Theoretical and experimental studies on output characteristics of an intracavity KTA OPO

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Abstract: An acousto-optically Q-switched Nd:YVO4/KTiOAsO4 (KTA) intracavity optical parametric oscillator (OPO) is efficiently realized in singly resonated scheme. With an end-pumping diode power of 25.9 W, output signal (1535 nm) power of 3.77 W and idler power (3467 nm) of 1.18 W are obtained at a pulse repetition rate of 50 kHz. A rate-equation model is set up to simulate the output power and time characteristics of both signal and idler waves. And both the numerical and experimental results show that the idler pulse width is shorter than the signal one in a singly resonant OPO.

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OCIS codes: (140.3460) Lasers; (140.3540) Lasers, Q-switched; (190.4970) Parametric oscillators and amplifiers.

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1. Introduction

Laser sources in mid-infrared (mid-IR) band (3–5 µm) have important applications in environmental monitoring, medicals and spectroscopy etc. Owing to the lack of directly available solid-state lasers, optical parametric oscillator (OPO) has attracted much attention as an effective technique for radiation generations in this band. During the last decade, researchers have paid most efforts on mid-IR OPOs employing LiInSe$_2$ (LISe) [1,2], ZnGeP$_2$ (ZGP) [3,4], CdSiP$_2$ (CSP) [5,6], KTiOAsO$_4$ (KTA) [7–12], and periodically poled LiNbO$_3$ (PPLN) [13,14]. Among these crystals, the growing techniques for KTA are mature and good crystal quality can be obtained with large size. KTA also possesses high damage threshold and wide transmission range from 0.35 to 5.3 µm. In addition, OPOs based on KTA can utilize 1-µm laser as the pumping source and satisfy non-critical phase-matching condition. In [7–12], mid-IR KTA OPOs were realized in different configurations such as extracavity OPOs, diode side-pumped intracavity OPOs (IOPO) and diode end-pumped IOPOs. Among these configurations, end-pumped intracavity scheme has the advantages of compactness, low threshold and high efficiency. In the previously reported diode-end pumped intracavity KTA OPOs [8,11], the mid-IR output powers were limited to lower than 0.5 W-level.

As for theoretical aspect, rate-equation models have been set up and employed for simulation of IOPOs since optical parametric oscillation was observed in 1965. The Oshman-Harris theory about CW IOPO was reported in 1968 [15]. Then this theory was extended by Falk to the case of Q-switched IOPOs [16]. In 1996, T. Debuisschert developed a simpler model giving the time evolutions of the population inversion, the pump and signal fields to describe the singly resonant OPOs (SROs) [17]. This model has been widely used to analyze...
and optimize the SRO experiments [18–20]. However, in this model, the idler field which is not resonated is removed in the rate equations. Hence it is not valid for the discussion of the idler wave performance.

In this paper, the SRO rate equation model is modified by adding an additional equation to describe the idler field. The output characteristics including temporal shapes, pulse widths and output powers are simulated for both signal and idler waves. In the experiment, we demonstrate a diode end-pumped AO Q-switched intracavity KTA OPO. By selecting a diffusion-bonded $a$-cut YVO$_4$/Nd:YVO$_4$ crystal as the laser gain medium and carefully designing the OPO cavity, we improve the mid-IR output power to 1.18 W with a pump power of 25.9 W and pulse repetition rate (PRR) of 50 kHz. Simultaneously the signal power is obtained to be 3.77 W. Total conversion efficiency from diode power to signal and idler power is 19.1%. And the comparisons between experimental and theoretical results are discussed.

