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Development of Optical Parametric Oscillator Tunable in the Range 970-1460 nm

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ABSTRACT

Optical parametric oscillator (OPO) tunable in the range 970-1460 nm has been developed using bet barium borate (BBO) crystal as the gain medium and second harmonic of Nd:YAG laser as pump source. Two sets of resonators were used to cover the range; first was nearly-degenerate (970-1180 nm) and the second was non-degenerate (1240-1460 nm). The measured threshold pump pulse energy was nearly 8 mJ. Maximum signal pulse energy of about 14 mJ was obtained for pump pulse energy of nearly 31 mJ. Power scaling efficiency was about 70 per cent. The signal pulse width was ~5 ns corresponding to the pump pulse width of ~ 9 ns. OPO signal beam quality was Gaussian, although the pump beam was top-hat multimode.

Keywords: Nonlinear optics, second harmonic generation, optical parametric oscillator, nanosecond OPO, synchronised OPO

1. INTRODUCTION

Optical parametric oscillator (OPO) is one of the most promising options for alternate tunable coherent radiation source as compared to the fundamental tunable laser sources. The development of OPO is a major field of research in laser technology. The wide tuning range, high efficiency, and capability of generating high peak and high average powers make the OPO sources attractive for many applications. The typical range of tunability of solid state lasers such as titanium:sapphire is about 200 nm, whereas OPOs can be tuned to a range > 3000 nm. The maximum pulse energy obtained from OPO is of the order of 100 mJ, whereas lasers can provide optical pulse energies more than 400 J. As spectral source, both are competing, linewidth reduction can be obtained in both OPO and laser sources. A linewidth < 0.5 cm^{-1} can be easily obtained in both. Pulse width of 4 fs has been reported in OPO. Infrared OPOs tunable in the range 2–20 μm play a particularly important role as these belongs to the 'molecular fingerprint' region of the spectrum. The molecular species have their fundamental absorption features in this range, and there is a lack of broadly tunable fundamental lasers similar to dye lasers in the visible, or titanium:sapphire in the near-infrared. The broad tuning range of optical parametric oscillators and efficient power conversion characteristics make them attractive sources in many applications such as physics, astronomy, spectroscopy, laser isotope separation, material diagnostics, material processing, free space communications, trace gas and vapour detection, remote sensing (lidar, ranging and designation), defence and biomedical.

Giordmaine and Miller[1] demonstrated the first OPO in 1965, using a $LiNbO_3$ crystal. The transition from being a research curiosity to an actual tool in real applications of OPO has happened due to many factors including the advent of novel nonlinear optical materials with low optical losses and high laser damage thresholds. Periodically structured nonlinear optical materials revolutionised nonlinear optics by enabling devices with extremely low pumping thresholds. Dramatic improvement in the optical quality of semiconductor materials having intrinsically very high second-order optical nonlinearities and deep mid-IR transparency made it possible to extend the tuning range of existing optical parametric oscillators far beyond 5 μm. The advances in high peak power all-solid-state pump lasers, including microchip and fibre lasers, and new OPO optical designs including cascaded OPO schemes, optical parametric generator (OPG), optical parametric amplifier (OPA) designs, etc. are also important.

There are different types of OPO depending on the pump sources and applications. Continuous wave (CW) OPOs[2,3] are important for high resolution spectroscopic application. But it requires very high pump power to overcome the threshold of OPO which poses threat for the damage of the crystal and optics in the OPO cavity. Thanks to the availability of periodically poled crystals, smart cavity configurations and the single longitudinal mode pump sources have made feasible the low threshold CW OPO sources.

Pulsed OPOs are of two types: Nanosecond[4, 5] and synchronised OPOs[6]. Synchronised OPOs work in the picosecond and femtosecond pulse regimes. As such, the cavity optics and the crystals are not prone to damage. Threshold pulse energy is also very low. Linewidth reduction mechanisms are not effective in this regime, limiting their use in high-resolution spectroscopic applications.

