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Nanosecond Eye-Safe Laser Generation by KTP- Based Optical Parametric Oscillator

Sa'ad Y. Jasim (1) **Mazin M. Elias** (2) and **Fadhil A. Umran** (2, 3)

(1) *College of Science, University of Baghdad, Jadiriah, Baghdad, IRAQ.* Diseased
(2) *Institute of Laser for Postgraduate Studies, University of Baghdad, P.0. Box 47314 Jadiriah, Baghdad, IRAQ e-mail: mazinmanuel@hotmail.com*
(3) *College of Engineering, University of Baghdad, Jadiriah, Baghdad, IRAQ*

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Abstract: In this work, an eye-safe laser at 1.57 µm wavelength was generated using an extra-cavity type and singly resonant optical parametric oscillator with a return pump beam configuration. It is based on a nonlinear optical crystal, KTP, which is oriented in a non-critical phase matching. Optical parametric oscillator (OPO) was pumped by a Q-switched Nd:YAG laser at 1.064 µm of 40mJ output energy and 30 ns pulse duration. The KTP- based OPO crystal was designed and constructed with a cavity length of 3.8 cm for maximum output energy. Laser pulses at 1.57 µm were obtained with output energies of 1.7 to 12 mJ for pump energies of 6 to 32 mJ. The signal-to-pump energy conversion efficiency up to 37% was achieved from the OPO when the Q-switched Nd:YAG laser is higher than 1 mJ. The overall (signal and idler) conversion efficiency reached 55%.

Introduction

Optical parametric oscillation is an important second–order nonlinear optical process for solid state lasers [1]. It is a convenient method to create a wide tunable laser source. Unlike conventional lasers, there is no population inversion involved in the parametric frequency conversion process, as it does not depend on any form of atomic or molecular transition [2]. An OPO begins with a pump laser. In many cases the pump laser is a solid- state laser such as Nd: YAG laser or its harmonics. To complete the system, a nonlinear crystal between a set of mirrors is required. As such, OPO by itself is an extremely simple device. Any wavelength longer than the pump wavelength and nominally within the transparency region of the nonlinear crystal can be generated [3]. The wavelengths of operation may be varied by changing the temperature or angular orientation of the crystal [4].

Simply stated, parametric oscillator splits one pump photon into two photons which satisfy conservation law of energy at every point in the nonlinear crystal [5]. To satisfy conservation of energy, the sum of the energy of the two created photons must equal the energy of the pump photon. With the energy of a photon of frequency w given by $\hbar w$, the conservation of energy can be written as $\omega_3 = \omega_1 + \omega_2$ where ω_3, ω_1 and ω_2 are the frequencies of the pump source, the signal and idler waves respectively. The specific idler and signal frequencies are usually determined by phase- matching [6].

The energy or power between the signal and idler is divided according to the ratio of the photon energies as [7]

$$\frac{E_s}{E_i} = \frac{l_i}{l_s} \qquad (1)$$

where Es and Ei are the energy of the signal and idler wavelengths respectively. The total output energy is ET = Es + Ei , hence the signal energy can be calculated from

$$E_s = \frac{E_T}{1 + \frac{l_s}{l_i}} \qquad (2)$$

Since the construction of the first tunable OPO by Maine et al. [8] in 1965, many other experimental works were reported as summarized in Table 1. This work aims to design, construction and generation of an eye safe laser radiation with as high as possible signal-to-pump energy conversion efficiency using KTP-based OPO extra-cavity, singly resonant with return pump beam configuration pumped by Q-switched Nd:YAG laser. The fundamental wavelength (1.064 µm) is converted into a signal wavelength (1.57 µm) and an idler wavelength (3.3 µm

Table 1: Historical review of some investigations in OPO.

