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Optimization of an AO Q-switched solid-state Raman laser

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ABSTRACT

An extension of the rate equation models for solid-state Raman laser is proposed and investigated with accounting for the dynamics of an acousto-optically (AO) Q-switch modulator and the effects of thermal lens provided by the pump beam. The improved model is aimed at outlining optimization strategies for wonderful laser performance with short pulse width and high peak power. A comparison between traditional intra-cavity and new couple-cavity configurations is made. The simulation results indicate that it is possible to realize an efficient sub-nanosecond coupled-cavity Raman laser by optimizing several important parameters.

1. Introduction

Sub-nanosecond Q-switched lasers emitted at eye-safe wavelength region (1.5 μm) attract great interest in many applications such as range-finding, lidar and telemetry [1,2]. Stimulated Raman scattering (SRS) process is an effective method for frequency conversion from 1.3 μm to eye-safe region. Moreover, due to the pulse-compression effect, SRS process is good for short pulse operation [3,4]. In recent years, many results about sub-nanosecond passive Q-switched solid-state Raman laser have been reported [5–7]. However passive Q-switched laser suffers from the serious time-jitter problem [8]. Compared with it, AO Q-switched solid-state Raman laser is more stable and controllable. Unfortunately, owing to the longer cavity length and the slower switching time of AO Q-switch, there is no report about sub-nanosecond AO Q-switched solid-state Raman laser. Therefore, it is essential to establish a precise model for AO Q-switched solid-state Raman laser, and then pulse width compression is possibly achieved by specific optimization of some dominant parameters.

Rate equations are a powerful tool for modeling solid state Q-switched laser [9]. In recent years, several rate equations models of intra-cavity Raman Q-switched laser are well established for output energy maximization [10–13]. The transverse spatial distributions of the fundamental and Stokes laser field have been taken into consideration [12,13]. However, the previous models have failed to pay attention to the longitudinal spatial distribution at different intra-cavity positions, the thermal lens effect in the active medium, and the transit time of ultrasonic wave across oscillating beam. Y. Wang et al. have pointed out that the transit time can significantly affect the switching speed of AO Q-switch. By optimizing the transit time to a low level, pulse width of an AO Q-switched laser was reduced to 2 ns [14].

The main goal of this paper is to develop a new coupled-cavity AO Q-switched solid-state Raman laser and present a clear and thorough analysis of its pulse characteristics. The major controlling factors governing the operation of the laser are investigated: the transit time of ultrasonic wave, the reflectivity of the output couple, the curvature radius of the insert mirror, and especially the thermal lens effect. In Section 2, a rate equations model is established in detail. Numerical simulation results are given in Section 3, where comparison of pulse characteristics between traditional intra-cavity and new coupled-cavity configurations is also presented.

2. Rate equations model

The laser designed here uses a coupled-cavity configuration, as illustrated in Fig. 1. The active medium ($Nd:YVO_4$) and AO Q-switch are eliminated from Raman oscillation cavity. The Raman medium (un-doped YVO_4) possesses its own cavity between the output couple M2 and the insert mirror M3. Obviously, on account of the impact of the insert mirror, the round-trip time for the fundamental and first Stokes photons differs from each other.

If the fundamental and first Stokes laser fields are the TEM00 mode, the intra-cavity photon densities will obey the Gaussian spatial distribution, and can be expressed as [12]:

$$\varphi_L(r,t) = \varphi_L(0,t) exp\left(-\frac{2r^2}{\omega_L^2}\right) \tag{1}$$

$$\varphi_S(r,t) = \varphi_S(0,t) exp\left(-\frac{2r^2}{\omega_S^2}\right) \tag{2}$$

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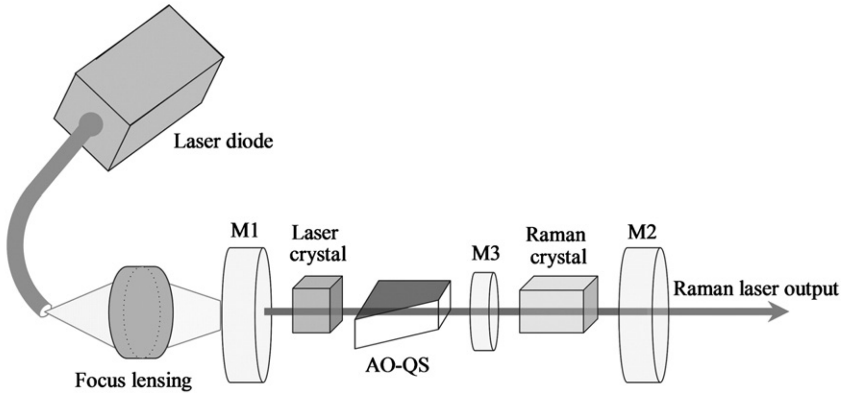

Fig. 1. Configuration of the coupled-cavity AO Q-switch solid-state Raman laser.

where r is the radial coordinate, ω_L and ω_S are the average radii of fundamental and first Stokes beams inside the resonator, respectively, and $\varphi_L(0,t)$ and $\varphi_S(0,t)$ are the intra-cavity photon densities in the laser axis.

