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Singly-resonant optical parametric oscillator based on KTA crystal

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Abstract. Tunable mid-infra-red radiation by singly resonant optical parametric oscillation based on KTA crystal pumped by multi-axial Gaussian shape beam from Q-switched Nd:YAG laser has been demonstrated. Threshold energy of oscillation at different idler wavelengths for different cavity length has been demonstrated. Single pass conversion efficiency of incident pump energy to infra-red wavelength has also been measured.

Keywords. Non-linear optics; optical frequency conversion; optical parametric oscillation; singly-resonant oscillation.

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1. Introduction

Optical parametric oscillators (OPOs) are useful for getting tunable coherent radiation in the spectral range where laser source is not available. Tunable radiation from UV to infra-red and even THz domain can be generated by optical parametric oscillation. In the infra-red region they play an important role in the 'molecular finger print' region (2–20 μm) of the electromagnetic spectrum where molecular species have their fundamental absorption features and where we lack broadly tunable laser source. The broad tuning range of optical parametric oscillation and efficient power conversion characteristic make OPOs very attractive in many applications requiring wide tunability and high peak power. The robustness and compactness of OPOs make them attractive for different applications in laser spectroscopy, remote sensing, detection of trace gases, biology, medicine and in laser radar.

Since the first demonstration of OPO by Giordmaine and Miller in 1965 using $LiNbO_3$ crystal [1] there has been a lot of improvement in this front making it a real tool for different applications. This becomes possible due to the advent of novel non-linear materials having wide transparency range with very low optical losses, high laser damage threshold and lot of improvement in optical coating technology. The advent of periodically poled material [2] revolutionized the non-linear frequency processes. There is the possibility to use the highest non-linearity of the material and can overcome the limitation on tunability due to the phase-matching condition in birefringent material, by engineering suitable quasi-phase-matched grating periods. OPOs in the mid-infra-red spectral range using KTP isomorphs, bulk as well as periodically poled crystals in nanosecond (ns), picosecond (ps) and femtosecond (fs) regimes have been demonstrated [3–22] and research is still going on for its further improvement. In this paper we report the generation of tunable radiation in 4–5 μm range using KTA crystal by singly resonant optical parametric oscillation pumped by 10 ns pulsed 1064 nm radiation from a Q-switched Nd:YAG laser. The advantage of KTA is that it can be tuned almost over its whole transparency range (KTA has long wavelength cut off down to 5.3 μm, inset of figure 1) covering the important 4–5 μm region, which is not accessible with KTP. Also, KTA possesses slightly higher non-linearity than KTP [3]. Periodically poled crystals like PPLN, PPKTA, PPKTP, PPRTA are useful to get tunable radiation in this region but it is difficult to handle the periodically poled crystal due to its thin size.

2. Experiment

For our experiment we use a 41° XZ cut ($\varphi = 90°$) KTA crystal of 15 mm long and 10×10 mm^2 cross-section with coating supplied by M/S Altechna Co. of Lithuania. The schematic experimental arrangement for singly resonant optical parametric oscillation is shown in figure 2. The crystal has the following coatings: input face is anti-reflection (AR) coated at 1064 nm (i.e. pump beam) and AR coated at 1.3–1.7 μm (i.e. the signal beam). The output face is AR coated at 1.3–1.7 μm. We use a hemispherical cavity configuration formed with a plano-concave input mirror having 5 m radius of curvature while the output mirror is plane parallel. The input mirror (M1) (substrate BK7) has the following coatings: The input plane face is AR coated at 1064 nm while the curved face is high reflection (HR) coated at 1.3–1.7 μm and high transmission (HT) coated at 1064 nm. The output mirror (M2) (substrate CaF_2) has the following coatings: face 1, i.e. the face toward the cavity is HR coated at 1064 nm and 1.3–1.7 μm and HT coated at 3–6 μm. The other surface is not coated. The cavity is pumped by multi-axial 1064 nm radiation having pulse length of 10 ns from a Q-switched Nd:YAG laser. The pump beam shape is Gaussian in nature having divergence <1 mrad and 3.5 mm in diameter. The input and output mirrors are placed in a holder both having tilt motions. In addition the output mirror also has translation motion along the cavity axis controlled by a micrometer attached with it to facilitate the change in cavity length. The crystal is placed on a precision circular table having least count of 0.04°, capable of rotating in the horizontal plane. The pump beam is horizontally polarized as such and it is made vertically polarized by a 90° polarization rotator to satisfy the o-eo interaction. The generated infra-red radiation (i.e. idler beam) is detected with a liquid nitrogen (LN_2) cooled MCT detector. Though the output mirror (M2) has high reflectivity (∼99.5%) at the pump beam, the detector sensed the residual and scattered pump beam radiation from different optics in the system. To avoid this we use an uncoated Ge filter to block the detection of the unwanted pump beam by the MCT detector and it is found that a 3 mm thick Ge filter completely blocks the residual/scattered pump beam. We also use a quartz beam