2. Theoretical model

In this section, we study the intracavity SROs theoretically. We use the plane-wave approximation to simplify the mathematics. Based on the theory in [17–19], the rate equations describing the behavior of an SRO can be expressed as follows:

$$\frac{dn(t)}{dt} = -\gamma c \sigma n(t) \phi_p(t) - \frac{n(t)}{\tau}$$ (1a)

$$\frac{d\phi_p(t)}{dt} = \sigma c \frac{l_f}{l_f} n(t) \phi_p(t) - g \frac{l_{\text{of}}} {l_f} \phi_p(t) \phi_s(t) - \frac{\phi_p(t)}{\tau_l}$$ (1b)

$$\frac{d\phi_s(t)}{dt} = g \frac{l_{\text{of}}} {l_{\text{opo}}} \phi_p(t) \phi_s(t) - \frac{\phi_s(t)}{\tau_s}$$ (1c)

where $n(t)$, $\phi_p(t)$ and $\phi_s(t)$ are the population inversion, intracavity fundamental and signal photon densities, respectively; $\sigma$ and $\gamma$ are the stimulated emission cross section and inversion reduction factor of Nd:YVO$_4$; $\tau$ is the fluorescence lifetime of the upper laser level; $c$ is the light speed in vacuum; $l_c$ and $l_{\text{id}}$ are the lengths of the laser crystal and OPO crystal, respectively. And the parameters $l_f$ and $l_{\text{opo}}$ are the optical lengths of the fundamental and OPO cavities.

$\tau_l$ and $\tau_s$ are the intracavity lifetimes of the fundamental and signal photons, respectively, and defined by:

$$\tau_j = \frac{t_{ij}}{L_j + \ln(\frac{1}{R_j})}$$ (2)

with $j = l, s$ and $t_{ij}, r_{ij}$ are the round-trip time of the fundamental and signal photons, respectively; $L_{ij}, r_{ij}$ are the round-trip intrinsic losses of the fundamental and signal waves, respectively; $R_{ij}, s$ are the reflectivities of output coupler at the fundamental and signal wavelengths.

The parameter $g$ is a factor related to parametric gain and defined by [18]:

$$g = \frac{\hbar \omega_s \omega_p \omega_{id} d_{\text{eff}}^2 l_{\text{of}}}{\epsilon_0 c n_p^2 n_s^2 n_{id}} (1 - \frac{\alpha_{id} l_{\text{id}}}{3})$$ (3)

where $\alpha_{id}$ is the absorption coefficient of the OPO crystal at the idler wavelength; $d_{\text{eff}}$ is the effective nonlinear coefficient; $n_p$ is the average refractive index of the fundamental wave; $n_s$, $n_{id}$ are the average refractive indices of the signal and idler waves; $\omega_p, s, id$ are circular
frequencies for the fundamental, signal and idler waves; \( \varepsilon_0 \) is the dielectric constant of the vacuum and \( h = h/(2\pi) \) with \( h \) being the Planck constant.

Equations (1a)-(1c) describe the time evolutions of the population inversion, fundamental and signal photons, respectively.

Here we assume a pure SRO with an output coupler perfectly transparent for the idler wave. This means the idler wave does not experience any cavity. In most of the second harmonic generation (SHG) processes, the frequency doubled laser experiences no cavity either [21], which is similar to the idler wave in SRO. And the theory for frequency doubled lasers has been verified by many researchers [21,22]. Therefore, we derive the equation describing idler performances with the idea employed in SHG theory.

Considering the possible absorption at idler wavelength in OPO crystals, the following equation can be given to describe the evolution of idler wave [17]:

\[
\frac{n_d}{c} \frac{\partial A_{id}^\pm}{\partial t} + \frac{\partial A_{id}^\pm}{\partial z} + \alpha_{id} A_{id}^\pm = \frac{\alpha_{id}}{2\varepsilon_0 n_d c} \times \left( \varepsilon_0 \mu_0 d_{eff} A_p A_s \sin(\Delta \phi^\pm) \right)
\]

(7)

where \( A_p, A_s, A_{id} \) are the pump, signal and idler field amplitudes and \( \mu_0 \) is the permeability of vacuum. The signs + and – denote the two directions of propagation. \( \Delta \phi^\pm \) account for the phase dependence of the parametric interaction.

