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Theoretical model of simultaneous dual-wavelength laser based on intra-cavity pumping

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Abstract

In this paper, the theoretical modeling of intra-cavity pumped laser used to simultaneously output quasi-three-level laser and four-level laser is proposed. Due to the two laser generating in different gain medium, the gain competition can be avoided. In the modeling, the plane wave approximation is employed, and the analytical expressions of the output power of dual-wavelength lasers are derived. The output characteristics are obtained by numerically simulating, and the impact of changing some critical parameters on the output characteristics are investigated. It is found that by increasing the absorption coefficient of the second gain medium at quasi-three-level radiation, or reducing the output mirror transmittance of the laser, the output power of four-level laser will be promoted, while the output power of quasi-three-level radiation will be turned lower.

Keywords: intra-cavity pumped, gain competition, dual-wavelength continuous wave lasers

(Some figures may appear in colour only in the online journal)

1. Introduction

Dual-wavelength lasers have been demonstrated in many papers, and the laser crystal Nd:YAG is most important. Bethea first reported 1.318 μm and 1.06 μm simultaneous oscillation dual-lasers which using Nd:YAG as gain medium [1], and the quasi-three-level and four-level simultaneous emission was presented in 2006 [2], and then the Q-switched 1318.8 nm/1338.2 nm dual-wavelength laser and the efficient 1319 nm/1338 nm dual-wavelength operation of LD end-pumped have been reported [3–5], respectively. Beside this, Nd:YVO$_4$ [6–10], Nd:GdVO$_4$ [11–15], Nd:LuVO$_4$ [16], and Nd:YAP [17, 18] used to generate dual-wavelength laser also have been reported. Recently, the 946 nm/1064 nm dual-wavelength operation by the combined Nd:YAG and Nd:YVO$_4$ crystals was proposed [19]. The realized simultaneous dual-wavelength lasers in neodymium doped crystals can be classified into two main categories. The first category involving two different transitions from $^4F_{3/2}$–$^4I_{9/2}$, $^4F_{3/2}$–$^4I_{11/2}$, or $^4F_{3/2}$–$^4I_{13/2}$, gives a large wavelength separation [2, 14, 18]. The second category is laser operated in a same laser transition with a smaller wavelength separation [3, 15]. However, dual wavelength operation with the same laser medium in the same cavity is rather difficult at these particular wavelengths due to strong gain competition between the very efficient transition $^4F_{3/2}$–$^4I_{11/2}$ around 1.06 μm and the quasi-three-level transition $^4F_{3/2}$–$^4I_{9/2}$ around 0.91 μm having an emission cross section 20 times lower [20]. Therefore dual-wavelength operation in a single laser crystal is inefficient. In recent years, diode-pumped intra-cavity pumped Nd doped lasers have attracted attention. In these lasers, a diode-pumped gain medium emits quasi-three-level radiation which pumps

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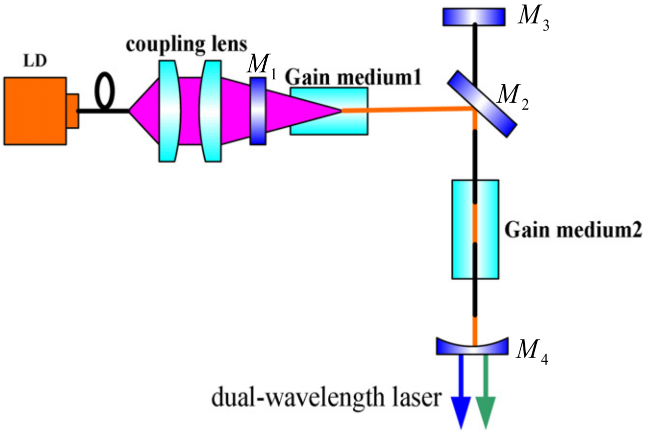

Figure 1. The scheme diagram of dual-wavelengths laser stable output at the same time.

another gain medium which emits four-level laser, therefore in a laser configuration, the simultaneous emission can be realized but gain competition is avoid.

