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Ultra-broadband gain spectra of Co^{2+}-doped fiber pumped at 1200 nm

Guishun Li [a], Chaomin Zhang [a,*], Pengfei Zhu [a,c], Chun Jiang [b], Pei Song [a], Kun Zhu [c]

[a] College of Fundamental Studies, Shanghai University of Engineering Science, Shanghai 201620, China
[b] State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 20040, China
[c] Department of Physics and Electronic Science, Liupanshui Normal University, Liupanshui 553004, China

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ABSTRACT

This work investigates the energy levels, transition configuration and numerical model of Co^{2+}-doped glass–ceramics fiber. A quasi-three-level system is employed to model the gain spectra of the doped fiber, and the rate and the power propagation equations are solved to analyze the effect of the fiber length, active ion concentration, pumping power as well as ambient temperature on the spectra. It is shown that the fiber has ultra-broadband gain spectra in 1.25–2.00 μm range via the 1200 nm pump, which is promising for full-band fiber amplifiers.

1. Introduction

For Optical transmission system and networks, Wavelength Division Multiplexing (WDM) technology is used to expand its capacity because it allows hundreds of channels to be transmitted simultaneously in an optical fiber. The usable transmission bandwidth in wavelength for a WDM system depends strongly on gain bandwidth of fiber amplifiers. To date, Pr^{3+}-doped fluoride amplifiers, Tm^{3+}-doped amplifiers, Er^{3+}-doped amplifiers have been used for 1.31 μm (O-band), 1.47 μm (S-band), 1.55 μm (C and L bands) windows, respectively. However, these devices cannot form a seamless gain spectrum to utilize the low loss windows of an all wave fiber.

As we know, transition metal ion-doped materials have shown broadband absorption spectra, such as Ni^{2+} ion-doped glass ceramics [1–2] and Cr^{3+} ion-doped glass ceramics [3–7]. In the Co^{2+}-doped glass and glass-ceramics [8–10], Co^{2+} ions enter into oxide crystals and occupy tetrahedral sites, there are four absorption bands peaking at the wavelength of 0.55 μm, which is assigned to the $^4A_2 \rightarrow {}^4T_1$ (^4P), and 1.20 μm, 1.40 μm and 1.60 μm which are contributed by transitions of $^3A_2$ to three stark split levels of $^4T_1(^4F)$. Among these absorption bands, the bands at 1.2 μm, 1.4 μm and 1.6 μm are so wide that they have large overlap each other to form the seamless absorption spectrum covering from 1.1 to 1.8 μm range.

In the present paper, we show the energy levels, the transition configuration and the numerical model of Co^{2+}-doped glass–ceramics fiber pumped at the wavelength 1.2 μm. A quasi-three-level system is employed to model the gain characteristics of the doped fiber, and the rate and power propagation equations are solved to analyze the effect of the fiber length, the ion concentration, the pump power as well as the ambient temperature on the spectrum.

2. Theoretical model

2.1. Energy level configuration

Electron configuration of shell layer of cobalt atom is $3d^74s^2$, and that of Co^{2+} ion is $3d^74s^0$, the s and d electrons of transition metal ions in glasses and crystals have stronger coupling to the phonons of the host surround the ions, and the energy levels of the ions are split into many sublevels due to stronger electron–phonon coupling and stark split effects. The ground level is $^4A_2$, the absorption bands, which correspond to $^4A_2$- $^4T_1(^4P)$, $^4A_2$-$^4T_1(^4F)$ transitions, are centered at 0.55 μm and in the range 1.2–1.6 μm [8–9], respectively. Thus, a quasi-three-level configuration may be used to describe the energy level, the electron transition process, which is shown in Fig. 1. It can be seen that a 1.2 μm laser may be availed to pump the doped fiber.

2.2. Rate and power propagation equations

According to Fig. 1, we assume that the electrons at ground state are populated into the excited state when pumping at 1.2 μm,

* Corresponding author.
E-mail address: zhangchaomin@sues.edu.cn (C. Zhang).

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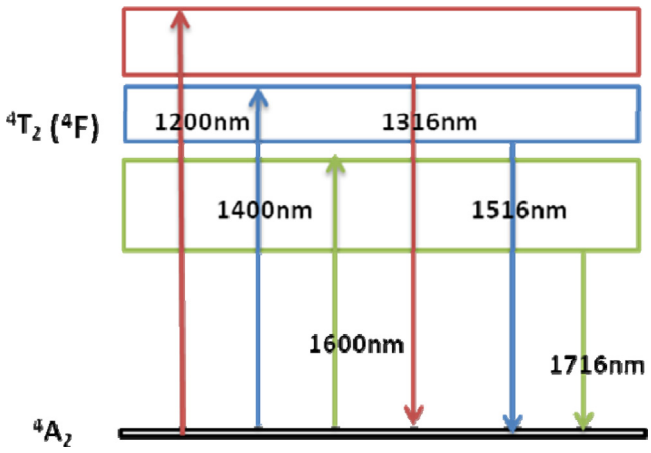

Fig. 1. Schematic of the energy level and the electron-transition of Co^{2+}-doped glass–ceramics fiber.

and then relax into meta-steady state. Due to the short lifetime at the excited state, the population at excited state equals to zero approximately. Thus, the rate equations describing the population densities of the ground state and meta-steady state are expressed as follows:

$$\frac{\partial N_1}{\partial t} = -(W_{12}+W_{pa})N_1+(W_{pe}+W_{21}+A_{21})N_2$$
$$\frac{\partial N_2}{\partial t} = (W_{12}+W_{pa})N_1-(W_{pe}+W_{21}+A_{21})N_2$$
$$N = N_1+N_2 \quad (1)$$

where W_{12}, W_{21}, A_{21} represent the absorption rate, stimulated emission rate and spontaneous emission rates between ground state and meta-steady state, respectively. W_{pa} and W_{pe} are pump absorption and emission rates between the ground state and excited state, respectively. N_1, N_2 are the populations densities of the ground state ($^4A_2$) and meta-steady state ($^4T_2(^4F)$), respectively.

