

High power diffusion bonded walk-off compensated KTP OPO

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Abstract

Recently, we have obtained a 23.5W of 2- μ m intracavity OPO output which is, to the best of our knowledge, the highest power from an intracavity OPO reported in the literature. To achieve such high average power 2- μ m OPO output in a simple and compact laser system, we have adopted the diffusion-bonded walk-off compensated (DBWOC) KTP OPO pumped by the anisotropy Nd: YALO laser. The walk-off compensated twin KTP crystals reduce the aperture effect due to Poynting's walkoff in the critically phase-matched parametric generation. At the same time, it increases the acceptance angle for the nonlinear interaction, resulting in more efficient OPO conversion. In addition, the diffusion-bonded configuration eliminates the optical losses at the in/out facets and the need for alignment of the crystals. In order to low down the OPO threshold and increase the effective gain of KTP OPO, we bonded two pairs of crystals together. In this paper, we will compare the recent results of the 2- μ m KTP OPO results with different pairs of DBWOC KTP OPO. With two pairs of DBWOC KTP device, we observed 78% higher 2- μ m average output power compared to one pair of KTP device.

Key words: Diffusion bonded, walkoff compensated, KTP, Nd: YALO

1. Introduction

Two microns laser sources are useful for several applications in remote sensing and medical applications. It also serves as a good pumping source for non-linear OPO crystals such as ZnGeP₂ to get into the mid-infrared spectral range [1-3]. Recently, our group has reported a 6.5W 2- μ m laser source [4] from a near degenerate, type II KTP OPO pumped within a Q-switched Nd: YAG laser cavity. The main difficulty in generating more than 10W of 2- μ m from this configuration lies in the serious presence of thermally induced birefringence effect that complicates the effort of generating polarised laser light with reasonable beam quality to pump OPO at high average power. Compensation for these thermal birefringence effects with a single laser module, especially with the presence of an intracavity OPO, is non-trivial [5] and requires complex cavity with more intracavity optical elements.

In addition, because of the aperture effect due to Poynting vector walk-off and the limited acceptance angle of this critically phasematched KTP crystal, the OPO efficiency is hampered by the inefficient wavelength conversion for both the lower and higher order laser modes. Therefore, in this work, we have exploited the advantages of walk-off compensated KTP crystal configuration [6~8], so as to enhance the OPO conversion efficiency by providing: firstly, a longer effective gain length for the lower order modes due to reduced aperture effect [6, 8]; secondly, an increased acceptance angle [7], which is especially beneficial for the higher order laser modes. To avoid optical losses and cumbersome alignment of crystals in walk-off compensated configuration, we designed a diffusion-bonded crystals in a correct orientation that preserves the same signs of the effective nonlinear coefficients [6] for crystals.

In Ref. [9], we have demonstrated the potential of diode pumped Nd: YALO rod in generating high power polarised laser beam. Nd: YALO is one of the few laser crystals that exhibit high conductivity, hardness and large emission cross-sections that are comparable to that of Nd: YAG. Its main advantage lies in its optical anisotropy that provides a simple solution (with much less optical elements) to generate polarised laser light for pumping OPO. In our laboratories, we have used a Nd: YALO laser to pump an intra-cavity OPO that utilises a pair of diffusion bonded walk-off compensated (DBWOC) KTP crystals, and have managed to push the 2 μ m intracavity OPO output power over 20W at a repetition rate of a few kilohertz [10]. To the best of our

knowledge, this is more than 3 times higher than the previous KTP OPO intracavity power pumped by Nd: YAG laser [4] and using Nd: YALO laser to pump OPO itself is a novel attempt. In addition, nonlinear processes utilising DBWOC nonlinear crystals had been reported in [6] with less than few watts level of average power output. In this paper, we have clearly illustrated the power handling capability of DBWOC KTP crystals in generating few tens of watts of OPO output with multi-pair of KTP crystals. We will also report the comparison of the OPO performances between different configurations of diffusion bonded KTP devices.