Neglecting the phase mismatch and considering only the forward transmitting wave, the solution of Eq. (7) is expressed as [17]:

\[
A_{id}^\pm(z,t) = \frac{\mu_0 \omega_0 c (\varepsilon_0 \mu_0 d_{eff} A_p A_s)}{2n_d \alpha_{id}} (1 - \exp(-\alpha_{id} z))
\]

(8)

Using the relation \( \phi = \varepsilon_0 n^2 A^2 \omega \hbar \omega [22] \), we can obtain the forward idler photon density:

\[
\phi_{id}(z,t) = \frac{\hbar \mu_0 d_{eff} \omega_p \omega_s \omega_{id}}{4n_p^2 n_s^2} \left( \frac{1 - \exp(-\alpha_{id} z)}{\alpha_{id}} \right)^2 \phi_p(t) \phi_s(t)
\]

(9)

If \( z = l \), \( \phi_{id}(l, t) \) will represent the forward transmitted idler photon density from the OPO crystal with a length of \( l \).

Commonly in the actual experiment, the inner OPO cavity mirror would be coated for high reflection at the idler wavelength to collect the backward transmitted idler photons. It can be approximately regarded as the OPO crystal length is doubled. Thus overall idler photon density come out from the OPO cavity is \( \phi_{id}(2l, t) \) (written as \( \phi_{id}(t) \) for simplicity) and is expressed as

\[
\phi_{id}(t) = \frac{\hbar \mu_0 d_{eff} \omega_p \omega_s \omega_{id}}{4n_p^2 n_s^2} \left( \frac{1 - \exp(-2\alpha_{id} l)}{2\alpha_{id}} \right)^2 \phi_p(t) \phi_s(t)
\]

(10)

When \( \alpha_{id} \to 0 \), e.g. for the case of KTA crystal at 3.5 \( \mu \text{m} \), it becomes

\[
\phi_{id}(t) = \frac{\hbar \mu_0 d_{eff} \omega_p \omega_s \omega_{id}}{4n_p^2 n_s^2} (2l_{\text{w}o})^2 \phi_p(t) \phi_s(t)
\]

(11)

Equation (11) shows the idler photon density fully extracted from an SRO. In this equation, the idler field is defined by the pump and signal fields. Equations (1a)-(1c) and (11) together provide sufficient descriptions for all the interacted items including population inversion density, fundamental, signal and idler photon densities. And the output powers for the signal and idler waves can be obtained by,

\[
P_s = P_{id} = \frac{\hbar \omega_p c \cdot \pi w^2}{2} \ln(\frac{1}{R_s}) \int_0^{t_f} \phi_p(t) dt
\]

(12a)
with \( f_p \) being the pulse repetition rate, \( w_s \) and \( w_{id} \) the beam radii for the signal and idler waves.

3. Experimental setup

Experimental configuration of the diode end-pumped KTA IOPO is shown in Fig. 1. We designed a straight and compact cavity in order to simplify the OPO configuration. The fundamental wave oscillated in a convex-plano cavity and inside it was a plano-plano OPO cavity. A fiber coupled CW diode laser (NA = 0.22, \( d_{core} = 600 \mu m \)) was used as the pumping source. The laser crystal was a diffusion-bonded \( \alpha \)-cut YVO\(_4\)/Nd:YVO\(_4\) crystal with 0.3 at. % Nd concentration. Its cross section was \( 3 \times 3 \) mm\(^2\) and the lengths of pure and doped YVO\(_4\) were 3 and 10 mm, respectively. Both surfaces of the laser crystal were anti-reflection (AR) coated at 808 nm and 1064 nm (\( R<0.2\% \)). The pump beam was re-imaged into the laser crystal and the waist diameter was 600 \( \mu \)m. The rear mirror (RM) was a 500 mm radius-of-curvature plano-convex mirror. Its entrance face was coated for AR at 808 nm (\( R<0.2\% \)). The other face was coated for high-reflection (HR) at 1064 nm (\( R>99.8\% \)) and high-transmission (HT) at 808 nm (\( T>99\% \)). The output coupler (OC) was a flat mirror made of CaF\(_2\). It was coated for HR at 1064 (\( R>99.9\% \)), partial reflection (PR) at 1535 nm (\( R = 80\% \)) and HT at 3470 nm (\( T>95\% \)). M1 was made of infrared silica glass. Its one surface was coated for AR at 1064 nm (\( R<0.2\% \)) and the other surface was coated for HT at 1064 nm (\( R>99.5\% \)) and PR at 1535 nm and 3470 nm (\( R>99.8\% \)). The fundamental wave oscillated between RM and OC. The signal wave at 1535 nm oscillated between M1 and OC. The idler wave at 3.47 \( \mu \)m would be coupled out through the OC. So this was a singly resonated OPO. The KTA crystal with a size of \( 4 \times 4 \times 25 \) mm\(^3\) was cut along its \( X \)-axis (\( \theta = 90^\circ, \phi = 0^\circ \)) to realize type II non-critical phase-matching. And its coating were AR (\( R<0.2\% \)) at 1064 nm and 1535 nm and HT (\( T>95\% \)) at 3470 nm on both surfaces. The Nd:YVO\(_4\) and KTA crystals were wrapped with indium foil and mounted in water-cooled copper blocks. And water temperature was maintained at 18 \( ^\circ \)C. The 38-mm-long AO \( Q \)-switch (Gooch and Housego) had AR coatings (\( R<0.2\% \)) on both faces at 1064 nm and was driven at 41 MHz center frequency with 15 W of rf power. The overall cavity length was 145 mm and the OPO cavity length was 50 mm. All laser powers were measured with an EPM2000 power meter (Coherent Inc.).