Nanosecond OPOs are particularly suitable for spectroscopic application as these provide low linewidth tunable output with large pulse energy. Short cavity length poses a technical challenge in incorporating the linewidth reduction

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elements in the cavity. Vodopyanov[7], *et al*. demonstrated an $AgGaS_2$ optical parametric oscillator with a tuning range of 3.9-11.3 µm[7]. The singly resonant, angle-tuned OPO was formed by two flat mirrors and OPO linewidth was ~ 1 cm^{-1} with the quantum conversion efficiency of 22 per cent. In 2000, the same group[8] reported the singly resonant, angle-tuned *ZGP* OPO pumped by 100 ns erbium laser pulses at 2.93 µm to obtain continuously tunable output in the range 3.8-12.4 µm. The OPO pump threshold was < 1 mJ in the whole 4-12 µm range of the output and the maximum conversion efficiency reached 35 per cent. In 2009, Das[9] reported tunable mid-infrared radiation in 3-5 µm spectral range in KTA crystal. Maximum energy obtained at 3.6 µm radiation with a grating having grooves density 85 l/mm was 4.6 mJ when the cavity was pumped by 42.6 mJ energy. The conversion efficiency from pump beam energy to generated idler beam energy was 10.8 per cent and maximum slope efficiency achieved was 23.6 per cent.

The development of a ns OPO pumped by the second harmonic of a Q-switched Nd:YAG laser was reported in the present work. A maximum conversion of 46 per cent was achieved in a BBO-based OPO. Although the spatial mode of pump laser was multimode, the OPO output beam mode is perfectly Gaussian in shape.

2. EXPERIMENT

The complete schematic experimental set-up is shown in Fig. 1. An electro-optically Q-switched *Nd:YAG* laser emitting radiation at 1064 nm was used as the master pump source for OPO. A type-I cut LBO crystal (5×5×15 mm) of length 15 mm was used for the second harmonic generation. The energy of the laser was controlled using an attenuator (combination of λ/2 plate and Glan polariser). The beam diameter of the pump radiation was reduced to 2 mm from 6 mm by Galilean telescopic arrangement (Fig.1 (a)). The second harmonic radiation was separated from the fundamental with the help of dichroic mirror (HR@45°@532 nm). The reflected 532 nm radiation from the dichroic mirror was cleaned from the trace amount of 1064 nm radiation by a BG-38 filter before launching into the OPO cavity. Another dichroic mirror (HR@45°@532 nm) was placed inside the OPO cavity to couple the pump beam onto the BBO crystal, which was used as the gain medium for the OPO. Undepleted pump radiation was blocked with a dumper placed outside the OPO cavity, as shown in Fig. 1(b). OPO cavity consists of a highly reflective (99.9 per cent) curve mirror (ROC-500 mm) and a plane output coupler having reflectivity 70-90 per cent at generated OPO signal wavelength. OPO output is characterised in terms of energy, linewidth, pulse-width, etc. with the help of energy meter (Newport Energy Meter, 841-PE), monochromator (Oriel-74001, USA), CCD camera (WinCam D), fast *InGaAs* photodiode and digital oscilloscope (Tektronix, TDS 3054B). The signal radiation was separated from the pump beam at the outside of the cavity using a dichroic mirror having high reflectivity at 532 nm radiation and 90 per cent transmission for the signal wavelength (Fig.1(c)). A colour glass filter (OG550) was used in the signal path to get rid of any trace amount of

