PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 82, No. 2
February 2014
pp. 227–231

Generation of 2.1 μm wavelength from degenerate high gray track resistant potassium titanyl phosphate optical parametric oscillator

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DOI: 10.1007/s12043-013-0668-3; ***e*Publication:** 12 February 2014

Abstract. This paper presents the experimental results of degenerate optical parametric generation using a high gray track resistant potassium titanyl phosphate (HGTR KTP) optical parametric oscillator (OPO). An average output power of 7 W at 10 kHz has been achieved that includes both signal and idler powers near degeneracy using 20 W average power from a 1064 nm Nd:YVO_4 pump source corresponding to an optical conversion efficiency of 35%.

Keywords. Laser; optical parametric oscillator; high gray track resistant potassium titanyl phosphate.

PACS No. 42.65.Yj

1. Introduction

Many laser sources having emission wavelengths covering the UV, visible and IR portions of the electromagnetic spectrum have been developed until now. However, gaps still exist in the wavelength regions which are not covered by the available laser sources. The mid-IR region, for example, is a potential region for which laser sources are not easily available. So, efforts are being made to generate wavelengths in this region as they are useful for a number of applications like spectroscopy, atmospheric studies and directed infra-red counter measures (DIRCM). An efficient way to generate wavelengths in this region is by frequency conversion using optical parametric oscillators. The 2.1 μm wavelength in particular is of interest in gas detection including long-range LIDAR applications, free-space optical communication, medical diagnostics, laser surgery, optical pumping of solid-state lasers and material processing. Though it can be generated by thulium-pumped Ho:YAG laser, laser emission at 2.1 μm requires optical pumping of holmium ion at 1.9 μm using thulium fibre lasers. Fibre lasers capable of generating high average powers required for pumping holmium ion are very bulky and expensive. Due to this reason an alternate way of generating 2.1 μm is presented in this paper using the well-established technology of Nd:YAG laser as pump source and widely used non-linear crystal like KTP for conversion of pump wavelength into the desired wavelength using OPO.

An OPO consists of an optical cavity and a non-linear crystal. The non-linear crystal is responsible for the parametric interaction which annihilates the pump photon at frequency ω_p by creating a pair of photons (signal + idler) of frequencies ω_s and ω_i fixed by the energy conservation ($\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$) and momentum conservation ($k_p = k_s + k_i$) principles. The non-linear crystal selected for the generation of 2.1 μm is KTP, i.e., potassium titanyl phosphate ($KTiOPO_4$). KTP has several features which make it attractive for degenerate OPO. It can be easily pumped by 1064 nm lasers like the Nd:YAG and Nd:YVO_4 which are readily available commercially with average powers up to 50 W. KTP has a large effective non-linear coefficient d_{eff} value of 3.1 pm/V near 1 μm, high transparency in the range of 350–4500 nm and a moderate walk-off angle of 1 to 3°. Other advantages of KTP include its non-hygroscopic nature and high optical damage threshold around 500 MW/cm^2 which is quite high when compared to other non-linear crystals suited for this application. KTP has an exceptionally large temperature bandwidth which maintains pulsed energy stability of the converted beam. It also has a high thermal conductivity which permits its use with high average power lasers [1].

Despite all these advantages, KTP crystals have a significant limitation in the form of photochromic 'gray track' damage [2]. Photochromic damage (gray tracking) often occurs in KTP during high peak power non-linear frequency conversion interactions. The origin of gray tracking in KTP has been observed and explained in several literatures [3]. It has been reported that two 532 nm SHG photons are absorbed during a non-linear process to reach the strongly absorbing band edge in the presence of 1064 nm laser pump source. This excitation into the band edge would trigger a reduction of normal state Ti^{4+} to Ti^{3+} via charge transfer from a neighbouring oxygen ion. This [Ti^{3+}–O^-] electron–hole pair should revert back to the ground state on a time-scale much faster than the laser pulse width and therefore not absorb any SHG photon. Impurities or vacancies, however, may stabilize these electron–hole pairs long enough to allow absorption of the SHG frequency, resulting in discolouration or localized heating that leads to gray tracking and catastrophic damage respectively [4].

