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# High energy output complex cavity pump optical parametric oscillator in the mid infrared

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**Abstract** The results of experimental study on a complex cavity Nd:YAG laser pumped $LiNbO_3$ crystal optical parametric oscillator(OPO) is reported. Average output pulse energies of 56.4mJ of the OPO and 22.8mJ of the idler at 3097nm were observed with the pulse width of 8ns. The conversion efficiency from 1060nm pumping laser to the OPO output (the signal and idler) was 46% at pulse repetition rates up to 10Hz. The tuning ranges of the OPO obtained by angle tuning the $LiNbO_3$ crystal were 1479nm~1621nm of the signal, and 3097nm~3793nm of the idler.

**Key words** solid-state laser; mid infrared; complex cavity pump; optical parametric oscillator(OPO)

# 中红外高能量输出复合腔抽运光参量振荡器

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摘要: 报道了采用复合腔技术研究 Nd:YAG 激光抽运 $LiNbO_3$ 晶体光参量振荡器(OPO)的实验研究结果。得到OPO输出单脉冲平均能量 56.4mJ, 闲频光(3097nm)脉冲平均能量 22.8mJ, 脉宽 8ns, 抽运光转换成参量光输出效率 46% (重频 1Hz~10Hz)。测得角度调谐的波长范围是: 信频光 1479nm~1621nm, 闲频光 3097nm~3793nm。

关键词: 固体激光; 中红外; 复合腔抽运; 光参量振荡器
中图分类号: TN242 文献标识码: A

## Introduction

The atmosphere visibility at visible or near-visible infrared wavelengths is primarily related to aerosol scattering. Systems operating at 1064nm are affected mainly by molecular absorption. The most promising atmospheric window for long-range applications appears to be 3500nm ~ 4100nm spectral region of the so-called 3000nm ~ 5000nm atmospheric transmission window, in which molecular attenuation and aerosol extinction are moderate. So the opto-electronic countermeasures in the 3000nm ~ 5000nm spectral region attract special attention.

The optical parametric oscillators (OPOs) offer a wide tunable output in the mid infrared region[1~5]. LAVE[4] reported highly efficient low-threshold tunable all-solid-state intra-cavity optical parametric oscillator in the mid infrared. Output energy as high as 640μJ was observed at the idler wavelength of 3700nm, which corresponds to a conversion efficiency of 1.8% from diode light to idler light. In literature [6], the idler output energy of 7mJ/pulse at 5Hz was observed by a $Q$-switched Nd:YAG laser pumped $LiNbO_3$ parametric oscillator.

It is necessary for some experimental tests to have as high output pulse energy/power and high conversion efficiency from pumping laser to OPO output as possible. There are some drawbacks for using intra-cavity or extra-cavity scheme. For obtaining high output pulse energy of the OPO, the complex cavity technology is used to study experimentally on a $Q$-switched Nd:YAG laser pumped singly resonant $LiNbO_3$ parametric oscillator. Average pulse output energies of greater than 56mJ of the OPO, 22mJ of the idler at 3097nm wavelength were observed. The tuning ranges of the OPO obtained by angle tuning the $LiNbO_3$ crystal were 1479nm~1621nm of the signal, and 3097nm~3793nm of the idler.

## 1 Basical laws

The energy conservation law of an OPO is $\omega_p = \omega_s +$

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$\omega_i$, that is, the wavelength relation must be satisfied in nonlinear interaction process of an OPO:

$$1/\lambda_{ep} = 1/\lambda_{os} + 1/\lambda_{oi} \tag{1}$$

where $\omega_p$, $\omega_s$, $\omega_i$ denotes frequency of pumping light, signal and idler respectively, and $\lambda_{ep}$, $\lambda_{os}$, $\lambda_{oi}$ denotes wavelength and polarization correspondingly. The moment conservation law must also be obeyed in nonlinear interaction process of an OPO, that is, $K_p = K_s + K_i$, that also is

