysis, the Pr^{3+}-doping was assumed to be 500 ppm (weight), the spontaneous emission lifetime $\tau = 110\,\mu s$, the pump wavelength $\lambda_p = 1017\,nm$ and the pump absorption cross section at 1017 nm $\sigma_{03} = 4.29 \cdot 10^{-26}\,m^2$ for the Pr^{3+}-doped fluoride glass [5]. For the Pr^{3+}-doped La-Ga-S these values were $\tau = 300\,\mu s$, $\lambda_p = 1015\,nm$ and the pump absorption cross section at 1015 nm $\sigma_{03} = 8.80 \cdot 10^{-26}\,m^2$ [3].

3. Analysis

In order to verify the numerical model, the data published by Ohishi *et al.* [2] were used to calculate the spectral dependence of small-signal gain, $P_{s0} = -30\,dBm$, for a PDFA with the numerical aperture NA=0.1536, cutoff wavelength of the LP_{11} mode $\lambda_c = 650\,nm$, fibre length $L = 23\,m$, pump wavelength $\lambda_p = 1017\,nm$ and launched pump power $P_{p0} = 925\,mW$. The amplification gain measured by Ohishi was obtained as the ratio of pumped and unpumped output signal intensities. For the purpose of comparison with experimental results, the wavelength dependent fibre internal loss coefficient $\alpha(\nu)$, appearing in Eqs.7, has therefore been ommited. Figure 1 shows the small-signal gain versus signal wavelength. The points are

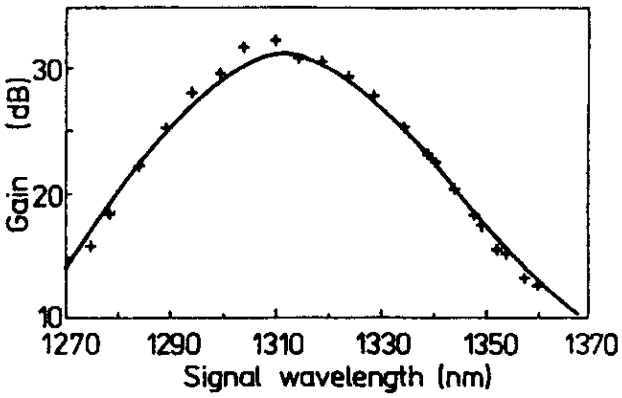

Fig. 1:
Spectral dependence of small-signal gain for ZBLAN PDFA. The crosses represent experimental data reported by Ohishi *et al.* [6]

the experimental results, the solid line is the result of calculations. Reasonable agreement between the experiment by Ohishi *et al.* and our calculations has been reached.

In figure 2 we compare the spectral gain of Pr^{3+}-doped

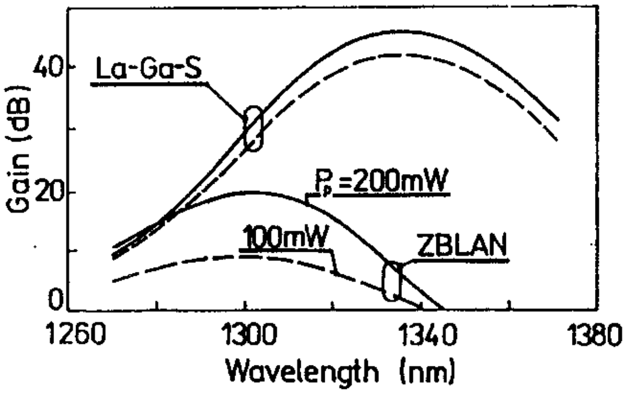

Fig. 2:
Small-signal gain as a function of signal wavelength with pump power as a parameter.

La-Ga-S and ZBLAN fibre amplifier for excitation with 100 mW and 200 mW pump power and input signal power of $1\,\mu W$. The fibre numerical aperture is NA=0.20, the cut-off wavelength of the LP_{11} mode is $\lambda_c = 700\,nm$ and the praseodymium doping is uniform across the fibre core. The fibre length has been optimized for maximum gain at each signal wavelength so that Fig. 2 shows the maximum obtainable gain. The highest gain occurs at 1334 nm for the La-Ga-S PDFA, which is slightly shifted from the value of 1316 nm for the ZBLAN PDFA. The small-signal gain of the La-Ga-S PDFA at $\lambda_s = 1310\,nm$ and $P_{p0} = 200\,mW$ is 36.77 dB which is about 17 dB more than that for the ZBLAN PDFA.