In this paper, we propose a theoretical modeling of a continuous-wave intra-cavity pumped laser. Based on rate equations, the theoretical model of quasi-three-level and four-level intra-cavity pumped dual-wavelength continuous wave lasers is constructed, and the analytical expresses of the output power of dual-wavelength lasers are derived. The output characteristics are simulated based on these expressions, and the impaction of changing some critical parameters on the output power are investigated numerically. While there is some uncertainty about the model, we aim here to determine the broad tendency rather than provide precise numerical predictions, and these estimates are sufficient for our purpose.

2. The scheme of dual-wavelengths stable output at the same time

The scheme diagram of intra-cavity pumped dual-wavelength continuous wave laser is shown in the figure 1, it shows that the laser includes two resonators, the first resonator which is used to generate quasi-three-level laser by the transition $^4F_{3/2}$–$^4I_{9/2}$ is composed of total reflection mirror M_1, gain medium 1, 45° mirror M_2, the output mirror M_4; the second resonator which used to generate four-level laser by another transition $^4F_{3/2}$–$^4I_{11/2}$ consists of reflection mirror M_3, gain medium 2, and the output mirror M_4. From figure 1 we can also see that the absorbed quasi-three-level intra-cavity laser by gain medium 2 is not only the pumping source of gain medium 2, but also can be seen as the loss of the quasi-three-level laser resonator, therefore, the two resonators are coupled by this absorption. Even though the absorption coefficient of the second laser gain medium at quasi-three-level is small, the large cavity power can produce strong absorption, so the intra-cavity pumped is possible.

3. Description of the model

In order to simplify the model, we assumed that the intensity distributions of the pump light, quasi-three-level lasers and four-level lasers are uniform, and they do not vary with the space position. Supposed that the length of gain medium of the quasi-three-level laser is l_{I}, refractive index is n_{I}, the laser cavity length is L_{I}, and the waist radius is $\omega_{0\mathrm{I}}$. The length of the gain medium of four-level laser is l_{II}, refractive index is n_{II}, the laser cavity length is L_{II}, and the waist radius is $\omega_{0\mathrm{II}}$. For the cavity pumping scheme in figure 1, the second gain medium pump source is intra-cavity quasi-three-level laser, and we can consider the absorption of second gain medium to cavity laser as intra-cavity loss of quasi-three-level laser. Based on above ideas, we have established rate equations of intra-cavity pump dual-wavelength continuous lasers

$$\frac{\mathrm{d}N_{\mathrm{I}}}{\mathrm{d}t} = R_{\mathrm{p}}(1+f) - \frac{(\sigma_{e\mathrm{I}} + \sigma_{a\mathrm{I}})c}{V_{\mathrm{I}}}\phi_{\mathrm{I}} N_{\mathrm{I}} - \frac{fN_t + N_{\mathrm{I}}}{\tau}, \tag{1}$$

$$\frac{\mathrm{d}\phi_{\mathrm{I}}}{\mathrm{d}t} = \left(\frac{V_{a\mathrm{I}}\sigma_{e\mathrm{I}}c}{V_{\mathrm{I}}}N_{\mathrm{I}} - \frac{1}{\tau_{c\mathrm{I}}}\right)\phi_{\mathrm{I}}, \tag{2}$$

$$\frac{\mathrm{d}N_{\mathrm{II}}}{\mathrm{d}t} = R_{\mathrm{pII}} - B\phi_{\mathrm{II}}N_{\mathrm{II}} - \frac{N_{\mathrm{II}}}{\tau}, \tag{3}$$

$$\frac{\mathrm{d}\phi_{\mathrm{II}}}{\mathrm{d}t} = \left(BV_{a\mathrm{II}}N_{\mathrm{II}} - \frac{1}{\tau_{c\mathrm{II}}}\right)\phi_{\mathrm{II}}. \tag{4}$$