$$n_{ep}/\lambda_{ep} = n_{os}/\lambda_{os} + n_{oi}/\lambda_{oi} \tag{2}$$

where $K_p$, $K_s$, $K_i$ denotes wave vector value of pumping light, signal and idler respectively, and $n_{ep}$, $n_{os}$, $n_{oi}$ denotes refraction index at corresponding light transmission direction in nonlinear crystal. This is also the phase matching relation of the OPO, i.e. phase velocity relation of light wave in an OPO. For the Nd:YAG 1064nm laser pumped $LiNbO_3$ crystal and type-I phase-matching, the phase matching angle $\theta_m$ at a certain temperature can be calculated using the formula (1), (2) and Sellmeier's equations[1] of refraction index of crystal. In the experiment the $LiNbO_3$ crystal was cut at $\theta_m = 48°$, $\varphi = -90°$.

## 2 Experimental setup

Experimental setup and measuring scheme are shown in Fig. 1. The flat mirror $M_1$ and $M_2$ consist 1064nm laser cavity and $M_3$, $M_4$ consist a singly resonating cavity of the OPO. The input coupler $M_3$ of the OPO is coated for high transmission ($T > 97.6\%$) at 1064nm, high reflection ($T < 1\%$) at 1400nm ~ 1600nm. The output coupler $M_4$ (CaF substrate) is coated for high transmission ($T > 85\%$) 2500nm ~ 5000nm, high reflection 1300nm ~ 1600nm ($T < 1\% \sim 6\%$) (signal wavelength range) and 1064nm radiation ($T \leqslant 0.25\%$). In order to obtain a high conversion efficiency from pumping source to the OPO output, it is need to increase reasonably pump laser pulse duration so that the signal makes round trip enough times in the OPO. According to the laser $Q$-switching theory[7], a $Q$-switched laser pulse width varies inversely as the ratio $\Delta n_0/\Delta n_t$, the initial population density $\Delta n_0$ to the threshold population density $\Delta n_t$. Therefore, a $Q$-switched YAG laser with low reflectivity mirror $M_2$ at 1064nm, and so with low ratio value $\Delta n_0/\Delta n_t$, is used for reasonable increment of the OPO pumping pulse width, and gaining as high pumping pulse energy output as possible.

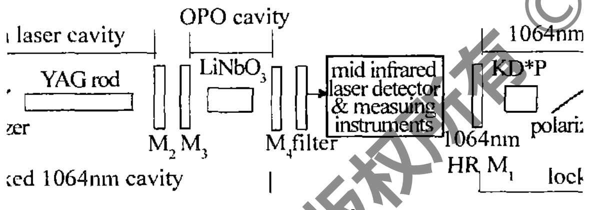

Fig. 1 Experimental setup

In the experiment the YAG laser back-mirror $M_1$ and the output coupler $M_4$ of the OPO simultaneously consist a high reflection cavity at 1064nm. Then, in this locked cavity the 1060nm laser radiation can be output through the $M_4$ only by the OPO conversion into signal and idler. As mentioned above this so-called complex pump cavity OPO is neither an intra-cavity nor an extra-cavity OPO scheme, but it combines both advantages and avoids their drawbacks. This experimental scheme is particularly valuable for obtaining high pulse energy output and a high conversion efficiency from 1064nm to the OPO output. The pulse outputs of the signal 1400nm ~ 1600nm and the idler 3000nm ~ 5000nm spectral region can be simultaneously obtained through $M_4$ depending upon the phase matched situation and the reflective characters of the $M_3$ and $M_4$.

It is also need to use as long nonlinear crystal as possible in permissive distance determined by walk-off angle of the crystal. The 10mm × 10mm × 40mm good quality $LiNbO_3$ crystal with antireflection, antioptic damage coating at the pump and signal wavelengths is used in the experiment.

## 3 Experimental results

The pulse output energies are measured with J25-MAX500 or EPM-2000 laser energy/power meter at the $M_2$ or $M_4$ output respectively. Under the same pumping input condition the Nd:YAG output pulse energies with average value of 122.9mJ and the OPO output pulse energies versus measurement numbers are shown in Fig. 2.