4. Experimental results and discussions

In order to study the output characteristics of signal and idler waves, we prepared a dichroic mirror (DM) to separate the idler from signal power. It was made of CaF\(_2\) and coated for HR at 1535 nm (\( R>99.8\% \)) and HT at 3470 nm (\( T>96\% \)). At different PRRs of 40, 50 and 60 kHz, we measured the output power of idler and the mixture (signal + idler) waves. And the signal power was the difference between the two values. The results for output signal and idler...
powers are shown in Fig. 2(a) and 2(b), respectively. When incident diode power was lower than 10 W, the output power fluctuations became severe. With certain cavity alignment status, the output power could even decrease from several hundred milliwatts to zero, which made it difficult to optimize the cavity alignments. This was because the mode overlap became worse at lower pump powers for OPO within the convex-plano cavity. So we did not give the experimental results with pumping power lower than 10 W. As a result, it was also difficult to measure the parametric oscillating threshold. The highest output signal and idler powers were obtained at 50 kHz. Under the incident diode power of 25.9 W, we obtained the highest output mid-infrared power of 1.18 W. This is the highest power reported for diode end-pumped KTA OPOs until now, and is 2.7 times of the highest value ever reported [11]. The signal power was up to 3.77 W, which was also higher than the highest value of 3.6 W ever reported [23]. The diode-to-mid-IR conversion efficiency was 4.6%, and the conversion efficiency from diode power to signal and idler power was 19.1%.

![Fig. 2. Output power versus the incident diode power at different PRRs. (a) Signal. (b) Idler.](image)

The high output power here could be attributed to two main factors. First, we selected a diffusion-bonded YVO₄/Nd:YVO₄ crystal as the laser medium. It can reduce the thermal load induced by quantum defect of the lasing process [24]. And linearly polarized beam produced from α-cut Nd:YVO₄ would improve the pumping efficiency for parametric conversions and reduce the thermal load in KTA crystal [25]. As a consequence, with the highest output power, the thermal focal length of KTA crystal was 1000 mm, which will be confirmed in the beam quality analysis part. The second factor was the reasonable cavity design. A convex-plano cavity was employed to counteract thermal lens effect inside the cavity and increase the cavity mode volume. As a result, this cavity can hold stable under a high pumping power of up to 25.9 W. And under 25.9 W of pumping power, the beam diameter of the signal wave in the center of KTA was calculated as 688 µm by ABCD matrix method. For the convex-plano cavity, beam diameters of the fundamental wave were 628 and 510 µm in Nd:YVO₄ and KTA, respectively. While if a plano-plano cavity was employed, the beam diameters were 738 and 366 µm, respectively. The overlapping of the convex-plano cavity was much better than that of plano-plano cavity. In addition, larger beam size would avoid damage to the KTA crystal and avoid the pulse-series phenomenon as shown in [18,23]. At the highest pumping power, we did not observe damage to either coatings or crystals. Limited by diode laser power, we did not try higher pumping power. If higher pump power was available, higher output power would be expected.