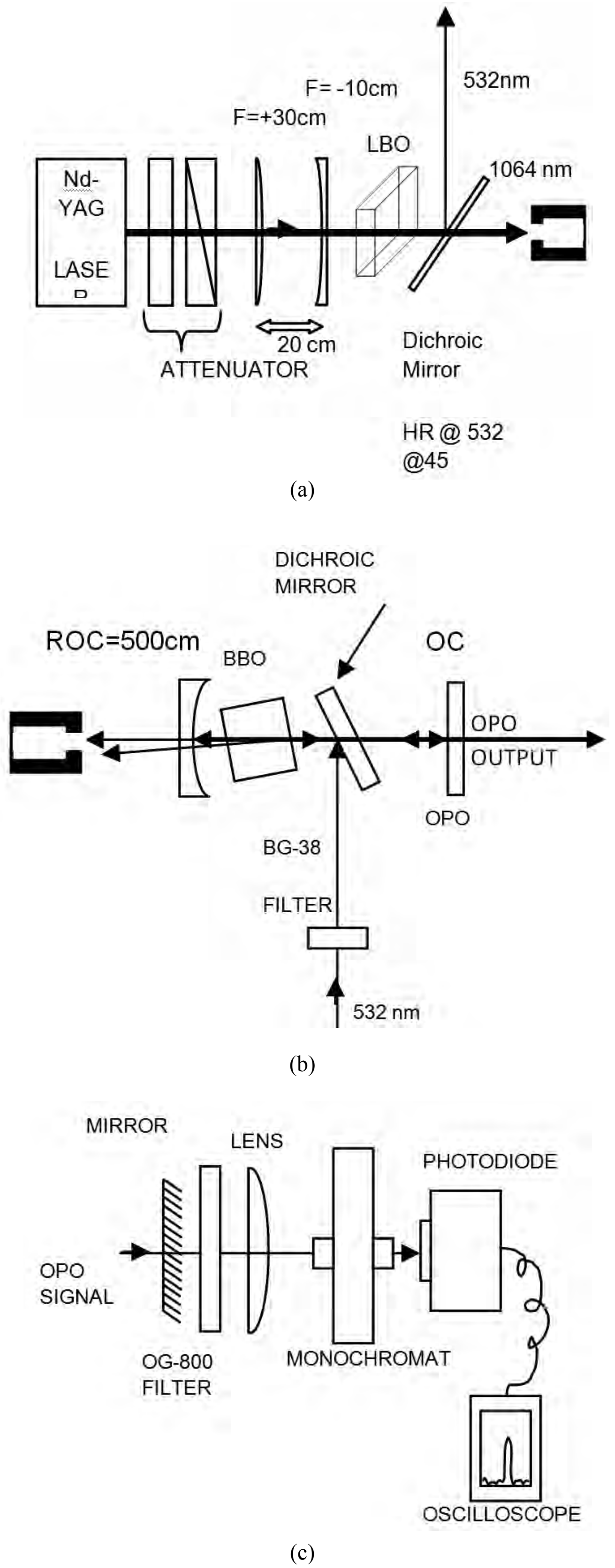
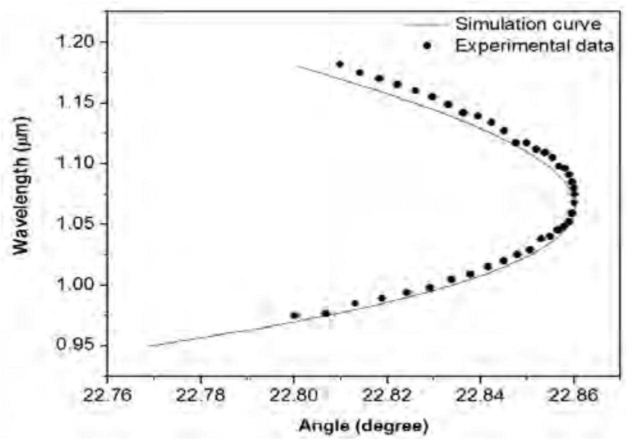


Figure 1. Schematic diagram of the experimental set-up. (a) set-up for the pump source at 532nm, (b) set-up for the OPO cavity, and (c) set-up for the detection of OPO signal.