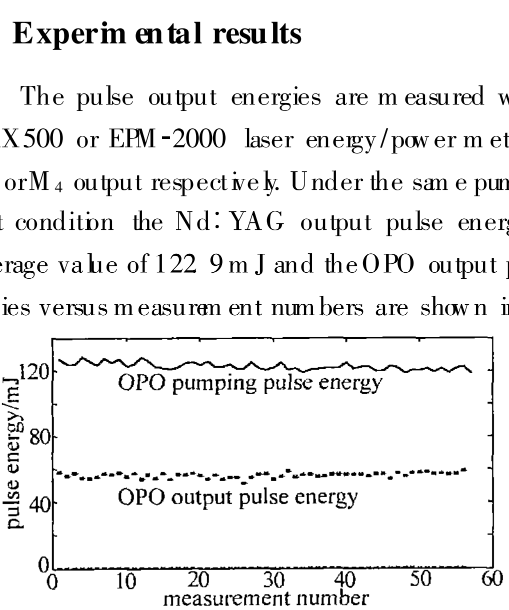

Fig. 2 OPO pumping pulse energy and OPO output pulse energy vs measurement number

The output fluctuations of the former are 4.6% ~ 6.2% and 4.8% ~ 7.0% of the later. By setting a filter, a K9 glass plate or the $M_4$ mirror with the same character at the output of the OPO to cut off above or below about 2700nm light radiation, the signal or idler wave is separated out of the OPO output. The pulse energy measured with the K9 glass plate or $M_4$ mirror filter correspond to the signal or idler output pulse energy respectively. The typical OPO output (signal and idler) pulse energies with the average value of 56.4mJ/pulse and the idler output pulse energies at 3097nm wavelength with average output energy of 22.8mJ/pulse are shown in Fig.3. The measured transmissivity of the OPO output coupler $M_4$ at 1064nm is 0.25%.

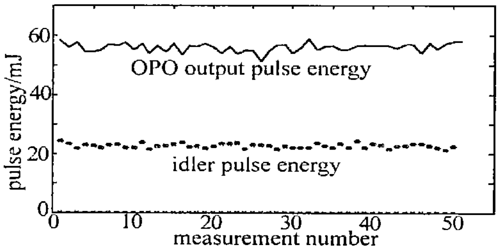

Fig.3 OPO output pulse energy curve and idler (at 3097nm wavelength) pulse energy

Therefore, there is only 0.31mJ at 1064nm in the OPO output pulse energy of 56.4mJ, so the average output conversion efficiency from 1060nm to signal and idler is 56.4/(122.9 − 0.31) = 46%. The results presented in Fig.2 and Fig.3 are taken at a repetition rate of 1Hz. No degradation of the conversion efficiency is observed at repetition rates up to 10Hz.

The pulse traces of the $Q$-switched YAG laser and the signal are separately measured by an InGaAs detector at the output of $M_2$, $M_4$ and a LeCroy LC584A oscilloscope. As shown in Fig.4, Fig.5, the pulse width of the $Q$-switched YAG laser is 20ns, and the signal pulse width is 8ns, which is obviously reduced because of nonlinear parametric interaction process and the OPO threshold condition.