We studied time characteristics of the signal and idler waves by using a digital phosphor oscilloscope (TDS 5052B, Tektronix). The signal pulses were detected by an InGaAs photodiode and the idler pulses by an HgCdZnTe photoconductive detector. The typical temporal shapes at the highest output power are shown in Fig. 3(a). We measured the response parameter with a CW mode-locked 1064 nm laser, which had a pulse width of around 40 ps. The result for InGaAs case was around 1 ns, and that of HgCdZnTe case was around 5 ns. Consequently, the values for signal pulse widths directly recorded from the
oscilloscope were reliable. And the idler pulse widths could be obtained from deconvolution of the recorded pulse shape and the equipment response function. We show the signal and idler pulse widths (FWHM) at 50 kHz as symbols in Fig. 4(a). Each point was obtained by averaging arbitrary ten experimental values. The signal pulse width was 3.7 ns and the idler pulse width was 2.9 ns under an incident pump power of 25.9 W and a PRR of 50 kHz. The peak power of the signal pulse was 20 kW, and that of the idler pulse was 7.8 kW.

![Fig. 3. Comparison of the temporal shapes at the highest output power. (a) Experiment. (b) Theory. The upper ones are for the signal laser and the lower ones for the idler laser.](image1)

![Fig. 4. Comparison of the theoretical and experimental results at 50 kHz. (a) Pulse width. (b) Average output power. The symbols are experimental results and the lines are the theoretical results.](image2)

We also give the theoretical simulation results for temporal shapes, pulse widths and output powers for comparison. The pulse shapes were calculated at the pump power of 25.9 W and PRR of 50 kHz. We show them in Fig. 3(b), where the upper one corresponds to signal and the lower one to idler. The pulse width and output power results are obtained at the PRR of 50 kHz. They are shown as lines in Fig. 4(a) and Fig. 4(b), respectively. The solid lines are for signal wave and dashed lines for idler wave. The parameters for simulations are shown in Table 1. From these figures we can see the output power results versus incident power are in good agreement between the theory and experiment. But the theoretical temporal characteristics are not well fit. The theoretical pulse widths are shorter than the experimental ones. The reasons may be as follows: Firstly, our theoretical model was obtained under plane-wave approximation. That is to say, we assumed the population inversion and the photon densities only depended on time. In fact, they also depended on space and satisfy a Gaussian distribution within the beam cross sections. Secondly, the effect of energy transfer...
upconversion was not considered in the analysis. Both these reasons could result in a narrower pulse width result [26,27]. In addition, the loss $L$ used in the calculation was not very accurate. $L$ included the insertion losses of the elements, the loss induced by the thermal load of crystals, and other dissipative losses in the resonator. Different $L$ values influenced the calculated results of the pulse widths $W$ and the output powers $P$. We take the intrinsic loss of the signal wave $L_s$ as an example. In our OPO cavity, $L_s$ was estimated to be between 0.002 and 0.05. When $L_s$ varied in this range, $W_s$ decreased from 1.87 to 1.63 ns and $W_{id}$ from 0.36 to 0.33 ns. $P_s$ was from 4.0 to 3.4 W and $P_{id}$ from 1.29 to 1.27 W.

