Optik 168 (2018) 677–683

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Dynamical equations of intra-cavity optical parametric oscillator synchronously pumped by SESAM mode-locked laser

Shipeng Liu, Jing Wang*, Peng Song, Wei Xia

School of Physics and Technology, University of Jinan, Shandong Province, Jinan 250022, China

ARTICLE INFO

Article history:
Received 25 April 2018
Accepted 25 April 2018

Keywords:
Intra-cavity OPO
Rate equations
Mode-locked lasers
Nonlinear optics

ABSTRACT

By considering the intensity fluctuation mechanism of the fundamental laser, the rate-equation-based model for the CW mode-locking intra-cavity OPO (IOPO) is developed, which includes the behavior of the fundamental laser, the signal and idle light. In the derived model, the OPO nonlinear conversion is considered as a loss for the fundamental laser and thus the mode-locked signal or idle profile originates from the mode-locked fundamental laser. In experiment, the CW mode-locked Nd^{3+}: $GdVO_4$/KTA IOPO with semiconductor saturable absorber mirror (SESAM) is realized. The near-infrared signal light is obtained, which are generated from the IOPO pumped by CW mode-locked fundamental laser. The signal and fundamental spectra are experimentally measured, and then the wavelength of the idle light is estimated to be 3.31 μm. The theoretical values from the rate equations agree with the experimental results well. The developed model explains the behavior of the mode-locked IOPO, which is helpful to system optimization.

1. Introduction

The laser sources in the wavelength of infrared atmosphere window are promising in many fields such as optical spectroscopy, infrared remote sensing, medical treatment, and military, etc. Recently, substantial work has been focused on the research of optical parametric oscillator (OPO) which could output 1.5 μm eye-safe light. Because of shorter pulse and higher peak energy, the picosecond and femtosecond mid-infrared pulses from OPOs attract more and more attention [1–5].

For an OPO pumped by mode-locked laser, the operation of fundamental laser is crucial. The mode-locked laser has developed rapidly since it was firstly realized in experiment. The saturable absorber is normally required to get self-start in the cavity [6,7]. The semiconductor saturable absorption mirror (SESAM) is highlighted for mode locking because of its simple structure, stability and reliability [8]. The efficient and stable signal pulse shold be generated when SESAM is used into the mode-locked fundamental cavity of OPO [9].

The parametric-oscillation cavity is another key factor to influence OPO's operation. The structure of intra cavity is usually applied in continuous-wave (CW) and Q-switched OPO, which is adjusted easily and operates with higher fundamental photon intensity in comparison of extra cavity [10]. Therefore the intra-cavity OPO (IOPO) pumped by mode-locking fundamental laser is expected to have good performance.

* Corresponding author.
E-mail address: wang_jing2588@163.com (J. Wang).

https://doi.org/10.1016/j.ijleo.2018.04.128
0030-4026/

Dynamical rate equations are efficient to predict the performance of OPOs. Some researchers turned to the dynamical theory of OPOs. Continuous-wave (CW) OPO's rate equation was firstly settled and then the model was extended to the repetitively Q-switched IOPOs [11–14]. Nevertheless, the rate equations of the CW mode-locking OPO with the fundamental mode-locking mechanism haven't been involved yet.

In this paper, an all-solid-state IOPO with signal light oscillating is realized, which is pumped by a SESAM mode-locked laser. The fundamental laser and OPO cavity is designed to satisfy the synchronously pumping. The output characteristics of signal are measured and the fundamental and signal spectra are obtained. In the meanwhile, based on the analytical formulation of the passive mode-locking laser, a set of rate equations IOPO is derived. The fluctuation mechanism is introduced into the rate equations of CW mode-locking OPO to explain the fundamental evolution and the gain of signal or idle field is considered as a loss for the fundamental laser. By numerically solving the introduced rate equations, the shape of the locking pulse are calculated. The theoretical results fit the experimental ones.

2. Theories

2.1. Equations of the mode-locked fundamental laser

In this section, an SESAM passively-mode-locking laser is considered. As is known, the intensity fluctuation mechanism explains passive mode-locking phenomena well. When the mode-locking pulsewidth is more than several picoseconds, the electrical field of the passive mode locking can be written as a Gaussian function in the form [15]

$$E_l(t) = E_0(t)\exp[2\ln 2(\frac{t}{\tau_p})^2] \tag{1}$$

where τ_p is related to the FWHM mode-locked pulsewidth by $\tau(FWHM) = \frac{2\ln 2}{\pi \cdot \tau_p}$. τ depends on the cavity length and the effective lasing bandwidth, which is approximated by $\tau = \frac{1}{N'} \cdot \frac{1}{\Delta\nu_g}$. $\Delta\nu_g$ is the line width of the gain medium and N' is the total number of longitudinal mode oscillating in the laser cavity.

In CW mode locking, the amplitude $E_0(t)$ is constant, which can be obtained from the following equations [16].

$$\frac{dE_0(t)}{dt} = \frac{1}{2t_r}[2\sigma l_g n(t) - \delta_T(t) - \delta_e(t) - L] \cdot E_0(t) \tag{2}$$

$$\frac{dn(t)}{dt} = R_{in} - \frac{n(t)}{\tau} - \frac{\sigma c \varepsilon_f n(t)}{4\hbar\omega_f} \cdot E_0^2(t) \tag{3}$$

Eqs. (2) and (3) are use to describe the operation of CW laser. n(t) is the population inversion intensity of the laser rod; l and l_g represent the physical length of the laser cavity and the gain medium; σ and τ are the stimulated-emission cross section and the stimulated-radiation lifetime of laser gain medium; t_r is the round-trip time of the laser; L is the intrinsic loss of the cavity; ω_f is the frequency of the laser; ε_f denotes the dielectric constant. δ_T is the diffractive loss caused by the thermal effect of the gain medium, which can be expressed by [17]

$$\delta_T = 1 - \left| \frac{\int_0^{r_b} \exp[i\Delta\varphi(r)]\exp(-\frac{2r^2}{w_g^2})rdr}{\int_0^{r_b} \exp(-\frac{2r^2}{w_g^2})rdr} \right|^2 \tag{4}$$

where r_b is the efficient radius of the laser crystal, and $\Delta\varphi(r)$ is the residual phase difference from the center of the crystal to the edge:

$$\Delta\varphi(r) = \frac{\pi\eta P_{in}}{\beta\lambda}\left\{ \begin{array}{ll} 1 + \ln(\frac{r_b^2}{\bar{w}_p^2}) & (r^2 \le \bar{w}_p^2) \\ \frac{r^2}{\bar{w}_p^2} + \ln(\frac{r_b^2}{r^2}) & (r^2 \ge \bar{w}_p^2) \end{array} \right\} \tag{6}$$

here $\bar{w}_p$ is the average radius of the pump laser ; The pump rate R_{in} can be expressed by:

$$R_{in} = \frac{P_{in}\left[1 - \exp(-\alpha l_g)\right]}{\hbar\bar{\omega}_p \pi \bar{w}_p^2 l_g} \tag{7}$$

P_{in} is the input power and α is the absorption coefficient of the laser gain medium. $\bar{\omega}_p$ is the frequency of the pump laser. Eqs. (1)–(3) depict the dynamics of the CW mode-locked laser.

2.2. Single mode-locking pulse simulation

In this section, the single mode-locking pulse from a mode-locked IOPO will be simulated from equations. An intracavity OPO pumped by the SESAM mode-locking laser is involved here. For fundamental laser, the nonlinear conversion acts as