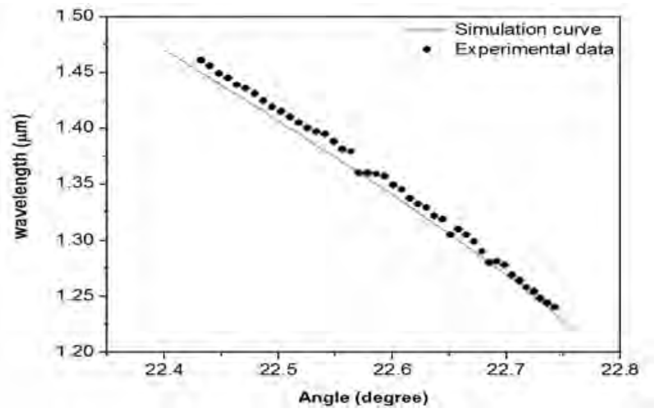
pump radiation before measuring the power and wavelength of OPO signal. The OPO signal was focussed at the input slit of the monochromator with a plano-convex lens of focal length 10 cm for the measurement of linewidth and bandwidth. An *InGaAs* photodiode was placed at the output slit of the monochromator to detect the output signal radiation. To know the energy of the OPO pump pulse, a reference beam was taken out with a glass plate immediately after the second harmonic generation in LBO crystal (Fig.1(a)). The energy of the OPO signal as well as the pump pulse was measured by an energy meter. The OPO was set-up for both the nearly-degenerate and non-degenerate regimes. A BBO crystal (6×6×12 mm) with anti-reflection coated (both at 1064 nm and 532 nm) was used to cover both the degenerate and non-degenerate regimes. The crystal was cut for SHG of 1064 nm, i.e., $\theta = 22.8°$ and $\phi=90°$. The tuning in generated signal wavelength was carried out by rotating the crystal in the horizontal plane. In nearly degenerate case, the cavity mirrors had reflectivity in the spectral range of 970-1180 nm while in non-degenerate case, it was from 1220-1460 nm. The cavity mirrors were adjusted for the optimum output whenever the crystal was rotated for tuning the signal wavelength.

3. RESULTS & DISCUSSION

The measured phase-matching angle for the OPO and the corresponding signal wavelength are plotted in Figs 2(a) and 2(b). The total tuning range achieved was 970-1460 nm using two sets of cavity mirrors. The solid curves in the Figs 2(a) and 2(b) were the calculated ones whereas the dotted points were experimental measurement data. It is evident from the curves that the experimental results are in good agreement with simulation. The OPO signal pulse energy was measured with varying pump pulse energy and the same is plotted in Figs 3(a) and 3(b) for the degenerate and non-degenerate OPOs, respectively. The maximum degenerate OPO output (signal + idler) pulse energy obtained without damaging the cavity optics was 14.8 mJ corresponding to the pump pulse energy of 31.9 mJ. The efficiency achieved in degenerate OPO configuration was about 46.6 per cent with the output coupler reflectivity of 70 per cent. The slope efficiency was approximately 70.3 per cent. While in case of non-degenerate OPO, the maximum efficiency achieved was 9.8 per cent and the slope efficiency was 18.7 per cent. Such a marked difference in conversion efficiency between the degenerate and non-degenerate OPOs is due to the fact that the degenerate OPO

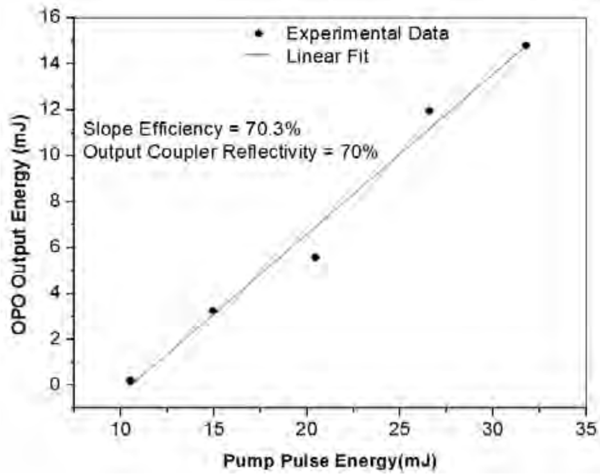


(a)

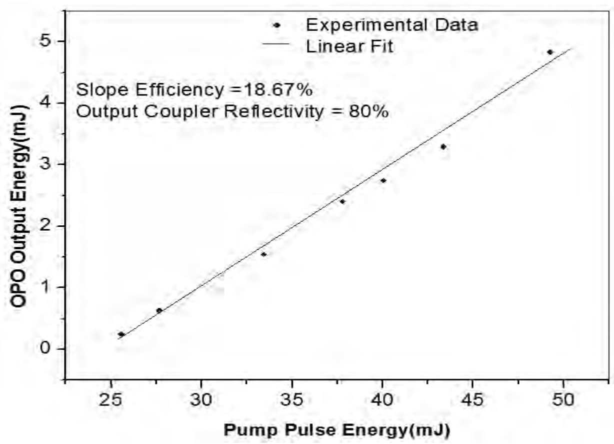


(b)

Figure 2. (a) Wavelength tuning curve of OPO for degenerate case, and (b) wavelength tuning curve of OPO for non-degenerate case.