The power propagation equations describing pump, signal and amplified spontaneous emission (ASE) powers propagating through the active fiber are expressed as

$$\frac{dP_p(z,t)}{dz} = -P_p\Gamma_p(\sigma_{pa}N_1-\sigma_{pe}N_2)-\alpha_pP_p$$
$$\frac{dP_s(z,t)}{dz} = P_s\Gamma_s(\sigma_{21}N_2-\sigma_{12}N_1)-\alpha_sP_s$$
$$\frac{dP_{ase}(z,t)}{dz} = P_{ase}\Gamma_{ase}(\sigma_{21}N_2-\sigma_{12}N_1)-\alpha_sP_{ase}+2\sigma_{21}N_2\Gamma_{ase}h\nu_{ase}\Delta\nu_{ase} \quad (2)$$

where

$$W_{12}=\frac{\sigma_{12}P_k}{h\nu_kA_{eff}},\ W_{21}=\frac{\sigma_{21}P_k}{h\nu_kA_{eff}},\ k=p,s,ase.$$

σ_{12}, σ_{21} represent the absorption and emission cross sections between the ground state and excited state. σ_{pa}, σ_{pe} represent absorption and emission cross sections at the pump wavelength 1.2 μm. Γ_p, Γ_s, Γ_{ase} are overlap factors of the pump light, signal light and ASE, respectively.

3. Result and discussion

3.1. Spectral parameters used in calculation

The absorption and emission cross-sections as functions of wavelength result from SiO_2–Al_2O_3–MgO glass–ceramics [8–9]. The absorption spectrum has four broad absorption bands centered at 0.55 μm, 1.2 μm, 1.4 μm and 1.6 μm. Among these absorption bands, the band at 0.55 μm is the strongest, and the absorption bands around 1.2 μm, 1.4 μm, 1.6 μm have so large overlap each other. Therefore, it could be formed to a seamless and broad absorption spectrum which covers the range from 1.0 to 1.8 μm centering around 1.4 μm. We use a normalized probability density function to present the line shape of absorption spectrum. According to the absorption spectra and emission spectra from references [8–9], the stokes shift or the difference between the center wavelengths of absorption and emission spectra approximates to 116 nm. Therefore, we use this stokes shift value to approximately present the difference between the center wavelengths of the super-broadband absorption and emission spectra in near-infrared region. The center wavelength of the absorption spectrum is 1.4 μm, and the center wavelength of the corresponding emission spectra is estimated to be 1.516 μm. The line shapes of absorption and stimulated emission cross sections as functions of wavelength are expressed by normalized probability density function:

$$\sigma(\lambda)=\frac{1}{\delta\sqrt{2\pi}}e^{\frac{-(\lambda-\lambda_0)^2}{2\delta^2}} \quad (3)$$

where λ is the wavelength, δ is the mean square root, λ_0 is the central wavelength. We can obtain the emission cross section at center wavelength through following procedure: the absorption and the emission spectral profiles are determined by the probability density function and reciprocal with quantum efficiency $\eta=0.55$. With this value we can get $\sigma(\lambda)$ at other wavelength. Additionally, the absorption and the emission cross sections at pump wavelength 1.2 μm are 2.5×10^{-23} m^2, 1.0×10^{-23} m^2, respectively. In present paper, the fiber we design has core radius of 2.5 μm and clad radius of 125 μm. The SiO_2–Al_2O_3–MgO glass system is used as host of the doped fiber, and the fiber dielectric loss coefficient is 0.1 cm^{-1} and the overlap factors Γ_p, Γ_s, Γ_{ase} are approximate 0.5, 0.8, 0.8, respectively (Fig. 2).

3.2. Effect of the fiber parameters on gain spectra

The variation of calculated gain spectra with fiber length is shown in Fig. 3 with active ion concentration $N=1\times10^{24}$ ions/m^3 and pump power $P=100$ mW. It is depicted that When the fiber length increases from 2 to 10 m, the peak of the gain spectra at 1580 nm varies from 9.0 dB to 42 dB, and the dip of the gain

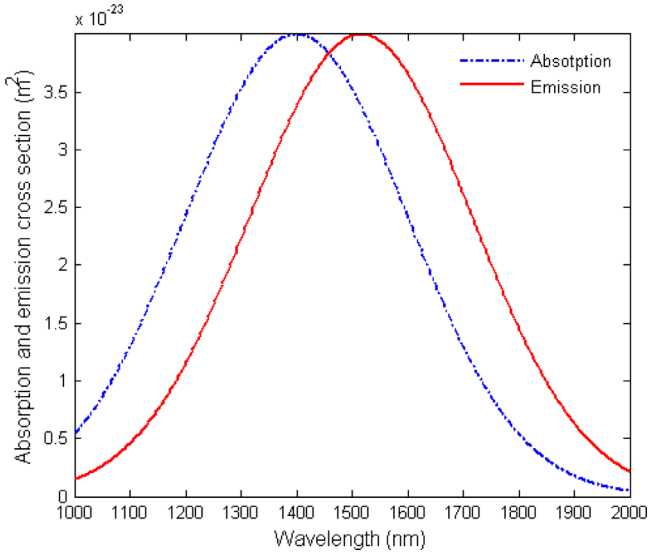

Fig. 2. Calculated absorption and emission cross sections as functions of the wavelength from the absorption and the emission spectra at excited at 1.2 μm [8,9].