Author (s), Year, Ref.	Pump Source	Nonlinear Crystal	Signal Wavelength (µm)	Signal Conversion Efficiency
Ammann et al. 1969 [9]	Q-switched Nd:YAG	$LiNbO_3$	2	8%.
Herbst et al. 1974 [10]	Q-switched Nd:YAG	$LiNbO_3$	1.4	15%
Fan et al. 1988 [11]	TH Nd:YAG	BBO	0.412	13%
Ebrahimzadeh et al. 1991[12]	SH Q-switched, diode-pumped Nd:YLF	KTP	0.94 1.075	- -
Bortz et al. 1994 [13]	Ti: Sapphire	LiNbO3	1.55	18%
Hellstron , 1994 [14]	Q-switched Nd:YAG	PPKTP	1.72	45%
Conroy et al. 1998 [15]	Q-switched Nd:YAG	KTP	1.53	
Yashkir and Driel 1999 [16]	Q-switched Nd:YAG	KTP (Intra-cavity)	1.57	45%
Elder and Terry 2000 [17]	Q-switched diode pumped Nd:YAL	PPL	1.465-1.565	28%
Vodopyanov et al. 2000 [18]	Er:YAG	ZGP	3.8- 12.4	35%
Wu et al. 2001 [19]	Q-switched diode pumped Nd:YALO	KTA	1.5	-
Fragenmann et al. 2003 [20]	Q-switched Nd:YAG	KTP	1.535	30%
Tillman et al. 2003 [21]	Nd:YAG	KTP	1.19- 1.45	35%
REDOPTRONICS Co. 2005 [22]	SH Q-switched Nd:YAG	BBO	0.68- 2.4	30%
Lempert et al. 2005 [23]	TH Nd:YAG	BBO	0.651	12%

Experimental Details

The experimental set-up is shown schematically in Fig. 1. The pump source was a Q-switched pulsed Nd:YAG laser at TEM00 mode with energy of 40 mJ, and pulse duration of 30 ns FWHM. It consisted of Nd:YAG rod of 4 mm diameter and 50mm length and a pulsed xenon flash lamp. Q-switching was achieved using dye foil of BDN-1 type (from ISKRA Co.). The laser was driven using a home-made 1kV pulsed power supply. An extra-cavity type OPO was designed and constructed as a singly resonant cavity with return pump beam.

The resonator was a plane-parallel with reflectivity of 99.9% at 1.57 μm (signal wavelength) and high transmission at the pumping wavelength (1.064μm) for high reflection mirror (M1) and reflectivity of 85%, 99.9% at 1.57 and 1.064 μm respectively for output coupler (M2). The diameter of each mirror was 8 mm. A KTP crystal was placed inside the resonator. In order to minimize losses, the end faces of the crystal were anti-reflected coated at 1.064μm. The spectral bandwidth of the KTP crystal used is between 0.35 and 4.4 μm. Its optical damage threshold is 500 MW/cm^2 at 1.064 μm. This crystal was with (4×4×12) mm dimensions, cut in non-critical angle.

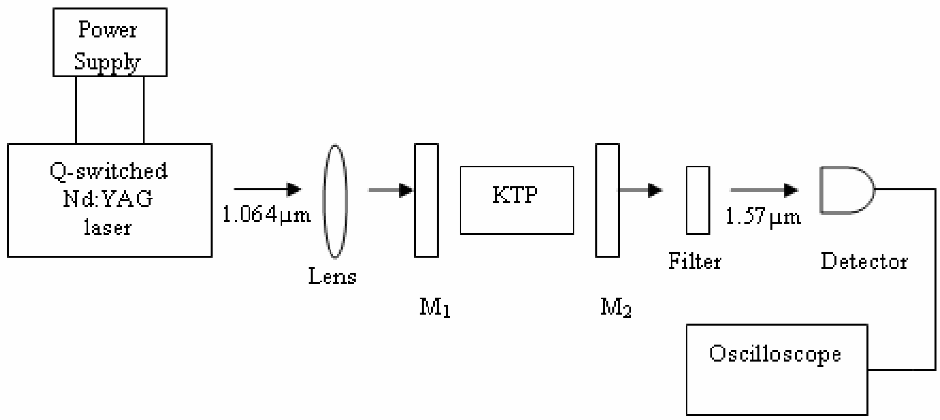

Fig. 1. Schematic of the present experimental layout.