This damage leads to catastrophic failure in the performance and operation of the device. In order to avoid this problem, high gray track resistant KTP (HGTR KTP) crystal has been used in the OPO cavity. HGTR KTP crystals (Raicol, Israel) have a higher gray track resistance than typical flux-grown KTP. Due to this, the chances of catastrophic damage reduce significantly. In addition to this, these crystals exhibit a higher optical damage threshold of about 600 MW/cm^2. These crystals also possess wider angular bandwidth, smaller walk-off angle and high thermal conductivity when compared to normal KTP crystals.

2. Theoretical design calculations

To design an efficient OPO cavity, several factors have to be considered. Major factors are crystal cut or phase matching angle of the crystal, length of the crystal, mode of

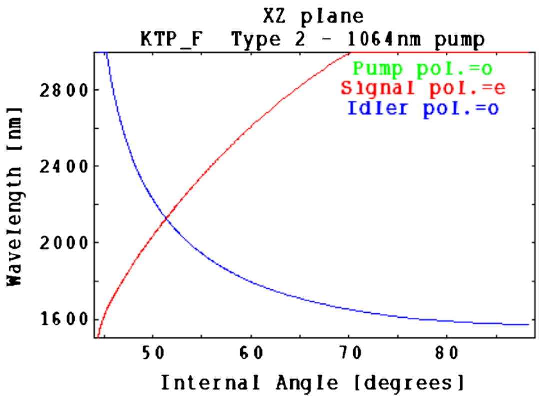

Figure 1. Tuning curve for KTP.

the pump beam and cavity length. Also the type of interaction (type-I/type-II) has to be selected so as to achieve higher non-linear coefficient at the phase-matching point. For KTP crystal type-II parametric interaction has higher efficiency. Type-II interaction involves an extraordinary signal wave and an ordinary idler wave. After solving the phase-matching expressions ($\omega_p = \omega_s + \omega_i$, $k_p = k_s + k_i$) for each signal–idler pair, tuning curves for different planes are obtained [5]. For KTP crystal, xz-plane has higher effective non-linear coefficient, d_{eff}. The tuning curve for KTP for type-II interaction in the xz-plane with a 1064 nm pump is shown in figure 1. As can be deduced from the curve, KTP crystal exhibits degeneracy at 2.1 μm for an internal angle of 53°. The xz-plane has a higher crystal acceptance angle and a smaller beam walk off. Hence this plane was chosen for the experiment and the crystals were cut at $\theta = 53°$ ($\varphi = 0°$). For optimum performance, HGTR KTP non-linear crystal has been used in the OPO cavity.

Simulations were carried out to determine optimum crystal length, OPO cavity length and output mirror reflectivity. The graph for crystal length is shown in figure 2. From the graph it can be seen that for smaller crystal lengths the output fluence is very low because the time of interaction is very short. The simulation results show that crystal lengths of 10–20 mm will give optimum output. Figure 3 presents the simulation data for optimum reflectivity of the output mirror. From the graph it can be seen that the optimum output reflectivity is around 70%.

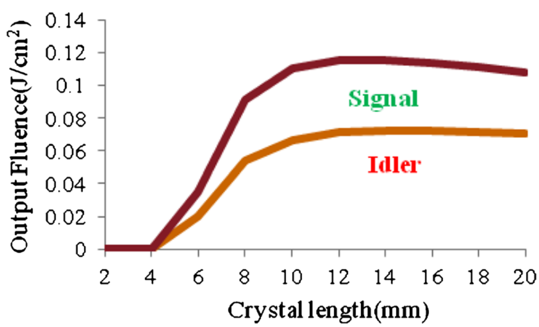

Figure 2. Variation in output fluence with crystal length.

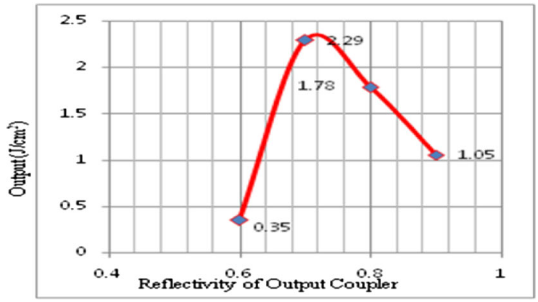

Figure 3. Variation in output fluence with output mirror reflectivity.