In which equations (1) and (2) are the rate equations of quasi-three-level laser and equations (3) and (4) are the rate equations of four-level laser. $R_{\mathrm{p}} = \frac{P_{\mathrm{p}}}{h\nu_{\mathrm{p}}}\frac{2\left[1 - \exp(-\sigma_1 l_1)\right]}{\pi l_1(\omega_{0\mathrm{I}}^2 + \omega_{0\mathrm{p}}^2)}$, it is pumping rate for the qussi-three-level laser, P_{p} is the laser-diode pump power, ν_{p} is the frequency of the pump light, σ_1 is absorption coefficient of gain medium at laser-diode pump wavelength, $\omega_{0\mathrm{p}}$ is the waist radius of the pump light, h is Planck's constant. $R_{\mathrm{pII}} = \frac{\eta P_{\mathrm{in}}}{h\nu_{\mathrm{I}}}\frac{2\left[1 - \exp(-\sigma_2 l_2)\right]}{\pi l_2(\omega_{0\mathrm{I}}^2 + \omega_{0\mathrm{II}}^2)}$ is pumping rate of the 1064 nm lasers. P_{in} is intra-cavity power of the qussi-three-level laser, σ_2 is absorption coefficient of gain medium for the quasi-three-level lasers, ν_{I} is the frequency of quasi-three-level lasers. ϕ_{I} is intra-cavity photon number of quasi-three-level laser, $\tau_{c\mathrm{I}} = \frac{L_{e\mathrm{I}}}{\gamma_{\mathrm{I}}c}$ is intra-cavity photon lifetime, where $\gamma_{\mathrm{I}} = \gamma_{0\mathrm{I}} + \frac{\gamma_{1\mathrm{I}} + \gamma_{2\mathrm{I}}}{2} + \alpha_{\mathrm{I}}$ is single pass loss of quasi-three-level lasers, it contains quasi-three-level laser resonator own loss $\gamma_{0\mathrm{I}}$, the loss caused by the absorption of four-level laser gain medium α_{I}, and the loss caused by totally reflecting mirror $\gamma_{1\mathrm{I}} = -\ln(1 - T_{1\mathrm{I}})$ and by output mirror $\gamma_{2\mathrm{I}} = -\ln(1 - T_{2\mathrm{I}})$. $\alpha_{\mathrm{I}} = 1 - \exp[-(\sigma_2 l_{\mathrm{II}})]$ is the loss caused by the absorption of gain medium of four-level lasers to quasi-three-level lasers. When the transmittance of totally reflecting mirrors $T_{1\mathrm{I}} = 0$, $\gamma_{\mathrm{I}} = \gamma_{0\mathrm{I}} + \frac{\gamma_{2\mathrm{I}}}{2} + 1 - \exp\left[-(\sigma_2 l_{\mathrm{II}})\right]$, ϕ_{II} is the intra-cavity photon number of four-level lasers, $\tau_{c\mathrm{II}} = \frac{L_{e\mathrm{II}}}{\gamma_{\mathrm{II}}c}$ is intra-cavity photon lifetime, γ_{II} is total single pass loss of four-level lasers. The same as above, we also know that $\gamma_{\mathrm{II}} = \gamma_{0\mathrm{II}} + \frac{\gamma_{2\mathrm{I}}}{2}$, the rate equations of the dual-wavelength lasers are coupled into a unit by $R_{\mathrm{p\,II}}$ and $\tau_{c\mathrm{I}}$.

In which, $B = \frac{2\sigma_{e\mathrm{II}} c}{\pi\omega_{0\mathrm{II}}^2 L_{e\mathrm{II}}}$, and $N_\mathrm{I} = N_{\mathrm{I}2} - fN_{\mathrm{I}1}$ is the inversion population of quasi-three-level lasers, $N_t = N_{\mathrm{I}2} + N_{\mathrm{I}1}$ is total populations. $N_{2\mathrm{I}}$, $N_{1\mathrm{I}}$ are the number of particles in the upper and lower levels of the lasers, respectively. N_II is the inversion population of four-level lasers. $f = \frac{\sigma_{a\mathrm{I}}}{\sigma_{e\mathrm{I}}}$, $\sigma_{e\mathrm{I}}$ and $\sigma_{a\mathrm{I}}$ are effective emission cross section and absorption cross section of quasi-three-level lasers. $\sigma_{e\mathrm{II}}$ is the effective emission cross section of the four-level lasers. $V_\mathrm{I} = \frac{\pi\omega_{0\mathrm{I}}^2}{2} L_{e\mathrm{I}}$, and $L_{e\mathrm{I}} = L_\mathrm{I} + (n_\mathrm{I} - 1)l_\mathrm{I}$ is the optical length of quasi-three-level lasers resonator, and $V_{a\mathrm{I}} = \frac{V_\mathrm{I}}{L_{e\mathrm{I}}} l_\mathrm{I}$. $V_\mathrm{II} = \frac{\pi\omega_{0\mathrm{II}}^2}{2} L_{e\mathrm{II}}$, and $L_{e\mathrm{II}} = L_\mathrm{II} + (n_\mathrm{II} - 1)l_\mathrm{II}$ is optical length of resonator cavity of four-level lasers, and $V_{a\mathrm{II}} = \frac{V_\mathrm{II}}{L_{e\mathrm{II}}} l_\mathrm{II}$. τ is upper level lifetime of inversion population of the gain medium, and we neglect the difference of lifetime between quasi-three-level lasers and four-level lasers.

