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Investigation of thermal induced diffraction loss on Q-switched intracavity optical parametric oscillator ☆

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ABSTRACT

In this paper the influence of thermal induced diffraction loss on the optical parametric oscillator has been investigated numerically by analysing the rate equations model. The model has been performed to the practical example of Q-switched $Nd:YVO_4$-KTA optical parametric oscillator to verify the theoretical model. The numerical analysis shows that the signal output power can be maximized for unique pump beam radius. The pump beam radius is calculated to be 297 μm which is reported 300 μm from experimental results.

1. Introduction

Laser sources in mid-infrared (mid-IR) band have wide applications in environmental monitoring, spectroscopy, etc. The coherent radiation in this band can be obtained using intracavity optical parametric oscillator devices, which is one more effective approach for a pulsed eye-safe laser compared to other two types of eye-safe lasers, Er-doped lasers and Raman lasers pumped by pulsed Nd-doped laser. Along with the construction of high power laser sources, the parametric devices have been developed. The practical laser sources which are tunable over mid-IR band have been provided by the Q-switched intracavity optical parametric oscillators (IOPOs) [1–5].

The characteristic of IOPOs in pulse regime is described by rate equations model which has been introduced in reference [6]. The rate equations have been studied under plane-wave approximation to describe characteristic of $Nd:YVO_4$-KTA IOPO theoretically and to predict optimum output couplers [7,8]. The most successful theoretical model has been introduced in which the rate equations with Gaussian beam profile of mode TEM_{00} have been used in [8–10]. The influence of energy transfer upconversion (ETU) on the IOPOs has been investigated using top-hat pump spatial profile, which has been resulted to estimate optimum pump size [11].

The pump power dependent beam radii of laser mode is also presented using well known ABCD matrix method included thermal lensing [12]. The thermal focal length has been obtained for solid state and self Raman lasers using optical path difference (OPD) method [13,14]. The thermal induced diffraction loss has been studied using diffraction theory of aberration [15–17]. The laser to pump mode radius ratio for Q-switched solid state laser has been optimized using rate equations included thermal induced diffraction loss [18–20].

As it is known, the influence of thermal induced diffraction losses has been never considered in the previous researches on the Q-switched IOPOs which plays an important role in the characteristic of the Q-switched IOPOs. Therefore, in this paper the rate equations included thermal induced diffraction losses have been investigated. The influence of thermal induced diffraction losses causes the pump beam radii to have the optimum size. The practical example of $Nd:YVO_4$-KTA, which has been introduced in reference [8], has been used to verify the presented model. The optimum beam radius calculated by presented model is 297 μm which has been reported 300 μm by experimental results for setup introduced in reference [8]. Good agreement between presented model and experimental results shows that the model can be used to design a Q-switched IOPO and to estimate optimum pump beam radius from which maximum signal output power can be obtained.

2. Theoretical model

In this section the theoretical model based on rate equations is presented for setup which is depicted in Fig. 1.

The general space dependent rate equations for setup which is depicted in Fig. 1 are given by [6,8,9]

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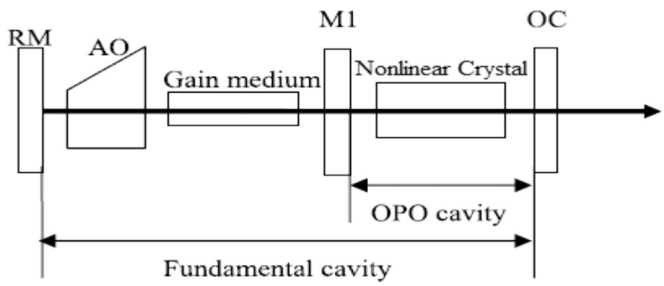

Fig. 1. Schematic diagram of an intracavity optical parametric oscillator.

$$\frac{dn(r,z,t)}{dt} = -\gamma c\sigma n(r,z,t)\phi_l(r,z,t) \tag{1}$$

$$\int_{C_1} \frac{d\phi_l(r,z,t)}{dt} dV = \int_{LC} c\sigma\phi_l(r,z,t)n(r,z,t)\, dV - \int_{NLC} c\sigma_{nl}\phi_{ls}(r,z,t)\phi_s(r,z,t)\, dV - \frac{1}{\tau_l}\int_{C_1}\phi_l(r,z,t)\, dV \tag{2}$$

$$\int_{C_2} \frac{d\phi_s(r,z,t)}{dt} dV = \int_{NLC} c\sigma_{nl}\phi_s(r,z,t)\phi_{ls}(r,z,t)\, dV - \frac{1}{\tau_s}\int_{C_2}\phi_s(r,z,t)\, dV \tag{3}$$

Eq. (1) is the rate equation for inversion population, Eqs. (2) and (3) are the rate equations for fundamental laser and signal photons generation respectively.