The cavity length of the OPO was calculated to be 3.8 cm according to the threshold condition in a singly resonant OPO, which can be reduced by reflecting the pump radiation for a second pass through the crystal. This creates signal gain on both the forward and backward passes through the crystal as recommended by Koechner [7]. A concave lens of focal length 15 cm was placed between the pumping source and the OPO. The power density was increased and the beam radius had become 112 μm, and thereby 84.6 MW/cm^2 threshold intensity was achieved.

The output energies that represent the total energies of the signal and idler wavelengths were detected by a joule-meter of Gentec type Ed-200 and Ed-100 and monitored using a 40 MHz storage oscilloscope (type HONG HUA model Dss 5040). These signals were checked using a germanium PIN photodiode with radiant responsivity of 700 mA/W, and 0.5 ns risetime. The pulse duration of the signal was 30 ns recorded with a 100 MHz storage oscilloscope (type Tektronics TD 220).

A silicon wafer was introduced between the OPO output and the detector to prevent any wavelength shorter than 1.1 μm.

Results and Discussion

Determination of the pumping energy

The maximum output pulse energy of the pump source was measured, and its value was 40 mJ. The behaviour of the output energy of the Q-switched Nd:YAG laser with the flash lamp energy was observed to be linear and about 0.9 J input energy was found to be enough to derive the laser.

Determination of total OPO energy:

Figure 2 illustrates the relation between the output energy of the total (signal and idler outputs) of the OPO and the pump energy of the laser in the range between 6 to 32 mJ. From the slope of the straight line obtained, the overall energy conversion efficiency was found to be 55 ± 0.15 %.

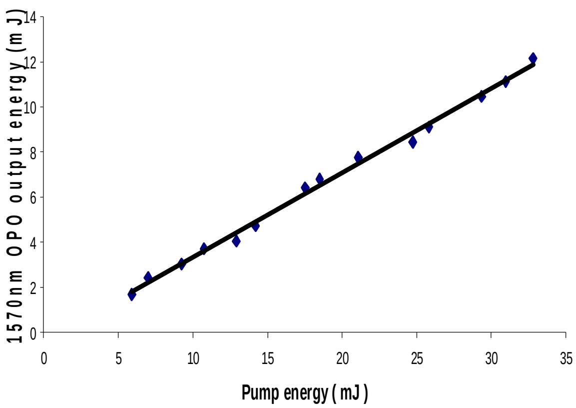

Fig. 2. Input output energy relation of total and signal wavelengths

Determination of 1.57 µm OPO output energy

The energies of the signal and idler wavelengths were calculated from Equ. 2. Figure 3 illustrates the change in the signal (1.57 µm) OPO output energy with laser pump energy. A linear dependence is obtained. The extrapolation of the line at zero pump energy, gives the minimum energy required to produce a 1.57 µm signal. In the present system, the value was 0.98 mJ.

From the slope of the straight line, the signal energy conversion efficiency (signal-to-pump energy) was determined to be 37 ± 0.8 %. This value is in a good agreement with the value 41% obtained by Rines et al. [24] for the extra-cavity OPO based on KTP and Nd:YAG laser. The 45% efficiency of Yashkir and Driel [16] was obtained with intra-cavity type as the losses in energy are usually less than those with extra-cavity types.

Determination of output energy for 3.3 µm idler wavelength

Figure 4 shows the relation between the pump energy and the output energy of idler at wavelength 3.3 µm. A linear dependence is obtained. The idler energy conversion efficiency (idler-to-pump energy) was about 18 ± 0.1%. This small component in the output energy can not be easily detected with the available devices.