(a)



(b)

Figure 3. (a) Energy scaling of OPO in degenerate case, and (b) energy scaling of OPO in non-degenerate case.

is doubly resonant OPO (DRO) whereas the non-degenerate OPO is singly resonant OPO (SRO). The threshold pump pulse energy for the nearly degenerate OPO was 8.1 mJ corresponding to the energy fluence of 0.52 J/cm^2. The output of the OPO was measured with output couplers of varying reflectivity (Fig. 4).

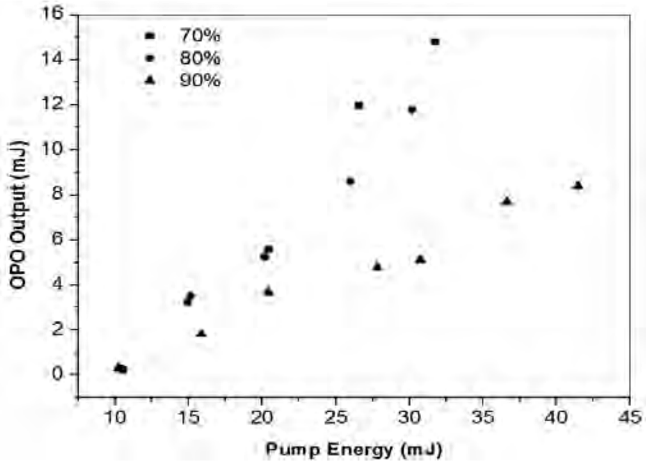
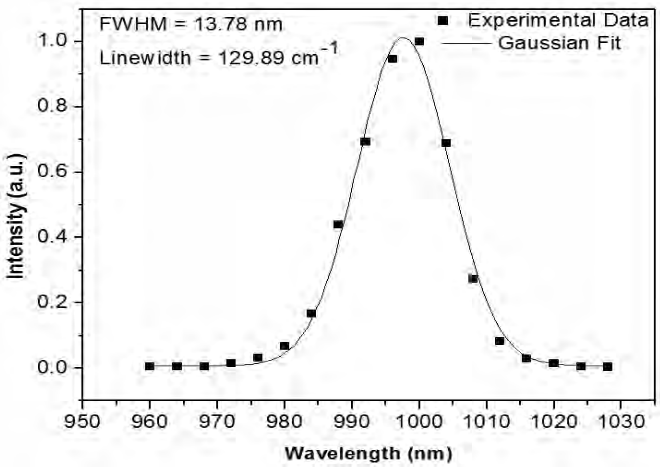
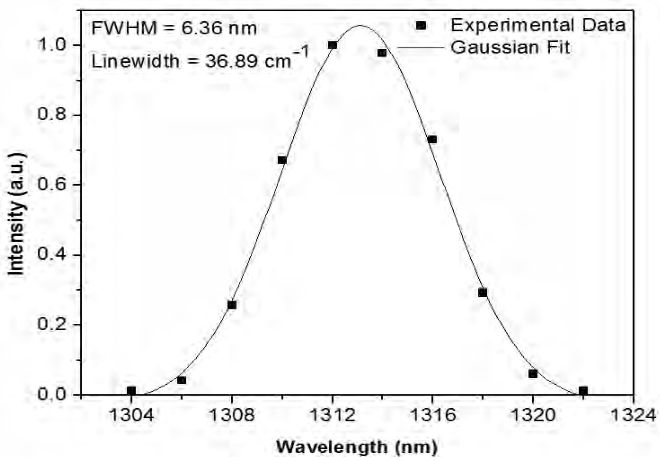


Figure 4. Energy scaling of OPO at different reflectivity for degenerate case.



