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A study on the role of transmittances effect the self-Raman dual-wavelength laser output characteristics ☆

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ABSTRACT

In this work, the coupled equations of self-Raman dual-wavelength continuous-wave lasers are constructed by introducing the loss item of fundamental photon number. The output power analytical expressions of the fundamental laser and Raman laser are obtained through solving the couple equations. The impaction of transmittances on the self-Raman dual-wavelength laser output characteristics are simulated. Under different transmittance combination conditions, the changing rules of the separate output power, total output power and the ratio of two different wavelengths output power are given. The coupled equations are solved in approximations such as plane wave and independent-space intensity distribution, however the simulated results can show the main tendency of self-Raman dual-wavelength continuous-wave lasers, this has a certain guiding significance for the experiment.

1. Introduction

Simple, compact and efficient solid-state simultaneous dual-wavelength lasers have attracted much attention for medical, military, and scientific applications [1,2]. Nd-ion-doped laser is the most important source because of its high gain and good thermal and mechanical properties. As we known, there exist three transitions: $^4F_{3/2}$–$^4I_{11/2}$, $^4F_{3/2}$–$^4I_{13/2}$ and $^4F_{3/2}$–$^4I_{9/2}$ in Nd^{3+} ion, leading to potential laser radiations around 1.0, 1.3 and 0.9 μm, respectively [3–5]. Over the last few years, several groups have reported dual-wavelength generation by using different Nd-doped media such as Nd:YAG, Nd:YVO_4, Nd:$GdVO_4$ [6–8]. Stimulated Raman scattering (SRS) is a method which has been widely employed for frequency conversion of laser wavelengths to different spectral ranges [9]. The first diode-pumped self-Raman laser was based on Nd:KGW [10]. Then in 2001, Kaminskii et al. predicted that Nd:YVO_4 and Nd:$GdVO_4$ would be the promising self-Raman crystals [11], and it was first proved by Chen [12,13]. In recent years, efficient intra-cavity second-harmonic generation (SHG) of Q-switched and cw self-Raman lasers has been widely developed [14–17]. Recently, Chang et al. reported efficient conversion in a pulsed self-Raman Nd:YVO_4 laser with intra-cavity SFG, generating at 559 nm [18]. Pask et al. reported a pulsed output at 559 nm from an intra-cavity Q-switched diode-pumped Nd:YAG/KGW Raman laser, with intra-cavity SFG in a β-BaB_2O_4 crystal [19]. Lee et al. reported a cw laser operation at 559 nm, based on intra-cavity SFG in a Nd:$GdVO_4$ self-Raman laser [20]. However, to the best of our knowledge, no research about the fundamental and first Stokes dual-wavelength laser in Nd-doped lasers has been reported. It can be applied to laser interferometry, spectral analysis and THz research, etc [21–24].

In this work we report, the model of self-Raman dual-wavelength continuous-wave lasers. And the impaction of transmittances on the self-Raman dual-wavelength laser output characteristics is studied. This paper will provide an overview of the running characteristics of self-Raman dual-wavelength lengths lasers, although the model may be of defective, but it can illustrate the main tendency of which how transmittances have function to the self-Raman lasers.

2. Description of the model

Supposing that doped crystal material is the gain medium of fundamental laser, whose length is l_f and refractive index is n_f, while non-doped material is mainly used to yield self-Raman laser, whose length is l_s and refractive index is n_s. The cavity length is l and the whole optical cavity length is $L_e = l + l_f(n_f - 1) + l_s(n_s - 1)$. Let's also suppose that T_f and T_s are the output coupling mirror transmission of fundamental and Raman lasers, and γ_{0f}, γ_{0s} are intra-cavity loses for the fundamental and Raman lasers, respectively. So the total loss are $\gamma_f = \gamma_{0f} - (1/2)\ln(1 - T_f)$ and $\gamma_s = \gamma_{0s} - (1/2)\ln(1 - T_s)$. ω_{0p} is the waist radius of pumping laser,

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ω_{0f}, ω_{0s} are the spot radius in laser crystal and Raman crystal, respectively. The rate equations for the self-Raman dual-length continuous lasers are:

$$\frac{dN_f}{dt} = R_P - B\Phi_f N_f - \frac{N_f}{\tau} \tag{1}$$

$$\frac{d\Phi_f}{dt} = V_f B\Phi_f N_f - G\Phi_f\Phi_s - \frac{\Phi_f}{\tau_f} \tag{2}$$

$$\frac{d\Phi_s}{dt} = G\Phi_f\Phi_s - \frac{\Phi_s}{\tau_s} \tag{3}$$

In which Eqs. (1) and (2) are the rate equations for fundamental laser, Eq. (3) is the rate equation of intra-cavity photon number of Raman laser. R_p is the average pumping rate. Φ_f and Φ_s are intra-cavity photon numbers of fundamental and Raman laser, respectively. τ is the upper level lifetime of fundamental laser, τ_f and τ_s are intra-cavity photon lifetime of fundamental laser and Raman laser, in which $\tau_f = (L_e/\gamma_f c)$ and $\tau_s = (L_e/\gamma_s c) \cdot V_f$ is model volume in gain medium of fundamental laser. $B = (\sigma_e c l_f / L_e) V_f$, in which σ_e is the fundamental laser crystal emission cross section. c is the speed of light in the vacuum. $G = (c^3 g_s l_s h / 2L_e^2 A_s \lambda_s)$ is constant which relating with Raman crystal, in which h is the Plank constant; λ_s, A_s, g_s are the wave-length for Raman laser, waist section in Raman crystal, Raman gain coefficient in Raman crystal, respectively.