2. Experiment setup

The schematic diagram of the experimental set-up is shown in Figure 1. The laser cavity (~33cm) is formed by high reflector M1 ($R > 99.5\%$ at $1\mu\text{m}$) and output coupler M2. To prevent optical damage when tuning the OPO cavity, we do not fully lock in the laser power inside its cavity. The OPO utilises Type II, 51° cut, $5\text{mm} \times 5\text{mm} \times 10\text{mm}$, walkoff compensated (WOC) KTP crystals, which are diffusion bonded together. The entrance and exit surfaces of this monolithic DBWOC KTP are AR-coated for both 1079nm and $2000\text{--}2300\text{nm}$. It is mounted on a water-cooled heat sink with indium thermal contacts, and is placed within the OPO cavity formed by mirrors M3 and M1. M3 is AR-coated at $1\text{-}\mu\text{m}$ and high reflective ($R > 99\%$) at $2\text{-}\mu\text{m}$. Besides acting as the rear mirror for the laser cavity, M1 also serves as the output coupler for the OPO. We have experimented with mirrors having $R = 60\%$ to 75% @ $2\mu\text{m}$ for M1. The distance between the surface of the laser rod and M2 is 11cm , while the distance between the other surface of laser rod and M1 is 11.5cm . All mirrors used in the experiment are flat. The stable laser cavity mode is derived from the thermal lensing induced in the strongly pumped Nd: YALO rod with its two concave end faces. The KTP OPO cavity is 2.5cm long and placed as near as possible to M1, which is the position of the laser beam waist. The A-O Q-switch is also positioned as near as possible to M2 in order to hold-off at high laser gain.

The Nd: YALO pumping module consists of a b-axis (Pbmn) cut, 4-mm diameter by 97-mm -long water-cooled Nd: YALO rod side-pumped by five close-coupled cw diode arrays [11]. Its end surfaces are curved (ROC = -0.3meter). The rod is aligned with its c-axis parallel to the vertical axis. The output of this 1079nm laser is polarised along the c-axis. The maximum diode pumping power available is approximately 570W .

3. Experimental results

3.1 Maximum Intracavity OPO

We did the experiment for such CW Nd: YALO laser in order to verify the loss of such DBWOC device. The distance between the M2 and the Nd: YALO rod is 12cm , and the distance between the M1 and the other end of Nd: YALO rod was 11.5cm . Without KTP crystal and M3, the highest 1079nm output power at 6.22kHz is 67W for Q-switched operation. This is obtained with $R = 80\%$ @ 1079nm for M2, while the CW output power is $\sim 100\text{W}$. When we placed the KTP crystal and M3 inside the laser cavity but without the OPO functioning (by changing M1 to a mirror with HR for $1\text{-}\mu\text{m}$ and AR for $2\text{-}\mu\text{m}$), the 1079nm output power slightly dropped to 62W at 6.22KHz . This shows that our DBWOC KTP intracavity OPO does not introduce much optical losses. We have the similar situation with the two pair of DBWOC KTP device.

Firstly, we would like to discuss about the performance of one pair of DBWOC KTP OPO. The arrangement of one pair of DBWOC scheme is shown in Figure 2. The bonded KTP crystals are placed inside the Nd: YALO laser cavity with its walk-off plane perpendicular to the c-axis of the Nd: YALO rod. We operated the $2\text{-}\mu\text{m}$ OPO with different M1's reflectivities ($R = 60\%$, 70% and 75% @ $2\text{-}\mu\text{m}$) and achieved highest $2\text{-}\mu\text{m}$ average output power (both signal and idler) of 23.5W at 6.2KHz with $R = 70\%$ @ $2\text{-}\mu\text{m}$. The exact wavelengths for the signal and idler waves are measured to be 2153nm and 2166nm and they are reasonably close to the degenerate wavelength of 2158nm . It is worthwhile to highlight the subtle advantage of pumping with Nd: YALO laser, as compared to Nd: YAG, which shifts the degenerate point further away from the $2\text{-}\mu\text{m}$ absorption edge of ZnGeP_2 if one intends to use this $2\text{-}\mu\text{m}$ OPO output to pump a ZnGeP_2 OPO subsequently. The measured FWHM linewidth for both signal and idler waves are $\sim 6\text{nm}$. This is comparable to what we have observed with a single KTP crystal OPO (4nm to $\sim 10\text{nm}$) reported in Ref. [4] which clearly indicates the precision of cutting and polishing when binding the crystals together. All these wavelength results are measured using an ORIEL Model: MS 257 monochrometer.