3. Oscillator structure

The schematic lay-out of HGTR KTP-based optical parametric oscillator [6] is shown in figure 4. The primary pump source is a commercial Nd:YVO_4 laser (SN0460, Edgewave GmbH). This source was used at 25 W average power at the pulse repetition frequency of 10 kHz. Here the pulse energy is 2.5 mJ and pulse width is around 10 ns. The pump beam has a divergence of 1 mrad and is Gaussian.

For retro-protection of the pump laser, a Faraday isolator (FI) has been used. A half-wave plate (HWP) and a cube polarizer (P) have been used to select and optimize the desired pump polarization in the cavity. The polarization of the pump beam is horizontal. An uncoated lens (L) of 40 cm focal length is used to focus the pump beam inside the OPO cavity. The beam diameter at the focus is 400 μm. The pump power after the lens was measured to be 20 W (2 mJ at 10 KHz) which is incident on the OPO.

The HGTR OPO cavity consists of an input mirror (M1), a non-linear crystal and an output mirror (M2). The input mirror is AR-coated for 1064 nm and highly reflective for 2.1 μm. The 5 mm $\times$ 5 mm $\times$ 20 mm HGTR KTP was wrapped on the sides in an aluminum sheet for spreading heat uniformly. The temperature of the crystal was maintained with the help of a thermoelectric device at 70°C for best performance. Though the change in performance with temperature is not appreciable, higher temperature helped in preventing the catastrophic damage of the crystal. During room temperature operation, occurrence of crystal damage was observed due to thermal shock produced in high average power operation.

The output mirror M2 is highly reflective for 1064 nm and partially reflective for 2.1 μm. The output reflectivities of M2 were varied from 60% to 90%. The best performance was found at 80%. However, the difference in OPO performance for 70% and 80%

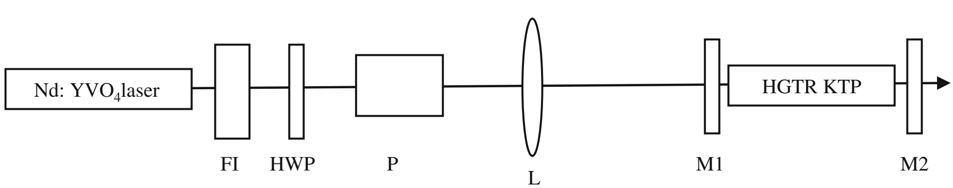

Figure 4. Experimental set-up for HGTR KTP OPO.

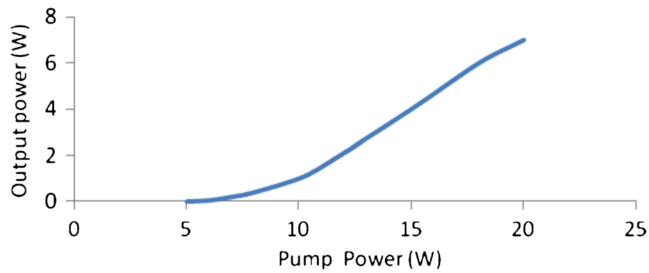

Figure 5. Output power from HGTR KTP OPO plotted as a function of 1.064 μm pump power.

reflectivity is only 2 μJ. The physical length of the OPO cavity is 35 mm including the crystal.

4. Experimental results

The maximum output power measured from the cavity was 7 W or 700 μJ at 10 kHz. A germanium filter (52% transmission at 2.1 μm) was used in front of the power meter to ensure that the output is at 2.1 μm. The pump power measured before the input mirror was 20 W. Hence the optical conversion efficiency is 35%. The pulse width of the output beam was measured using an InGaAs detector (Newport) and found to be around 7 $\pm$ 1 ns. Figure 5 shows the output power of the OPO as a function of input pump power.

Acknowledgements

Authors acknowledge Dr A K Gupta, Director, IRDE, for his encouragement. Authors also express their sincere gratitude to Mr Neeraj Bhargava and Mr Atul Tomar for mechanical support, Mr Saurabh Verma for software support, Mr B D Joshi for electronics support and Mr R K Goel and Mr Vinay Balooni for electro-optical support.

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