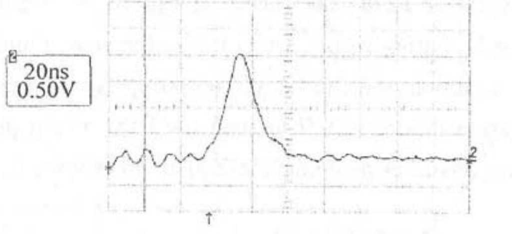

Fig.4 The oscilloscope trace of the OPO pumping laser pulse

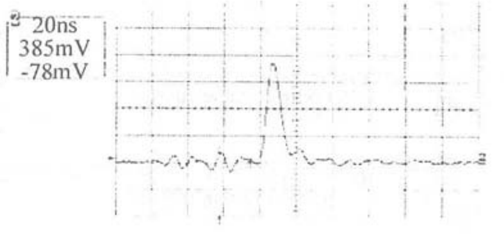

Fig.5 The oscilloscope trace of the OPO signal output pulse

Wavelengths of the signal and idler are measured with WDG30 grating spectrometer. An InGaAs or pyroelectric detector is used to measure signal or idler wavelengths respectively. Actually, the wavelength range of idler can be derived by measured signal wavelength according to the equation (1). The measured idler wavelength is coincident with the calculated value. Tuning ranges of the OPO obtained by angle tuning the $LiNbO_3$ crystal at 20℃ are shown in Fig.6. Realigning the OPO's mirrors while tuning the OPO wavelength is not conducted. Measured wavelengths of the signal are 1479nm ~ 1621nm, and 3097nm ~ 3793nm of the idler. Because of machining tolerance of the $LiNbO_3$ crystal the lower idler wavelength (3097nm) of the tuning range is shorter than that expected.

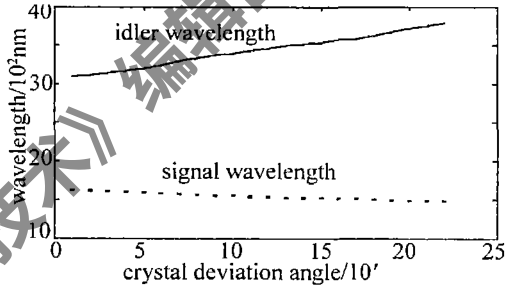

Fig.6 Tuning range of the OPO obtained by angle tuning the $LiNbO_3$ crystal at 20℃

## 4 Summary

The optical parametric oscillator with high pulse output energy and wide wavelength range are experimentally studied using complex cavity pump technology. The average pulse output energy of 56.4mJ of the OPO and 22.8mJ of the idler at 3097nm wavelength is obtained respectively. The conversion efficiency from 1064nm to signal and idler is 46% at pulse rate up to 10Hz. A large number of experimental data demonstrates that it is beneficial to raise conversion efficiency from 1064nm to signal and idler by means of a Nd:YAG laser pumped good quality $LiNbO_3$ crystal OPO and complex cavity pump technology. It is also very important for obtaining high pulse output energy of the OPO to coat antireflective, anti-optic damage film at the optical surfaces of the $LiNbO_3$ crystal.

The signal in 1479nm ~ 1621nm spectral region of the Nd:YAG 1060nm laser pumped $LiNbO_3$ crystal OPO is just in the atmospheric transmission window, and also in the eye-safety spectral region. In case the wide spectral applications are desired, for example, it is required that

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是由于烧结道距其后方边沿的距离更近的原因造成的。可通过对粉末进行预热来减少应力的不均衡性。这些趋势与先前的研究[6]相吻合。

## 8 结 论

对直接金属选区激光烧结过程的瞬态热应力场分布进行了数值模拟，并形成如下结论：(1) 建立了直接金属选区激光烧结的三维瞬态有限元分析模型，在模型中考虑了热传导、比热容等变物性参数的影响。热量在粉床中的传播机制复杂，其导热系数的考虑可以通过折算的方式进行。(2) 对于多道烧结的热力耦合分析，激光移动热源可以通过 ANSYS的 APDL进行模拟，热力耦合采用间接法具有更大的灵活性。(3) 在烧结进行过程中，由于已烧结部分的影响，最大热应力有逐渐减少的趋势。(4) 在扫描烧结道的前方比其后方具有更大的热应力分布，这是由于扫描烧结道前方具有更大的温度梯度。

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laser jammer can simultaneously jam the elder infrared missiles operating 1000nm ~ 2000nm spectral region and the new infrared missiles operating 3000nm ~ 5000nm, it perhaps is very useful that the signal and idler are simultaneous outputs. The laser jamming source of high bright and high directionality can easy saturate detectors of infrared missiles; moreover the chemical absorption spectra of the light hydrocarbons in the infrared region 3000nm ~ 4000nm allows the use of mid-infrared DIAL lidar techniques for petroleum exploration and pipeline monitoring these chemicals[8].

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