Figure 3 shows the 2- μm output power versus the diode pumping power with reflectivity of $R=70\%$ for M1. The maximum 2- μm average OPO power obtained is 23.5W, with 19W of 1- μm coming out from the laser output coupler, M2 ($R=95\%$ @ 1- μm), when the diode pumping power is 570W. This was obtained when the laser was Q-switched at 6.2kHz. Even without locking in the full laser intensity inside the laser cavity, we have demonstrated an OPO efficiency of 39%, with respect to the maximum achievable 62 W of 1- μm from this laser (at this particular repetition rate). By varying the repetition frequency from 3.5 KHz to 8 KHz, the 2- μm OPO power peaks at 6.22kHz and stays above 16W for this entire frequency range. We observed the OPO threshold almost coincides with the laser threshold. This proves the low threshold of intracavity OPO, which gives ease of access to OPO compared with extracavity configuration. Moreover, the 2- μm output is much more stable than our previous experiment [4] and we do not observe any long-term drift after more than 1-hour of operation. The instability is $\sim 0.4\%$ within 1 minute. We also didn't suffer the non-repeatable operation of OPO with this configuration, hence, we believe this novel configuration provides high potential possibility for commercialisation of high power OPO device.

The measurements of 1- μm and 2- μm pulsewidths are carried out with a fast ORIEL InGaAs detector and HgCdZnTe detector, respectively. At the highest 2- μm OPO power, the pulsewidths (FWHM) of the 2- μm and 1- μm laser pulses are around 73.5ns and 80.1ns, respectively. The pulse shapes of both 1- μm and 2- μm are shown in Figure 4. We have also measured the M^2 values for both 1- μm and 2- μm outputs (at the 2- μm OPO power of 23.5W). This is done by focusing the beams with a $f=20\text{cm}$ lens, sampling the second moment diameters along various positions with the Spiricon Beam Analyser (Model LBA-300PC) and then fitting these data with the standard beam propagation equation. The M^2 values for 2- μm are 16.2 (vertical) and 8.5 (horizontal), while the M^2 values for 1- μm are 20. (vertical) and 16.2 (horizontal), respectively. The better M^2 for 2- μm in the horizontal axis is expected due to the more stringent phase-matching requirement in the walk-off plane. The better OPO beam quality as compared to the laser beam quality indicates that the lower order laser transverse modes (which have better beam quality) generate the OPO output more efficiently than the higher order ones. To support this, we have also measured the laser beam quality without the OPO operating and they are 17.3 (vertical) and 15.1 (horizontal). The degradation in the laser's beam quality when we operate the OPO is consistent with the idea that the lowest order laser modes are more efficiently converted to 2- μm radiation.