In Eqs. (1)–(3), γ is the inversion reduction factor of gain medium, $n(r,z,t)$ is the inversion population density, $\phi_l(r,z,t)$ and $\phi_s(r,z,t)$ are the fundamental and signal photon densities respectively. $\phi_{ls}(r,z,t)$ is fundamental photon density in nonlinear crystal, C_1, C_2, LC and NLC represent the spatial integral area in fundamental cavity, OPO cavity, laser crystal and nonlinear crystal respectively. c is the speed of light in vacuum, σ is the stimulated emission cross section of laser gain medium, σ_{nl} is the effective nonlinear process cross section and is given by [8]

$$\sigma_{nl} = \frac{\hbar\omega_l\omega_s\omega_{id}d_{eff}^2 l_{nl}}{\varepsilon_0 c^2 n_l^2 n_s^2 n_{id}}\left(1 - \frac{\alpha_{id}l_{nl}}{3}\right) \tag{4}$$

where $\hbar = \frac{h}{2\pi}$ with h being plank constant, ω_l, ω_s and ω_{id} are the circular frequency of fundamental, signal and idler photons, d_{eff} is the effective nonlinear coefficient, l_{nl} is the nonlinear crystal length, α_{id} is the absorption coefficient at idler wavelength, ε_0 is the dielectric constant of the vacuum, n_l, n_s and n_{id} are the average refractive index at fundamental, signal and idler wavelength respectively.

τ_l and τ_s are the cavity lifetimes of fundamental and signal photons, respectively and defined as

$$\tau_j = \frac{t_{rj}}{L_j + \ln\left(\frac{1}{R_j}\right)} \quad \text{with } j = l, s \tag{5}$$

with t_{rl}, t_{rs} being the round-tip time of fundamental and signal photons respectively. R_l and R_s are the output coupler reflectivity at fundamental and signal wavelengths; L_l and L_s are the round-trip losses of fundamental and signal photons respectively. In this paper the thermal induced diffraction loss has been added to the round-trip losses which has been never considered in the previous research on the IOPOs system, as

$$L_l = \delta_d + \delta_0 \tag{6}$$

where δ_d is the thermal induced diffraction loss and δ_0 is the intrinsic round-trip loss for fundamental laser cavity. In Eq. (6) δ_d is added to take the thermal induced diffraction loss into account.

Thermal induced diffraction loss is due to thermal effect. Therefore δ_d depend on fraction of pump power which is converted to heat and pump beam radius. The thermal induced diffraction loss is given [13,19,20]

$$\delta_d = 1 - \left|\frac{\int_0^{r_b} r\,\exp(i\Delta\varphi(r))\exp\left(\frac{-2r^2}{w_l^2}\right)dr}{\int_0^{r_b} r\,\exp\left(\frac{-2r^2}{w_l^2}\right)dr}\right|^2 \tag{7}$$

where w_l and r_b are the fundamental laser mode beam radii and radius of gain medium respectively. $\Delta\varphi(r)$ is given by

$$\Delta\varphi(r) = \varphi(r) - \varphi(0) - \eta r^2 \tag{8}$$

where η is a constant adjusted to give best quadratic approximation resulting in smallest value for the diffraction losses and φ is given by

$$\varphi(r) = \int_0^{l_{lc}} \frac{2\pi}{\lambda_l}\Delta T(r,z)\, dz \tag{9}$$

Here, l_{lc} is the gain medium length and λ_l is the fundamental laser wavelength. ΔT is the radial temperature difference and can be obtained by the heat equation which depends on spatial pump beam distribution [19,20]

$$\Delta T(r,z) = A(z)\times\left[\ln\left(\frac{r_b^2}{r^2}\right) + E_1\left(\frac{2r_b^2}{w_p^2}\right) - E_1\left(\frac{2r^2}{w_p^2}\right)\right] \quad \text{(for Gaussian pump beam spatial profile)} \tag{10}$$

and

$$\Delta T = A(z)\left\{\left[1 - \frac{r^2}{w_p^2} + \ln\left(\frac{r_b^2}{w_p^2}\right)\right]\Theta(w_p^2 - r^2) + \ln\left(\frac{r_b^2}{r^2}\right)\Theta(r^2 - w_p^2)\right\} \quad \text{(for top–hat pump beam spatial profile)} \tag{11}$$

$A(z)$ is given by

$$A(z) = \frac{\alpha\eta_h P_p\exp(-\alpha z)}{4\pi K[1 - \exp(-\alpha l_{lc})]}\times\left[\frac{dn}{dT} + (n_l - 1)(\nu + 1)\alpha_T\right] \tag{12}$$

where α is the absorption coefficient of gain medium, η_h is the fraction of absorbed pump power converted to heat, P_p is the pump power, K is the heat conductivity, $\frac{dn}{dT}$ is the thermal dispersion, ν is Poisson's ratio and α_T is the thermal expansion coefficient.

Assuming pump beam spatial profile to have top-hat distribution and taking energy transfer (ETU) into account the rate equations (1)–(3) can be modified as

$$\frac{d\phi_l(t)}{dt} = G\frac{\phi_l(t)}{F(t)}\left\{\exp\left[-F(t)\exp\left(\frac{-2w_p^2}{w_l^2}\right)\right] - \exp[F(t)]\right\} - \Gamma_s c\sigma_{nl}\frac{l_{nl}}{l_f}\phi_l(t)\phi_s(t) - \frac{\phi_l(t)}{\tau_l} \tag{13}$$