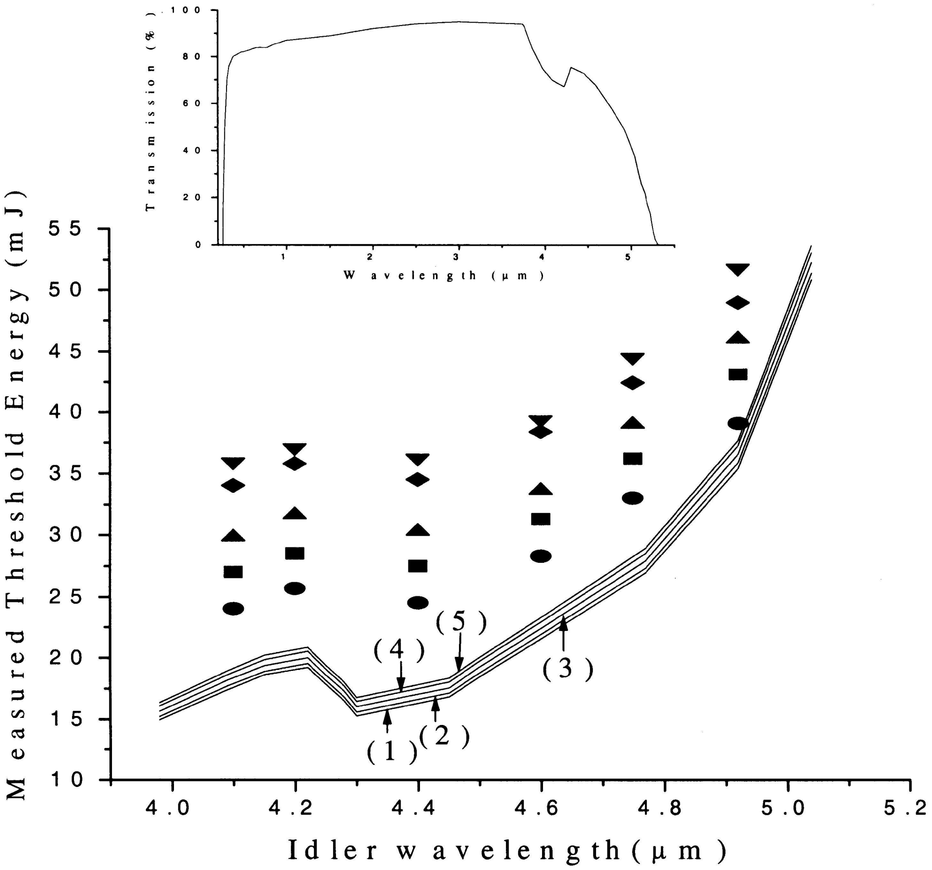

Figure 1. Illustration of threshold energy of oscillation for KTA (crystal length 15 mm) singly-resonant optical parametric oscillator in XZ-plane (o–eo interaction) with infra-red wavelengths at different cavity lengths. Here the smooth curves are theoretically calculated using the expression given in expression (A) as stated in the text while different dots represent the measured values. The smooth curves (1), (2), (3), (4) and (5) respectively are the theoretical prediction of threshold energy of oscillation for the cavity lengths of 20, 22, 25, 28 and 30 mm respectively at different idler wavelengths while the corresponding measured values are represented by the symbols (●), (■), (▲), (◆) and (▼). Inset of this figure shows the general transmission characteristics of KTA crystal.

splitter (uncoated) to monitor the pump beam energy simultaneously and also a Faraday isolator to prevent any reflected pump beam entering back into the pump laser cavity. The electrical signal from the detector is displayed on a 100 MHz-storage oscilloscope. At first the cavity length is fixed at 20 mm and later on the cavity length is increased to 30 mm by steps through the micrometer screw attached with the output mirror and the corresponding threshold energy of oscillations are measured. We have also measured the generated idler beam energy. The input pump beam energy as well as output infra-red energy are measured with an energy meter of M/S Scientech.