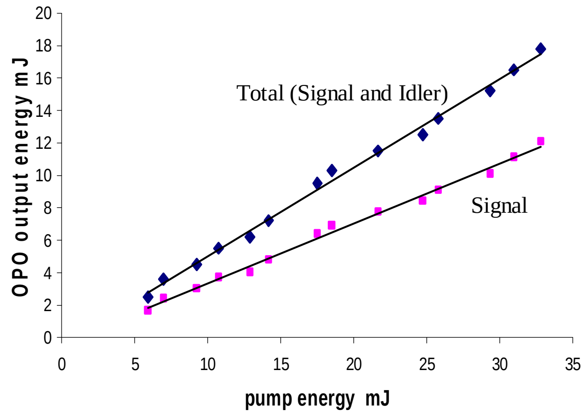

Fig. 3. Input-output energy relation at the signal wavelength

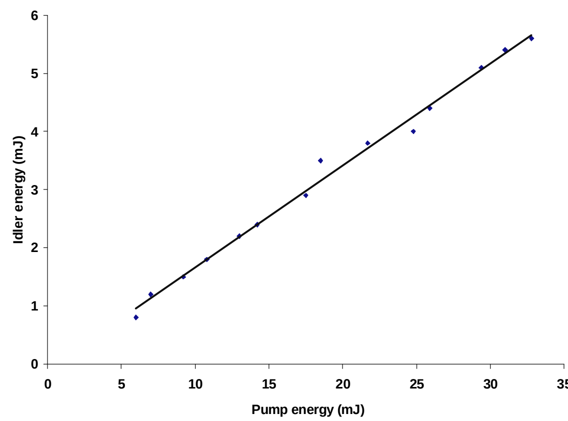

Fig. 4. Input-output energy relation at the idler wavelength

Conclusions

Up to 37% signal-to-pump energy conversion efficiency was achieved from the OPO when the Q-switched Nd:YAG laser is higher than about 1mJ. The overall energy conversion efficiency can reach 55% at this threshold pump energy. The decreasing the OPO cavity length leads to an increase in the conversion efficiency until a limited value

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متذبذب معلمي بصري فعال في مدى النانوثانية بأستخدام بلورة KTP المضخة بليزر النديميوم ياك

سعد ياسين جاسم [1] **مازن مانوئيل الياس** [2] **فاضل عباس عمران** [2،3]

(1) كلية العلوم ، جامعة بغداد ، جادرية ، بغداد ، العراق
(2) معهد الليزر للدراسات العليا ، جامعة بغداد ، جادرية ، بغداد ، العراق
(3) كلية الهندسة ، جامعة بغداد ، جادرية ، بغداد ، العراق

الخلاصة **يتضمن البحث دراسة عملية لتوليد الليزرالآمن للعين ذي الطول الموجي 1.57 مايكرومتر باستخدام التذبذب المعلمي البصري (OPO). وقد استخدم مرنان من نوع الفجوة الخارجية احادي الرنين ذي شعاع ارتدادي وقد اعتمد على استخدام بلورة لاخطية نوع بوتاسيوم تيتانيل فوسفات KTP التي تم وضعها ورصفها داخل المرنان بحيث يصنع الضوء المار فيها زاوية مقدارها صفراً مع اتجاه المحور البصري وبما يسمى توافق الطور غيرالحرج . تم ضخ هذا المرنان بنبضات ليزر النيوديميوم ياك بطول موجي 1.064 مايكرومتر الذي تم بناؤه و تشغيله عمليا بطاقة خارجة بحدود 40 ملي جول وبنبضة امدها 30 نانوثانية . تم تصميم هذا المرنان وبناؤه عملياً بطول 3.8 سم ليكون مناسبا لطاقة الضخ الخارجة من الليزر المستخدم في هذا العمل . فحصت المنظومة وتم تشغيلها وقياس الطاقات الخارجة للطول الموجي المتولد 1.57 مايكرومتر وكانت بين (1.7- 12) ملي جول عندما كانت طاقات ليزر الضخ (6- 32) ملي جول . تمثلت النتائج المتحققة من هذا العمل بنسبة كفاءة تحويل عالية للطاقة بلغت 37% لليزر الآمن للعين (1.57 مايكرومتر) وبنسبة وصلت الى 55% بالنسبة الى مجموع الطاقات الخارجة للمنظومة.**