### Table 1. Parameters for simulation

| Parameters                        | values                  | Ref. |
|-----------------------------------|-------------------------|------|
| $\sigma$ Stimulated emission cross-section of Nd:YVO$_4$ crystal | $25 \times 10^{-23}$ m$^2$ | [26] |
| $\gamma$ Inversion reduction factor of Nd:YVO$_4$ crystal       | 0.71                     | [26] |
| $\tau$ Fluorescence lifetime of the upper level                  | 98 $\mu$s                | [29] |
| $l_{Nd}$ Length of Nd:YVO$_4$ crystal                            | 10 mm                    |      |
| $l_{KTA}$ Length of KTA crystal                                    | 25 mm                    |      |
| $d_{eff}$ Effective nonlinear coefficient of KTA crystal          | $-2.99$ pm/V             | [30] |
| $L_1$ Intrinsic loss of the resonator at 1064 nm                  | 0.054                    |      |
| $L_2$ Intrinsic loss of the resonator at 1355 nm                  | 0.02                     |      |
| $R_1$ Reflectivity of OC at 1064 nm                               | 99.8%                    |      |
| $R_2$ Reflectivity of OC at 1355 nm                               | 80.0%                    |      |
| $n_p$ Average refractive index of fundamental wave                | 1.367                    |      |
| $n_s$ Average refractive index of signal wave                     | 1.385                    |      |
| $n_{id}$ Average refractive index of idler wave                   | 1.4                      |      |

As depicted in Fig. 3 and Fig. 4(a), both the theoretical and the experimental results have shown a similar phenomenon: under the same incident pump power, the idler pulse width is shorter than the signal one in SRO. In previous works, it was considered that the idler and signal had the same pulse widths because two photons came out synchronously whenever a pump photon was depleted. But there was no practical experimental data about the comparison between the signal and idler pulse widths to support this statement. In our experiment, it was obvious that the idler pulse widths were much shorter than the signal ones. And the theoretical model could also confirm this statement. As we described in the theory part, the idler pulse was entirely driven by the pump and the signal field in an SRO. Hence it only existed in the period where the signal pulse overlapped with the pump pulse. As a result, the idler pulse width was shorter than the signal one. This phenomenon was also observed in our previous experimental results in [28].

Output optical spectra of the fundamental and signal waves were monitored by a wide range spectrum analyzer (Yokogawa AQ6315A). The wavelengths were measured to be 1064.2 and 1535.0 nm, respectively. The idler spectra were measured by a monochromater and a pyroelectric detector. The scanned results from 3400 to 3500 nm are shown in Fig. 4, from which a central wavelength of 3467 nm could be obtained. Considering the accuracy of the monochromater, the idler wavelength could be 3467 ± 3 nm. The output beam profiles
were monitored by a Nanoscan beam analyzer. And typical beam profile of the idler wave is shown as the inset of Fig. 5. By focusing the beam with a ZnSe lens ($f = 100$ mm), we measured the beam quality factors ($M^2$) of the 3.47 $\mu$m idler wave at the highest output power of 1.18 W. The values in horizontal and vertical directions were determined to be $9.5 \pm 0.5$ and $8.8 \pm 0.5$, respectively. At the highest output power, the signal $M^2$ factors were $2.1 \pm 0.1$ and $2.0 \pm 0.1$, respectively. With $M^2$ results of the signal wave, we could deduce the thermal focal length of the KTA crystal through the beam propagation law. A result of 1000 mm was obtained, which was adopted to calculate the cavity mode sizes.

5. Conclusion

In summary, a diode-end pumped actively Q-switched YVO$_4$/Nd:YVO$_4$ KTA OPO has been studied theoretically and experimentally. With an incident diode power of 25.9 W, the output power of 3.47 $\mu$m idler wave was obtained to be up to 1.18 W. This is the highest mid-infrared power obtained from a diode end-pumped intracavity KTA OPO. The signal power was obtained to be 3.77 W at 1535.0 nm simultaneously. Diode-to-mid-IR conversion efficiency was 4.6% and the conversion efficiency from diode power to total OPO output power was 19.1%. We derived the expression of the idler photon density to modify the rate equation model for SROs. This model was used to analyze the performance of this KTA OPO. The average output powers and the temporal characteristics were simulated for both signal and idler waves. Both the theory and the experiment have shown the same phenomenon: in a singly resonant OPO, the idler pulse width is shorter than the signal pulse width under a same incident diode power.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (No. 60908010), Science and Technology Development Program of Shandong Province (No. 2007GG10001026), Special Grade of China Postdoctoral Science Foundation (No. 201003632) and Independent Innovation Foundation of Shandong University, IIFSDU (No. 2009JC003).