(a)

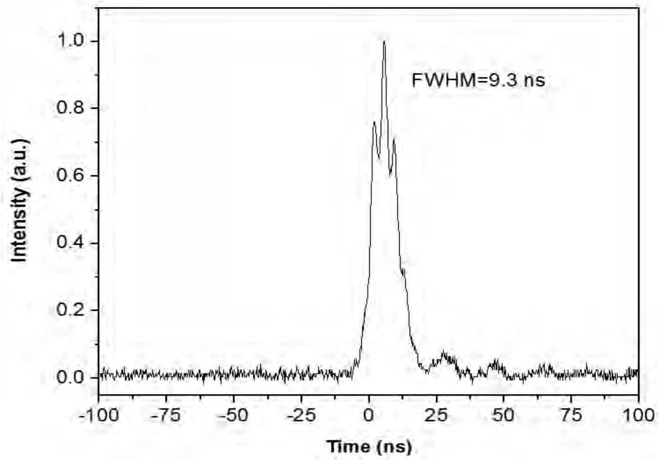


(b)

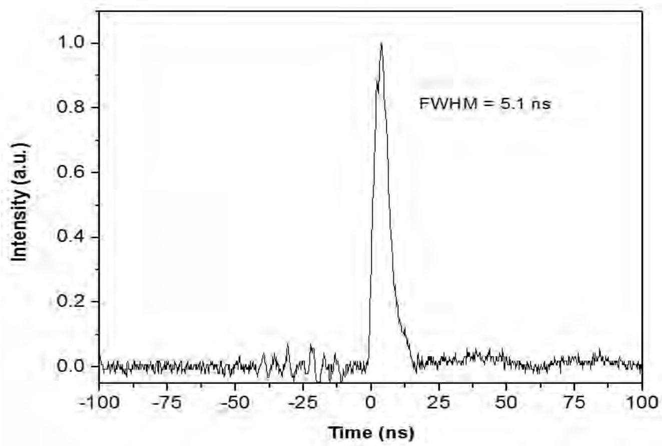
Figure 5. (a) Linewidth of OPO signal in degenerate case, and (b) linewidth of OPO signal in non-degenerate case.

It is evident from the figure that the output energy of the OPO radiation increases with the increase in output coupling for the range used in this measurement. However, the threshold of the OPO decreases with the increase in reflectivity of the output coupler as the cavity loss decreases. In case of non-degenerate OPO, the threshold pump pulse energy was 20.3 mJ corresponding to the energy fluence of 1.3 J/cm^2.

The measured linewidth of the OPO signal is plotted in Figs. 5(a) and 5(b) for the degenerate and non-degenerate OPOs, respectively. In degenerate case, the linewidth is as broad as 130 cm^{-1} (Fig. 5(a)) while it is 6.36 nm or 36.7 cm^{-1} in non-degenerate case (Fig. 5(b)). The OPO signal pulse and the pump pulse was detected by a high-speed *InGaAs* PIN photodiode and was traced in a 500 MHz oscilloscope. The pulses recorded in the digital storage oscilloscope for the pump and the non-degenerate OPO signal is plotted in Figs. 6(a) and 6(b). The pulse-width of the pump radiation was 9 ns whereas the width of OPO signal pulse was 5 ns. Such a sharp difference is due to the fact that the wings of the pump pulse have energy below the threshold for the OPO oscillation. The variation of OPO threshold with the pulse-width of the pump radiation is plotted in Fig. 7. The pulse width of the pump radiation is changed by changing the delay between the flash-



(a)



(b)

Figure 6. (a) Pulse width of pump radiation, and (b) pulse width of OPO radiation.

lamp excitation pulse and Q-switch trigger pulse. It is clear from Fig. 7 that the threshold decreases with the decrease in width of pump pulse. But for very short pulse, OPO threshold increases because of build-up time of the OPO signal in the cavity, i.e., the generated OPO signal does not get sufficient time to build-up in the cavity. The beam profile of OPO signal was also compared with the Nd:YAG pump laser beam. In this regard, the measured beam profile of both the pump and signal beam with a CCD camera in the near-degenerate interaction is shown in Figs 8(a) and 8(b). In spite of the multimode top-hat pump beam profile, the OPO signal is Gaussian in nature.