3.2 Compare of OPO results of two pair of DBWOC KTP OPO with one pair of DBWOC KTP OPO.

We also setup the similar experiment with two pair of DBWOC KTP device, in order to compare with the one pair of DBWOC KTP. The schematic diagram is the same as Figure 1, however, the reflectivity for M2 is with $R=85\%$ @1- μm . We have achieved maximum output power of 9.6W at the maximum LD pumping power, with 49.5W of 1- μm output power, simultaneously. This is also obtained at the repetition rate of 6.2KHz. The output power for both 2- μm and 1- μm versus the LD pumping power is shown in Figure 5. It is also worthwhile to know the temporal behaviour of both 2- μm and 1- μm laser at different LD pumping power. The 2- μm laser doesn't always follow well with the pumping laser. In figure 6, the pulsewidth (FWHM) of both 1- μm and 2- μm versus the LD pumping power is shown. From this figure, we found that the behaviour of this one pair of DBWOC KTP OPO grows stable with the increment of LD pumping power.

We have done experiment with two pair of DBWOC KTP device with the same arrangement as shown in Figure 1. This time, the DBWOC KTP device is bonded with 4 pieces of $5 \times 5 \times 6 \text{mm}^3$ KTP crystal, while the total length of this DBWOC KTP device is 24mm long with $5 \times 5 \text{mm}$ aperture. The detail of the WOC arrangement is shown in Figure 7. The increasing length of such device also help to increase the total gain length, hence, we expect better performance for such OPO device. The Nd: YALO laser cavity is the same as previous one, however, the OPO cavity length is $\sim 30\text{mm}$ due to the long DBWOC KTP crystals. We have achieved almost the same CW output for the 1- μm laser. This indicated the loss due to more KTP crystals is very low, as well as good quality of these two pair of DBWOC KTP device. From the other point of view, the compact Nd: YALO laser design also allows more tolerance of loss and thermal effect that may be caused by the intracavity elements, such as this DBWOC device. We have achieved 17.2W of 2- μm output power at the maximum LD pumping power, together with 48W of 1- μm output power from mirror M2. This is obtained at the repetition rate of 6.2KHz. Figure 8 show the 2- μm and 1- μm laser output power versus the LD pumping power for these two pairs of DBWOC KTP

OPO. Comparing with the performance of OPO with one pair of DBWOC KTP, we have ~78% increment at the maximum LD pumping power. The pulsewidth (FWHM) of both 2- μm and 1- μm versus the LD pumping power is also shown in Figure 9, which behaviours more dynamically than one pair of DBWOC device.

4. Conclusion

In this paper we have obtained 23.5W of 2- μm intracavity OPO output and, to the best of our knowledge, this is the highest intracavity OPO power reported in the literature. To achieve such high average power 2- μm OPO output in a simple and compact laser system, we have adopted the diffusion-bonded walk-off compensated KTP OPO pumped by the anisotropic Nd: YALO laser. Using Nd: YALO laser to pump OPO itself is new attempt that offers good potential in generating high power compact tunable laser source. We also reported the increment of performance of such device by increasing from one pair to two pairs of DBWOC crystals, however, the behaviours with more pairs of DBWOC device are more dynamical and further study is needed.

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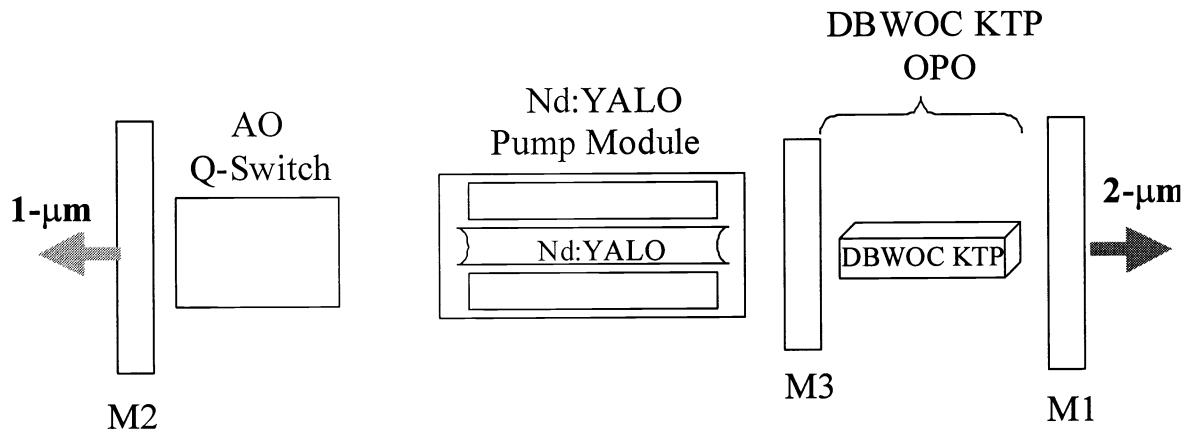