When intra-cavity pump dual-wavelength lasers runs at stable state, from equation (2), we can make $\frac{\mathrm{d}\phi_\mathrm{I}}{\mathrm{d}t} = 0$, and the inversion population of quasi-three-level laser at this state can be obtained as:

$$N_1 = \frac{V_1}{\tau_{c1} V_{a1} \sigma_{e1} c}. \tag{5}$$

Substituting equation (5) into equation (1), and making $\frac{\mathrm{d}N_\mathrm{I}}{\mathrm{d}t} = 0$, the intra-cavity photon number of quasi-three-level lasers will be obtained as:

$$\phi_1 = \frac{\left[R_{\mathrm{p}1}(1 + f) - fN_t\right] V_{a1}\sigma_{e1}\tau_{c1} c - V_1}{(\sigma_{a1} + \sigma_{e1})\tau c}. \tag{6}$$

According to the cavity photon number expressions of the quasi-three-level lasers, the intra-cavity power and output power can be solved as:

$$P_\mathrm{in} = \left(\frac{c}{2L_{e1}}\right)(h\nu_1)\frac{\left[R_{\mathrm{p}1}(1 + f) - fN_t\right] V_{a1}\sigma_{e1}\tau_{c1} c - V_1}{(\sigma_{a1} + \sigma_{e1})\tau c}, \tag{7a}$$

$$P_{1\mathrm{out}} = \left(\frac{T_{2\mathrm{I}} c}{2L_{e1}}\right)(h\nu_1)\frac{\left[R_{\mathrm{p}1}(1 + f) - fN_t\right] V_{a1}\sigma_{e1}\tau_{c1} c - V_1}{(\sigma_{a1} + \sigma_{e1})\tau c}. \tag{7b}$$

In which, equation (7a) is intra-cavity power expression of the quasi-three-level lasers, and meanwhile, the intra-cavity power is the pump source of the four-level lasers. Equation (7b) is output power expression of the quasi-three-level lasers. The output characteristics of the quasi-three-level lasers can be obtained by simulating equation (7b).

Similarly, to make $\frac{\mathrm{d}\phi_\mathrm{II}}{\mathrm{d}t} = 0$ in equation (4), the inversion population of four-level lasers at stable state can be obtained as:

$$N_2 = \frac{1}{\tau_{c2} B V_{a2}}. \tag{8}$$

Table 1. Parameter values of 946 nm and 1064 nm intra-cavity pumped dual-wavelength continuous-wave lasers.

Parameter	Value	Parameter	Value
l_1	5 mm	σ_1	10.5 cm^{-1}
l_II	5 mm	σ_2	0.08 cm^{-1}
L_1	100 mm	τ	230 μs
L_II	80 mm	N_t	6×10^{25}
$\sigma_{e\mathrm{I}}$	5.3×10^{-20} cm^2	$\omega_{0\mathrm{p}}$	200 μm
$\sigma_{e\mathrm{II}}$	2.8×10^{-19} cm^2	$\omega_{0\mathrm{I}}$	200 μm
$n_1\gamma_{0\mathrm{I}}$	1.72	n_2	1.82
$\gamma_{0\mathrm{I}}$	0.01	$\gamma_{0\mathrm{II}}$	0.01