In order to utilize the available pump power efficiently, waveguide parameters of a PDFA must be optimized for maximum gain. For given signal and pump wavelengths, the overlap between the pump and signal waves and the Pr^{3+} ion distribution is determined by the fibre numerical aperture, core radius and the Pr^{3+} ion distribution. In the following optimization we assume that the Pr^{3+} ions are equally distributed in the fibre core. Figures 3 and 4 show

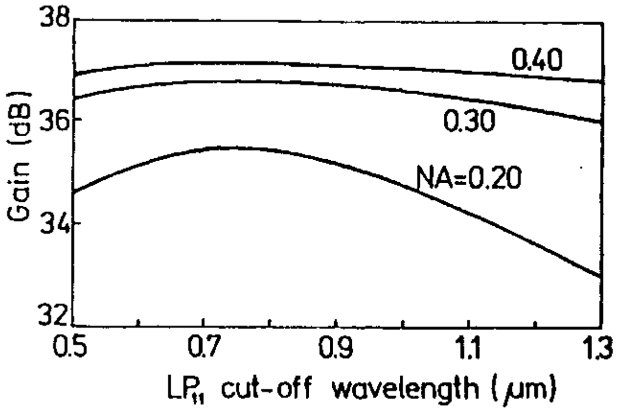

Fig. 3:
Small-signal gain in a La-Ga-S PDFA as a function of the LP_{11} cut-off wavelength, with NA as a parameter.

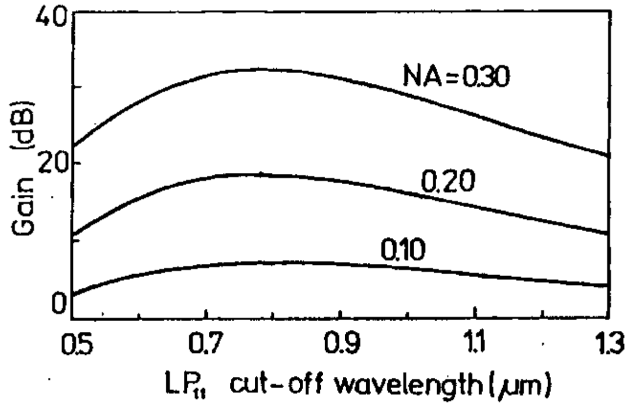

Fig. 4:
Small-signal gain in a ZBLAN PDFA as a function of the LP_{11} cut-off wavelength with NA as a parameter.

the maximum obtainable small-signal gain as a function of the LP_{11} mode cut-off wavelength for several values of numerical aperture for a La-Ga-S and ZBLAN PDFA, respectively. The input pump power is $P_{p0} = 200\,\mathrm{mW}$, the fibre length has been optimized for maximum gain. The signal wavelength and input signal power are 1310 nm and $1\,\mu\mathrm{W}$, respectively. In the case of the La-Ga-S PDFA, the maximum gain is obtained for $\lambda_c = 700\,\mathrm{nm}$, in the case of the ZBLAN PDFA for $\lambda_c = 750\,\mathrm{nm}$. The corresponding core radius can be determined from $R = 2.405\lambda_c/(2\pi\mathrm{NA})$.

The effect of fibre numerical aperture and input pump power on small-signal gain has been examined. A fibre core radius corresponding to the optimum cut-off wavelength has been chosen, fibre length has been adjusted for maximum gain. Figure 5 shows the dependence of small-signal gain on NA for input pump powers 100 mW and 200 mW for La-Ga-S and ZBLAN PDFAs. Independent of pump power and PDFA type, the gain increases with increasing NA due to the better overlap between the Pr^{3+} ions and the pump and signal waves, until the amplifier is saturated by amplified spontaneous

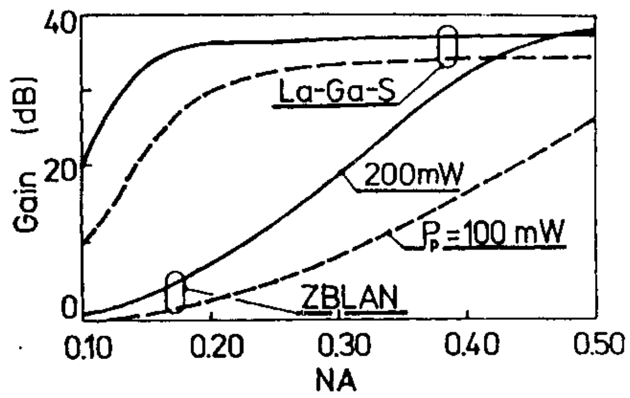

Fig. 5:
NA dependence of PDFA small-signal gain for several values of input pump power.

emission. As the pump absorption cross section, σ_{03}, for the Pr^{3+}-doped La-Ga-S is twice as high as that for ZBLAN, the inflexion in the La-Ga-S due to the ASE saturation of the amplifier for a given pump power occurs at half the numerical aperture than in ZBLAN. In order to reach gains higher than 35 dB for 100 mW of pump power at $\lambda_s = 1310\,\mathrm{nm}$, the numerical aperture of a ZBLAN PDFA would have to be higher than 0.45 in contrast to NA> 0.20 for a La-Ga-S PDFA.