3. Result and discussion

By rotating the crystal in the horizontal plane the phase-matched situation is achieved and by rotating the crystal in clockwise and anti-clockwise direction the phase-matched peak is ascertained. The angular tuning characteristics for OPO in this crystal in XZ plane for o–eo interaction is shown in figure 3. The smooth curves (1), (2) and (3) in figure 3 are theoretically predicted from the Sellmeier coefficients given by Kato *et al* [4], Fanimore *et al* [13] and Feve *et al* [14] respectively while the dots (•) represent our measured phase-matched angles internal to the

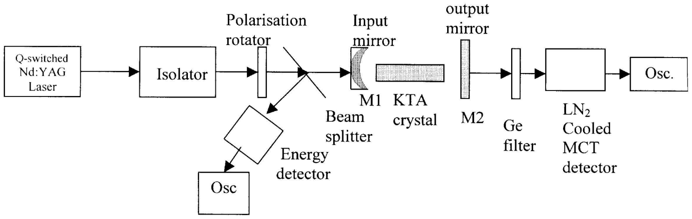

Figure 2. Schematic experimental arrangement for singly-resonant optical parametric oscillator for the generation of 4–5 μm tunable radiation.

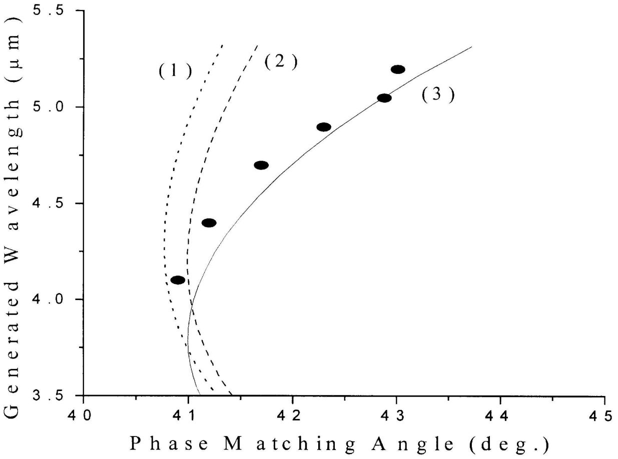

Figure 3. Illustration of angular tuning characteristics for KTA optical parametric oscillator in XZ-plane, i.e., $\varphi = 90^\circ$ for o–eo interaction. The smooth curves (1), (2) and (3) are theoretical predictions obtained from the Sellmeier coefficients given by Kato *et al* [4], Fanimore *et al* [13] and Feve *et al* [14] respectively. The dots (•) represent our measured phase matching angles internal to the crystal.

crystal. It is seen from this figure that our measured phase-matched angles follow closely the theoretical prediction from the Sellmeier coefficients of Feve *et al* [14]. Maximum error in our measurement is of ±0.04°. We detect infra-red radiation up to 5.2 μm from about 4.0 μm. From theoretical calculation it is seen that for a particular phase-matched angle there is the possibility to get two infra-red radiations simultaneously. But we detect idler radiation from 4.0 to 5.2 μm by blocking the radiation in the 3 μm spectral range with a polystyrene sheet. The wavelength of the generated infra-red radiation is checked with a monochromator of M/S Spex. Again we also observe very weak red light, which is the non-phase-matched second harmonic of the signal beam, lies in the 1.337 to 1.45 μm spectral range, confirming that the generated radiation must be in 4–5 μm spectral range. It is seen from this figure that, there is a slight departure of the experimental value from the theoretically predicted value. This may be due to inaccurate Sellmeier coefficients or some error associated with the measurement or minor crystal cutting error. Such type of departure is also reported in ref. [14]. Again our measurement shows that the generated infra-red beam is of the same size as that of the pump beam, i.e. ~3.5 mm in diameter and having similar divergence.

We measure the threshold energy of oscillation for this OPO at first keeping the cavity length at 20 mm at different infra-red wavelengths and then also by increasing the cavity length by steps to 30 mm. These are shown in figure 1. Smooth curves in these figures are the theoretical prediction calculated by using the analytical expression for threshold of energy fluence for a singly resonant OPO of Brosnan and Byer's equation [23–25]

$$J_{\mathrm{th}} = \frac{1.8\tau}{K g_{\mathrm{s}} L_{\mathrm{eff}}^2 (1+g^2)} \left[\frac{25L}{c\tau} + 2\alpha l + \ln \frac{1}{\sqrt{R}} + \ln 2 \right]^2, \tag{A}$$

where τ is the full-width at half-maxima (FWHM) of the pump pulse, l is the length of the crystal, α is the loss coefficient of the crystal, L is the optical length of the OPO cavity, g_{s} is the mode coupling coefficient, R is the overall reflectivity of the end mirrors and L_{eff} is the effective parametric gain length. g is the ratio of backward to forward pump field amplitude inside the crystal. The physical path length of the cavity is appropriately converted to optical path length of the cavity by considering the crystal. The gain coefficient K is given by the expression