Substituting equation (8) into equation (3), and to make $\frac{\mathrm{d}N_\mathrm{II}}{\mathrm{d}t} = 0$, the expression of cavity photon number of 1064 nm lasers can be expressed as:

$$\phi_2 = \frac{R_{\mathrm{p}2} B V_{a2} \tau\tau_{c2} - 1}{B\tau}. \tag{9}$$

From equation (9), the output power of the four-level lasers can be obtained as:

$$P_{2\mathrm{out}} = \left(\frac{T_{2\mathrm{II}} c}{2L_{e2}}\right)(h\nu_\mathrm{II})\frac{R_{\mathrm{p}2} B V_{a2} \tau\tau_{c2} - 1}{B\tau}, \tag{10}$$

where, ν_II is photon frequency of the four-level lasers. Under the conditions that various parameters do not vary with the spatial location and two waves are approximately plane waves, the analytical expressions of output power of the quasi-three-level and the four-level lasers are derived, as shown in equations (7b) and (10). The output characteristics of intra-cavity pump dual-wavelength lasers under different conditions are achieved by numerical simulation.

4. The output characteristics of the dual-wavelength continuous-wave lasers

Assuming Nd:YAG crystal was employed in the intra-cavity pumped laser as the gain medium. The quasi-three-level laser and the four-level laser are 946 nm and 1064 nm respectively. It can be seen from equations (7b) and (10) that the output characteristics of 946 nm and 1064 nm dual-wavelength lasers have close relationship with various of parameters. In this paper, we are mainly concerned about that how the transmittances of the output mirror and intra-cavity absorption efficiency of the second Nd:YAG crystal at 946 nm impact on the output characteristics of 946 nm and 1064 nm dual-wavelength lasers. The values of related parameters used in this numerical simulation are shown in table 1.

According to the data in the table 1, the output characteristics of dual-wavelength lasers when output mirror transmittance $T_{2\mathrm{I}} = 5\%$, $T_{2\mathrm{II}} = 2\%$ is shown in figure 2.

It can clearly be seen from figure 2 that when transmittances of output mirror are given, the output power of dual-wavelengths lasers increase linearly with increasing pump power. The pumping threshold of 946 nm lasers is less than that of 1064 nm lasers, which is due to the working mechanism of the intra-cavity pumping. 946 nm quasi-three-

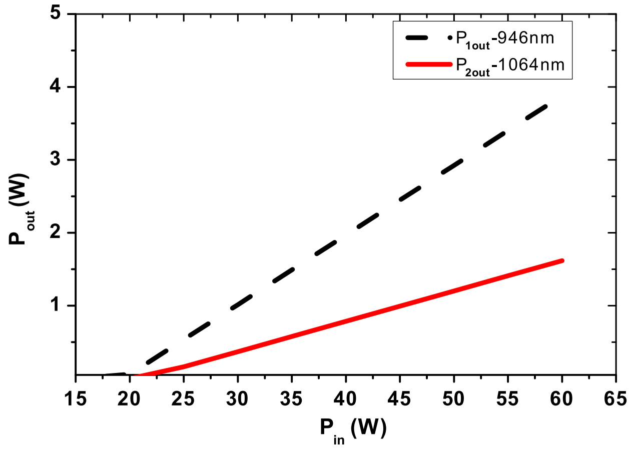

Figure 2. Output characteristics of the dual wavelength lasers when transmittance of output mirror are given.

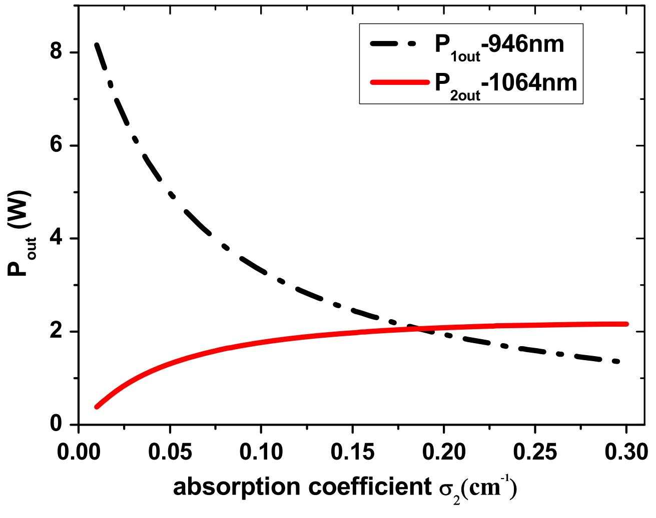

Figure 3. The impact of absorption coefficient of second gain medium on the output characteristics of dual-wave length lasers.