Figure 1: Schematic diagram of the intracavity DBWOC KTP OPO set-up.

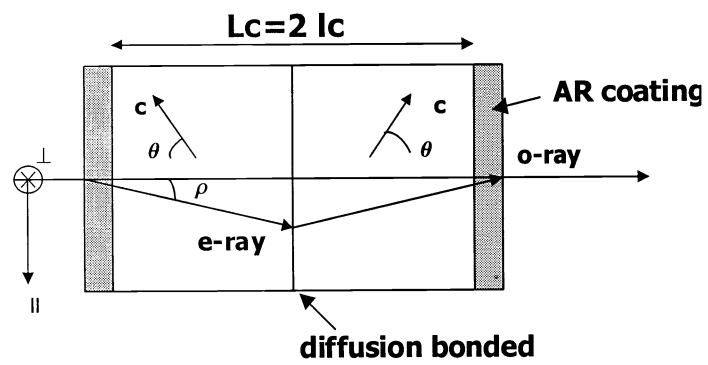


Figure 2 Schematic diagram of one pair of DBWOC KTP device.

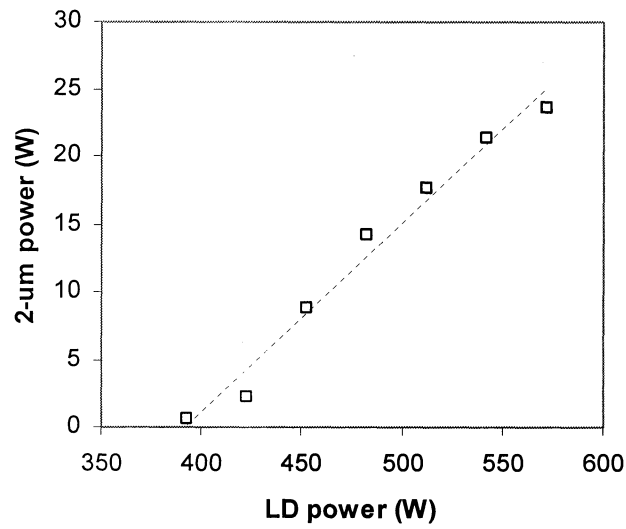


Figure 3. 2- μm intracavity OPO output power versus LD pumping power (W) for one pair of DBWOC KTP OPO device.