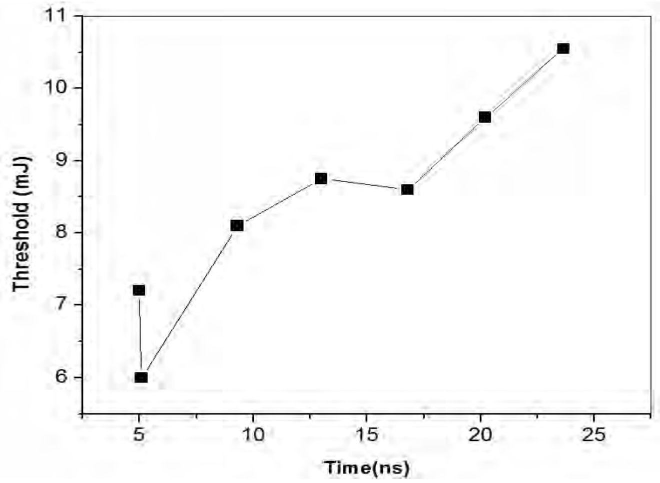
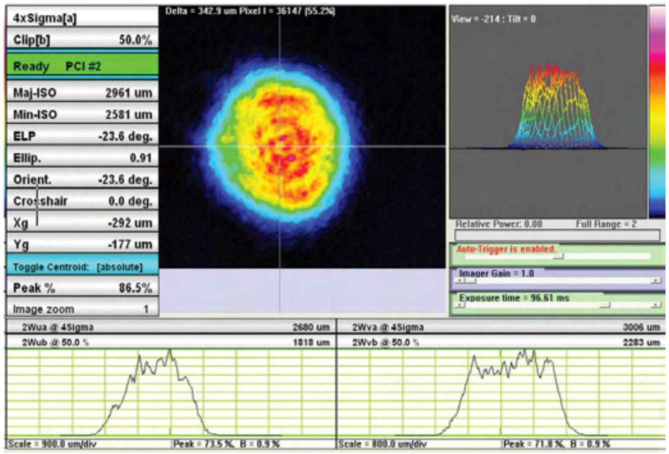
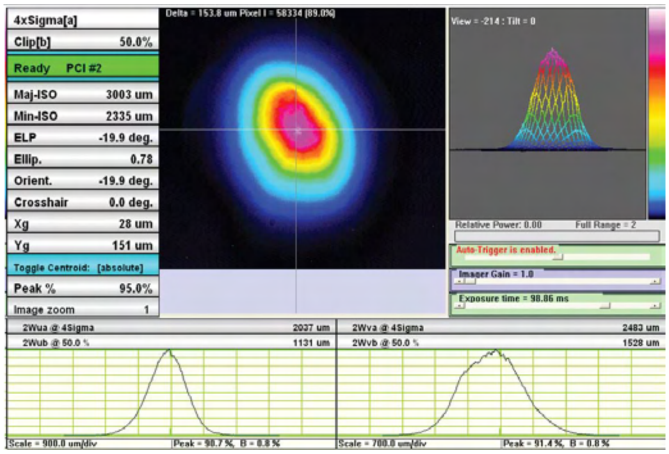


Figure 7. Variation of OPO threshold with the pulse-width of the pump radiation.



(a)



(b)

Figure 8. (a) Beam profile of pump, and (b) beam profile of OPO.

4. CONCLUSIONS

The BBO-based OPOs are set-up to generate tunable coherent radiation in the range 970-1460 nm. An overall conversion efficiency of 46 per cent is obtained in case of degenerate OPO. The generated signal is very stable and useful for spectroscopic applications. The linewidth of the non-degenerate OPO output is about 6 nm, whereas, the degenerate value is about two times of it. The beam quality of the OPO signal is Gaussian although the pump beam is multimode top-hat type.

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