level lasers have been generated from $^4F_{3/2}$–$^4I_{9/2}$ transitions in the first gain medium of Nd:YAG crystal which is pumped by 808 nm laser, one part of 946 nm laser is used for output, while the other part is used for maintaining their own oscillation and pumping the second gain medium of Nd:YAG crystal, and then generating 1064 four-level lasers from transition $^4F_{3/2}$–$^4I_{11/2}$. When the pump power is greater than the threshold of 946 nm quasi-three-level lasers (such as $P_p = 20$ W), the 946 nm laser begins to oscillate and output, but at this time the intra-cavity power of 946 nm laser is not high enough to generate 1064 nm laser. Only when intra-cavity power is high enough to meet the demand of minimum power for the second gain medium of Nd:YAG crystal transition $^4F_{3/2}$–$^4I_{11/2}$, so we must increase the pump power to reach 22 W. Therefore, the power threshold of 1064 nm four-level laser must be greater than that of 946 nm quasi-three-level lasers for the intra-cavity pumped continuous dual-wavelength lasers.

Furthermore, the power curves in figure 3 indicate that the output power of 946 nm lasers is always greater than that of 1064 nm. There are two main reasons for this phenomenon, for one the transmittance of the 946 nm laser is too high, which decreases the intra-cavity power and the absorbed intra-cavity power by the second Nd:YAG crystal, so the gain of 1064 nm laser is not enough to generate high power output; also, due to the low transmittance of 1064 nm, more 1064 nm laser oscillates in the cavity and cannot generate laser output efficiently.

The value of 946 nm absorption coefficient of the second gain medium Nd:YAG crystal at 946 nm lasers determines the output characteristics of dual-wavelength laser. The absorption coefficient plays a dual role in the scheme of the intra-cavity pump. On the one hand, the absorption of second gain medium Nd:YAG crystal at 946 nm intra-cavity laser can be seen as a kind of loss of 946 nm intra-cavity laser oscillation, the absorption coefficient is greater (Nd^{3+} doping concentration higher), the loss of 946 nm intra-cavity laser is bigger, which will lead to increase the threshold of 946 nm laser and decrease the output power; on the other hand, the increase of absorption coefficient will make the second gain medium Nd:YAG crystal absorb more intra-cavity pump power of 946 nm laser, and the 1064 nm laser can obtain higher gain and increase the output power of the 1064 nm four-level lasers. Therefore, under conditions of that other parameters are constants, varying the value of absorption coefficient of second gain medium Nd:YAG crystal at 946 nm laser, only one of the 946 nm laser and 1064 nm laser output power will increase and that never increases output power of two wavelengths laser simultaneously. To further illustrate how the value of absorption coefficient of the second gain medium of Nd:YAG crystal impact on the output characteristics of dual-wavelength lasers, which can been seen from figure 3, while pump power $P_p = 60$ W, output mirror transmittance of 946 nm laser $T_{2I} = 5\%$, output mirror transmittance of 1064 nm laser $T_{2II} = 2\%$, the variable values are same as that in table 1 in the simulation process.

From figure 3 we can see that the output power of 946 nm laser nonlinearly decreases when the 1064 nm laser output power nonlinearly increases with the raising of absorption coefficient of the second gain medium Nd:YAG crystal at 946 nm laser, which is consistent with above analysis. When the absorption coefficient is small, the output power of 946 nm and 1064 nm lasers decrease and increase rapidly, respectively. Meanwhile, the output power of lasers varies slowly when the absorption coefficient is bigger than 0.18 cm^{-1}. This is due to that under the condition of the pump power is given, the absorption coefficient is smaller and the power of 946 nm intra-cavity laser is higher, so the second gain medium can absorb more power which results the loss of 946 nm intra-cavity laser become greater. So the output power of 946 nm decreases rapidly when the absorption coefficient is very small (e.g., 0.01–0.18 cm^{-1}), meanwhile, the output power of 1064 nm laser increases rapidly. When the absorption coefficient (0.18 cm^{-1}or more) further increases, the intra-cavity power is very low and the output power of the dual-wavelength lasers varies slowly, although the absorption