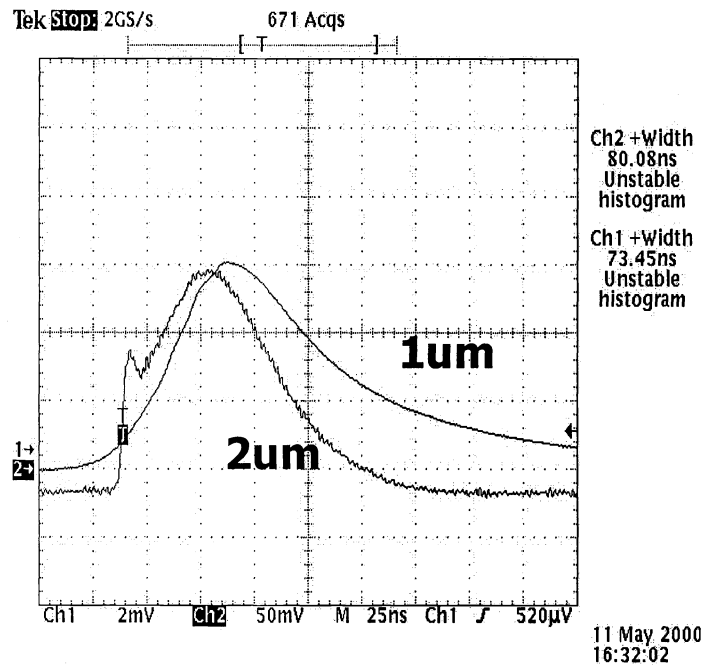


Figure 4 Temporal profile of 2- μm and 1- μm at the maximum 2- μm output power.

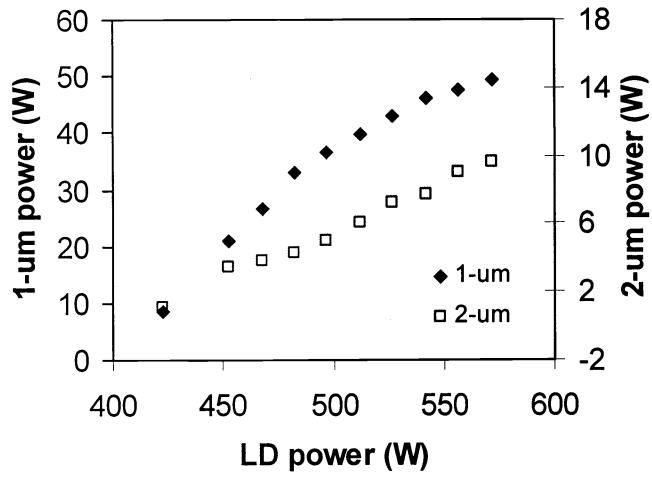


Figure 5 2- μm and 1- μm output power of one pair of DBWOC KTP OPO versus the LD pumping power with $R=85\%$ @ 1- μm for mirror M2.

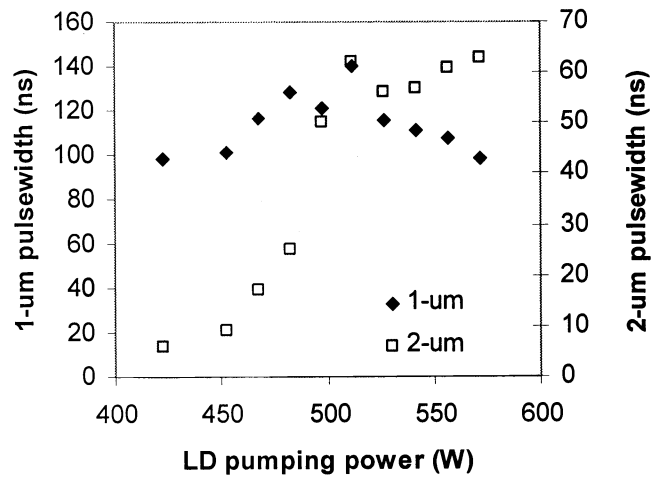


Figure 6 2- μm and 1- μm pulsewidth from one pair of DBWOC KTP OPO versus the LD pumping power with $R=85\%$ @ 1- μm for mirror M2.