Large-signal operation of a PDFA has been analyzed. The relationship between gain and input signal power for La-Ga-S and ZBLAN PDFAs is shown in Fig. 6, with

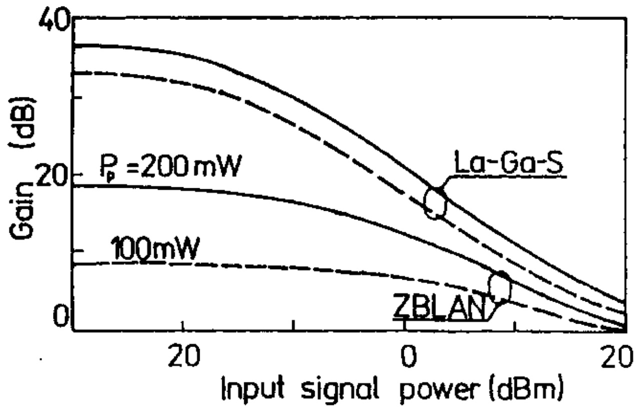

Fig. 6:
Dependence of gain on input signal power for input pump power 100 mW and 200 mW.

NA=0.30, a cut-off wavelength equal to the optimum value, pumped with $P_{p0} = 100\,\mathrm{mW}$ and $200\,\mathrm{mW}$ at a signal wavelength $\lambda_s = 1310\,\mathrm{nm}$. In Fig. 7 the related output signal power is displayed. The saturation output signal power corresponding to a 3 dB reduction from small-signal gain is 14.5 dBm and 10.1 dBm at 100 mW of pump power and 18.4 dBm and 9.3 dBm at 200 mW of pump power for the La-Ga-S PDFA and the fluoride PDFA, respectively.

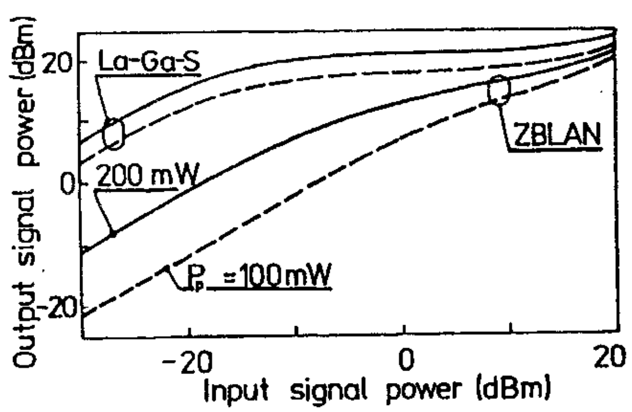

Fig. 7:
Dependence of output signal power on input signal power for input pump power 100 mW and 200 mW.

4. Conclusion

We have modified a numerical model for a three level erbium-doped laser system to a four level laser system to analyze praseodymium-doped La-Ga-S and fluoride fibre amplifier. The model takes into account modal properties of the signal and pump LP_{01} waves in single-mode step-index fibre and experimentally obtained signal emission and absorption cross section spectra for Pr^{3+} ions in La-Ga-S and ZBLAN glasses.

An extensive numerical analysis has been performed for the La-Ga-S and ZBLAN PDFAs so that their theoretical performance could for the first time be compared. It follows from the analysis that, due to the threefold greater metastable level lifetime and emission cross section and twofold greater pump absorption cross section of the Pr^{3+}-doped La-Ga-S glass, the small-signal and large-signal properties of the Pr^{3+}-doped La-Ga-S PDFA are superior to those of the ZBLAN PDFA. The small-signal gain of the La-Ga-S PDFA at $\lambda_s = 1310\,nm$ and $P_{p0} = 200\,mW$ is 36.77 dB, which is about 17 dB more than that for the ZBLAN PDFA. In order to achieve the same small-signal gain at $\lambda_s = 1310\,nm$ and $P_p = 200\,mW$, the numerical aperture of the ZBLAN PDFA must be twice as high as that of the La-Ga-S PDFA. The saturation output signal power is 18.4 dBm and 9.3 dBm at 200 mW of pump power for the La-Ga-S PDFA and the fluoride PDFA, respectively.

5. References

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