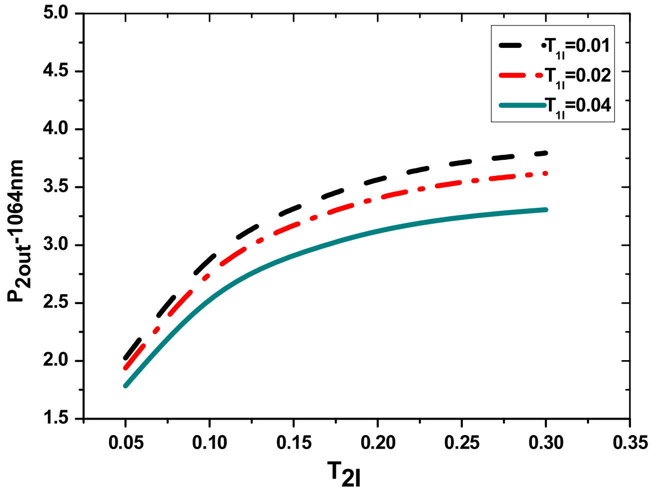

Figure 4. The influence of output mirror transmittance to the output characteristics of 1064 nm laser.

coefficient increases, it turns too slow to make the second gain medium absorb more intra-cavity power.

Under the conditions that other parameters are fixed values, the transmittance of output mirror of 946 nm laser directly affects intra-cavity power of 946 nm laser, and also determines the value of intra-cavity pump power of second gain medium Nd:YAG crystal. To further study the tendency of how the transmittance of the dual-wavelengths lasers impact on the output characteristics of the 1064 nm lasers, the relationship between output power of 1064 nm and the transmittance T_2 is given in this paper when pump power P_{in} = 60 W, the transmittance of 946 nm T_1 = 0.01, 0.02, 0.03 and 0.04. The variable values are same as table 1 in the numerical simulation.

It can be seen from figure 4 that under the conditions of other parameters are fixed values, the output power of the 1064 nm laser decreases while the output mirror transmittance of 946 nm increases. It is mainly due to the output power of 946 nm increasing when its transmittance is turning bigger, which makes the intra-cavity power of 946 nm lower, and further leads to the absorbed power by the second Nd:YAG turn down, and lowers the gain of which, so the output power of 1064 nm laser decreases when the output mirror transmittance of 946 nm increasing. Besides, when the transmittance at 1064 nm linearly rises in the smaller range, the output power of the 1064 nm laser exhibits a nonlinearly increasing tendency, however the output power increases slowly when the transmittance is turning bigger. It indicates that surplus power in the resonator can not output effectively when the transmittance of output mirror of 1064 nm is small, the surplus power gradually reduces when the transmittance of 1064 nm rises and the increasing tendency of output power becomes slow.

5. Conclusion

In conclusion, the intra-cavity pumped scheme is proposed, and this scheme can generate stable dual-wavelength lasers, which can effectively avoid gain competition between the quasi-three-level lasers and the four-level lasers. Based on laser rate equations, the theoretical model of the quasi-three-level and the four-level intra-cavity pumped dual-wavelength continuous-wave lasers is proposed, and the analytical expressions of the output powers of a intracavity pumped Nd: YAG dual-wavelength laser configuration are derived, the output characteristics are obtained by numerical calculation. The results show that output power of *e* 946 nm laser and 1064 nm laser linearly increases with the increase of pump power, and the threshold power of 946 nm laser is lower than that of 1064 nm lasers, the absorption coefficient of the second laser crystal Nd:YAG at 946 nm can simultaneously affect on the output characteristics of the 946 nm and 1064 nm lasers. The output power of 1064 nm is turning bigger when raised the absorption coefficient, while the output power of 946 nm turns out the opposite tendency. Besides, the output power of 1064 nm will be promoted by reducing the transmittance of output mirror of the 946 nm lasers under the condition of other parameters are constant values. Although there is little uncertainty about the model, we aim to determine broad tendency rather than provide precise numerical predictions, and these estimates are sufficient for our purpose.

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