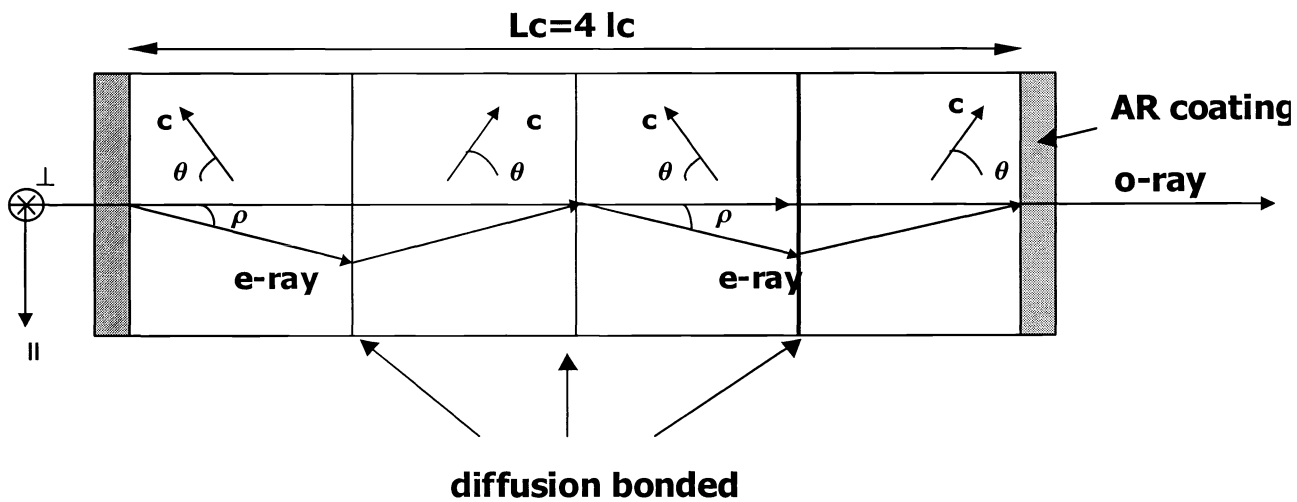


Figure 7 Schematic diagram of two pairs of DBWOC KTP device.

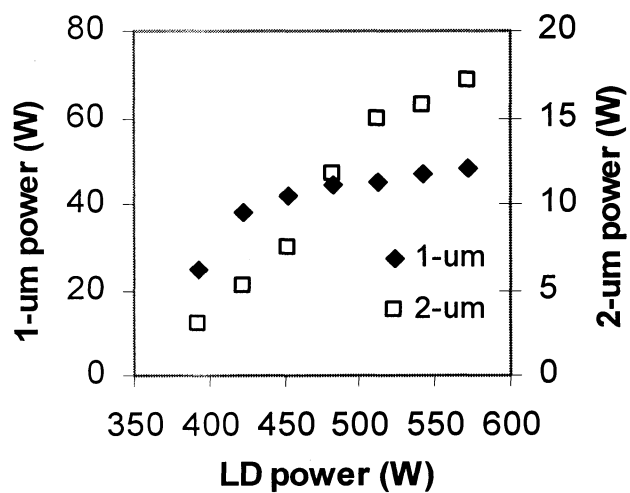


Figure 8 2-um and 1-um output power versus LD pumping power from two pairs of DBWOC KTP OPO with $R=85\%$ @ 1- μm for mirror M2.

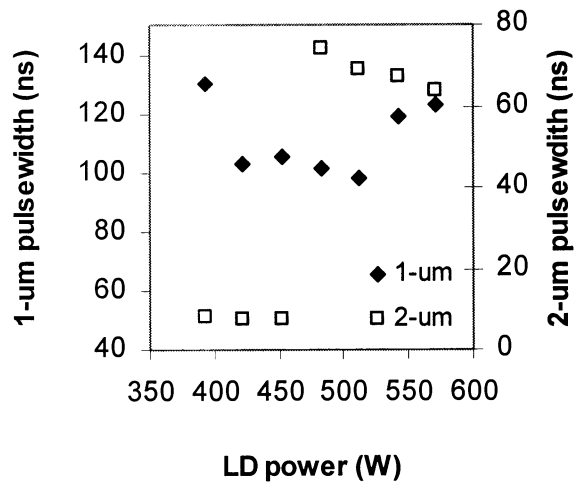


Figure 9 2- μm and 1- μm pulsewidth for two pair of DBWOC KTP OPO versus LD pumping power with $R=85\%$ @ 1- μm for mirror M2.