On account of the long cavity length, the radius of the fundamental beam varies dramatically at different intra-cavity positions. Thus it is necessary to consider the longitudinal distribution of the fundamental laser beam. The fundamental photon densities in the active medium, the AO Q-switch, and the Raman crystal can be expressed as:

$$\varphi_{L,g}(r,t) = \frac{\omega_L^2}{\omega_{L,g}^2}\varphi_L(0,t)\exp\left(-\frac{2r^2}{\omega_{L,g}^2}\right) \quad (3)$$

$$\varphi_{L,a}(r,t) = \frac{\omega_L^2}{\omega_{L,a}^2}\varphi_L(0,t)\exp\left(-\frac{2r^2}{\omega_{L,a}^2}\right) \quad (4)$$

$$\varphi_{L,s}(r,t) = \frac{\omega_L^2}{\omega_{L,s}^2}\varphi_L(0,t)\exp\left(-\frac{2r^2}{\omega_{L,s}^2}\right) \quad (5)$$

where $\omega_{L,g}$, $\omega_{L,a}$ and $\omega_{L,s}$ are the radii of the fundamental beam at the corresponding positions, respectively.

Considering the SRS process and the longitudinal spatial distribution, rate equations of the couple-cavity AO Q-switched Raman laser can be established as follows [6]:

$$\begin{aligned}\int_0^\infty \frac{d\varphi_L(r,t)}{dt}2\pi r dr = \frac{1}{t_{RL}}\int_0^\infty \{ & 2\sigma l\cdot n(r,t)\varphi_{L,g}(r,t) - \delta_a(t)\varphi_{L,a}(r,t) \\ & -2gh\nu_L c l_S \varphi_{L,s}(r,t)\varphi_S(r,t) \\ & -[L_L - ln(R_L)]\varphi_L(r,t)\}2\pi r dr\end{aligned} \quad (6)$$

$$\begin{aligned}\int_0^\infty \frac{d\varphi_S(r,t)}{dt}2\pi r dr = \frac{1}{t_{RS}}\int_0^\infty & 2gh\nu_L c l_S \varphi_{L,s}(r,t)\varphi_S(r,t) \\ & -[L_S - ln(R_S)]\varphi_L(r,t)\}2\pi r dr \\ & +\int_0^\infty k_{SP}\varphi_S(r,t)2\pi r dr\end{aligned} \quad (7)$$

$$\frac{dn(r,t)}{dt} = -\gamma c\sigma\varphi_{L,g}(r,t)n(r,t) \quad (8)$$

where $n(r,t)$ is the instantaneous population-inversion density in the active medium, t_{RL} and t_{RS} are round-trip time of fundamental and first Stokes cavity, respectively, σ is the stimulated-emission cross-section of Nd:YVO_4 active medium, g is the Raman gain of un-doped YVO_4 crystal, l and l_S are the lengths of gain medium and Raman medium, L_L and L_S are the intra-cavity insert losses of fundamental and first Stokes laser beams, R_L and R_S are the reflectivities of output couple, h is the Plank constant, ν_L is the frequency of fundamental beam, γ is the inversion reduction factor of active medium, k_{SP} is the spontaneous Raman scattering factor, and $\delta_a(t)$ is the loss function of the AO Q-switch.

The opening time of an AO Q-switch is determined primarily by the transit time of ultrasonic wave across the laser beam, which can dominate the loss curve after the switch is open. Because of the transit time, the loss of AO Q-switch cannot rapidly decline to the high-Q level. The loss function of AO crystal can be written in the following form [15]:

$$\delta_a(t) = \delta_a\exp\left(-\frac{t^2}{t_{cross}^2}\right) \quad (9)$$

where δ_a is the diffraction loss of AO crystal, and t_{cross} is the transit time of ultrasonic wave.

For a fiber-coupled diode end-pumped solid state laser, the pump beam is not Gaussian. Top-hat distribution has been proved to be more fit for fiber-coupled pump configuration. If residual population inversion density is so small that it can be neglected, the initial population-inversion density $n(r,0)$ can be assumed to follow the same top-hat distribution as pump beam, which can be expressed as [16]:

$$n(r,0) = n(0,0)\Theta\left(r-\omega_p\right) \quad (10)$$

where ω_p is the average pump beam radius in the gain medium, and $n(0,0)$ is the initial population-inversion density in the laser axis. From Eq. (8), we can obtain the expression of population-inversion density versus the intra-cavity photon density of fundamental laser beam:

$$n(r,t) = n(0,0)\Theta\left(r-\omega_p\right)\exp\left(-\gamma c\sigma\int_0^t\varphi_{L,g}(r,t)dt\right) \quad (11)$$

Substituting the transverse distribution Eqs. (1) and (2), the longitudinal distribution Eqs. (3), (4), and (5), the loss function Eq. (9) and population-inversion density Eq. (11) into the initial rate Eqs. (6) and (7), we can acquire the final expressions of the rate equations:

$$\begin{aligned}\frac{d\varphi_L(0,t)}{dt} = \frac{1}{t_{RL}}8\sigma l\varphi_L(0,t)n(0,0)\int_0^{\omega_p} & \frac{1}{\omega_{L,g}^2}e^{-\frac{2r^2}{\omega_{L,g}^2}} \\ & \exp\left(-\frac{\omega_L^2}{\omega_{L,g}^2}\gamma c\sigma\int_0^t\varphi_L(0,t)e^{-\frac{2r^2}{\omega_{L,g}^2}}dt\right)rdr \\ & -\frac{\omega_{L,s}^2}{\omega_L^2}\frac{\omega_S^2}{\omega_{L,s}^2+\omega_S^2}\frac{1}{t_{RL}}2gh\nu_L c l_S\varphi_L(0,t)\varphi_S(0,t) \\ & -\frac{\omega_{L,a}^2}{\omega_L^2}\frac{1}{t_{RL}}\delta_a exp\left(-\frac{t^2}{t_{cross}^2}\right)\varphi_L(0,t) - \frac{L_L - ln(R_L)}{t_{RL}}\varphi_L(0,t)\end{aligned} \quad (12)$$