$$K = 2\omega_{\mathrm{s}}\omega_{\mathrm{i}} d_{\mathrm{eff}}^2 / n_{\mathrm{s}} n_{\mathrm{i}} n_{\mathrm{p}} \varepsilon_0 c^2, \tag{B}$$

where ω_{s} and ω_{i} are the signal and idler frequencies, d_{eff}^2 is the effective non-linear coefficient of the crystal, $n_{\mathrm{s}}, n_{\mathrm{i}}$, and n_{p} are the refractive indices at signal, idler and pump frequencies respectively and ε_0 is the permeability of free space. The energy fluence J_{th} is appropriately converted to energy by multiplying it with the area of the incident pump beam. The pump beam size is determined by taking the burn pattern of the pump beam on a photographic plate near the input mirror (M1) of the OPO cavity and diameter of the same is measured with a traveling microscope.

In figure 1 the smooth curves (1), (2), (3), (4) and (5) respectively represent the estimated threshold energy of oscillation using the above stated expression (A) for the cavity lengths 20, 22, 25, 28 and 30 mm while the corresponding measured values are represented by the symbols (●), (■), (▲), (◆) and (▼). It can be seen from figure 1. that, the threshold energy of oscillation follows the general transmission characteristics of the crystal represented in the inset of figure 1 and increases as expected with increase in cavity length. It is also found that the measured threshold energy of oscillation is slightly higher than theoretically predicted value. This is due to the losses occurred of the pump beam energy at the different coating faces of different optics as well as loss at the crystal faces in spite of anti-reflection coating (>99%). In addition we detect the infra-red radiation by LN_2 cooled MCT detector operated without any preamplifier using uncoated Ge filter. There is a lot of (∼40%) reflection losses occurred at the infra-red radiation from the uncoated Ge filter. We also measured the threshold of oscillation energy at different cavity lengths keeping the infrared wavelength fixed at 4.9 μm. It is found that the measured threshold energy of oscillation increases with the increase in cavity length as expected.

We also measure the single pass energy of the generated infra-red beam with increase in input pump beam energy. The infra-red beam is kept fixed at 4.9 μm. It is found that the energy of the generated infra-red wavelength increases with the increase in incident pump beam energy. We get idler power of 70 kW on the incident of 6.0 MW pump power which corresponds to conversion efficiency of about 1.17%. It is possible to get higher conversion to idler energy by increasing the pump power density and better coupling between pump beam and the signal beam. But we do not increase the pump beam energy too much so that no further damage occurs on the crystal coating.

4. Conclusion

In conclusion, we have demonstrated and studied the operation characteristics of KTA optical parametric oscillator in singly resonant mode using a multi-axial Q-switched Gaussian shape pump beam with the capability of tuning in 4–5 μm region of infra-red having finger prints of important atmospheric constituents.

In addition to OPO, the practical tunable laser sources for wavelength beyond 2 μm are color centre lasers, ternary lead salt diode laser, sources based on difference frequency mixing (DFM) and free electron laser (FEL). But all these sources possess advantages and disadvantages. The color centre lasers operate extremely well with single frequency, power level up to 100 mW but only in a limited spectral range from 1.1 to 3.5 μm and at liquid nitrogen temperatures. Diode lasers on the other hand cover a wide wavelength range (2–30 μm) based on semiconductor composition. But single diode laser has a very limited tuning range ($\sim$100 cm^{-1}) and power level in mW. Moreover, commercially available diode lasers do not cover continuously their nominal wavelength ranges and also require low temperatures (<100 K). By DFM we can also get coherent radiation in this range or long wavelength. This method can give a wide spectral tunability but the tunability depends on the input tunable source. The main difficulty of this route is that it requires two input laser sources one of which should be tunable (such as dye, Ti:sapphire or Alexandrite laser), and this makes complexity in developing a portable, compact, tunable source particularly for outdoor application for trace gas detection, pollution monitoring etc. Handling of one laser is much easier and user friendly than two lasers if it is a dye laser. Again due to its bulky size, FEL is not suitable for outdoor application.

On the other hand, OPO can be achieved with a single pump laser. Now-a-days very stable, long-lived, compact, solid-state pumped laser source in visible to near infra-red (NIR) region is available to make a compact, stable, portable, long-lived, all solid-state tunable source in infra-red (IR) based on OPO. The only disadvantage of OPO is that this process demands very high optical quality crystal, good pump beam quality and high pump power threshold for stable and practical operation particularly in singly resonant oscillation (SRO) mode.

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