When self Raman dual-wave length laser running at steady state, above equations are shown as:

$$\frac{dN_f}{dt} = 0 \tag{4}$$

$$\frac{d\Phi_f}{dt} = 0 \tag{5}$$

$$\frac{d\Phi_s}{dt} = 0 \tag{6}$$

From Eq. (6) the photon number of fundamental laser can be solved as:

$$\Phi_f = \frac{1}{G\tau_s} \tag{7}$$

From Eq. (4) the inversion population can be solved as:

$$N_f = \frac{R_p}{B\Phi_f + (1/\tau)} \tag{8}$$

Substituting Eq. (7) into Eq. (8) , the inversion population of fundamental under the condition of self-Raman dual-wave length continuous-wave laser running at steady state is solved as:

$$N_f = \frac{R_p G\tau_s\tau}{B\tau + G\tau_s} \tag{9}$$

Likewise, from Eq. (5) the intra-cavity photon number of Raman laser can be obtained when self-Raman dual-wave length continuous-wave laser is running at steady-state, it is shown as:

$$\Phi_s = \frac{BV_f N_f - (1/\tau_f)}{G} \tag{10}$$

Substituting Eq. (9) into Eq. (10) , the intra-cavity photon number of Raman laser can be finally obtained as:

$$\Phi_s = \frac{BV_f R_p G\tau_s\tau_f\tau - (B\tau + G\tau_s)}{G(B\tau + G\tau_s)\tau_f} \tag{11}$$

Now that the photon number of fundamental and Raman laser have been solved, respectively. According to the known formula $P_{out} = (-\ln(1-T)c)/(2L_e)(h\nu)\Phi$, the output power of fundamental and Raman laser can be obtained as:

$$P_f = \frac{-\ln(1-T_f)c}{2L_e}(h\nu_f)\frac{1}{G\tau_s} \tag{12}$$

$$P_s = \frac{-\ln(1-T_s)c}{2L_e}(h\nu_s)\frac{BV_f R_p G\tau_s\tau_f\tau - (B\tau + G\tau_s)}{G(B\tau + G\tau_s)\tau_f} \tag{13}$$

Eqs. (12) and (13) are the output power analytical expression of the self-Raman dual-wavelength continuous-wave laser. We can obtain the output characteristic of this kind laser under different conditions by numerical simulating the two formulas.

3. Analog simulation

In this simulation, the bonding Nd:YVO_4 as the laser material is considered. The concentration of ion is 1%. And the known parameters are $\omega_{0p} = 200\ \mu m$, $\omega_{0f} = 150\ \mu m$, $\omega_{0s} = 100\ \mu m$. $g_s = 4.5 \times 10^{-7}$ cm/GW, which is the gain coefficient of Raman crystal. $\sigma_e = 15.6 \times 10^{-19}$ cm^2, which is the laser crystal emission cross section, and $\tau = 100\ \mu s$ is the upper level lifetime. The average pumping rate can be defined as:

$$R_p = \eta_a \left(\frac{P_p}{h\nu_p}\right)\frac{2}{\pi(\omega_{0f}^2 + \omega_{0p}^2) l_f} \tag{14}$$

In which $\eta_a = 1 - \exp(-\alpha l_f)$ is absorbed efficiency of pumping laser, α is the absorption coefficient. When the wavelength of pumping laser is 808 nm and the fundamental laser radiating at π polarization, $\alpha = 37\ \text{cm}^{-1}$. Substituting Eq. (14) into Eq. (13) , and from above known parameters, we can obtain the output characteristics of self-Raman dual-wave length lasers under different conditions.

3.1. *The output characteristics of different transmittances combination when $l_f = 5$ mm and $l_s = 15$ mm*

As shown in Fig. 1, the threshold for fundamental laser is a little lower and the output power increase lineally with the pump power. When the pump power is required to reach the threshold of Raman laser, Raman laser begin to generate, while the output power curve of fundamental laser has an inflection point, at this point, output power of fundamental laser no longer increases with pump power, while the output power of Raman laser begin to increase linearly with the increase of output power of pump laser.

Compared with (a) and (b), (c) and (d) in Fig. 1, under the given transmittance of Raman laser, we find that when the transmittance of Raman laser increases, the threshold of Raman laser will increase from 40 W in (a) to 54 W in (b) and increase from 49 W in (c) to 65 W in (d), while the output power of fundamental laser increases from 6.4 W in (a) to 8.2 W in (b) and increases from 12.6 W in (c) to 16.8 W in (d). Output power of pump laser must promote in order to offset the decreased gain of intra-cavity Raman laser, and then threshold of Raman laser will increase. Simultaneously, from Eq. (12) ,when the transmittance of fundamental and Raman is low, Eq. (12) can be simplified as:

$$P_f = \frac{T_f c}{2L_e^2}(h\nu_f)\frac{\gamma_s c}{G} \tag{15}$$

Above equation reveals that the output power of fundamental laser is irrelevant to that of pump laser. So when the threshold of