Available online at www.sciencedirect.com
SCIENCE DIRECT®
Optics Communications 244 (2005) 333–338
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

# A novel $La_3Ga_5SiO_{14}$ electro-optic Q-switched Nd:LiYF (Nd:YLF) laser with a Cassegrain unstable cavity

Yunchu Li [a,*], Qingpu Wang [a], Shaojun Zhang [b], Xingyu Zhang [a,*], Zejin Liu [a], Zongfu Jiang [a], Zhaojun Liu [a], Shutao Li [a]

[a] School of Information Science and Engineering, Shandong University, Jinan 250100, PR China
[b] State Key Laboratory of Crystal Materials, Shandong University, Jinan 250100, PR China

Received 24 July 2004; received in revised form 15 September 2004; accepted 15 September 2004

**Abstract**

A Nd:LiYF (Nd:YLF) laser which is actively electro-optic Q-switched with a $La_3Ga_5SiO_{14}$ single crystal was designed. Each end of the Nd:YLF rod was cut at Brewster's angle, which ensures operation at 1.053 μm and saves the need of a polarizor. The dynamic to static rate, the insertion loss and the optical damage threshold of LGS Q-switch is 76%, 2% and 950 MW/cm$^2$, respectively. Compared with $KD_2PO_4$, LGS is lack of water-solubility in air. When the pump energy is 121 J, the energy of single pulse output is 275 mJ with the repetition rate of 3 Hz and the beam divergence angle of 0.7 mrad. The mode of operation, the input–output characteristics and linear polarization ratio of this laser are also discussed.


*PACS:* 42.55.Rz
*Keywords:* Nd:LiYF (Nd:YLF); Brewster cut; $La_3Ga_5SiO_{14}$; Unstable cavity; Electro-optic Q-switch

## 1. Introduction

Electro-optic (E-O) Q-switched lasers are main sources for obtaining high power radiation. After long period work, great progress has been made in both theoretical and experimental fields [1,2]. As to those lasers pumped with xenon flash lamp, primary gain media consist of Nd:YAG, Nd:LiYF and so on. On the other hand, for making E-O Q-switch, crystals such as $KD_2PO_4$ (DKDP) and $LiNbO_3$ (LN) are commercially available. A good E-O Q-switch demands high E-O coefficients, low half-wave voltage, high optical damage threshold, broad transparent range, good physical and chemical characteristics and the facility for growth. Among those current E-O crystals, DKDP is the

* Corresponding authors. Tel.: +865316691931.
*E-mail addresses:* wayofflying@yahoo.com.cn (Y. Li), xyz@sdu.edu.cn (X. Zhang).

0030-4018/$ - see front matter 
doi:10.1016/j.optcom.2004.09.048

best candidate. However, since DKDP grows in water solution, it is apt to deliquesce in air, which brings much inconvenience in manufacture and application. LN grows in high temperature and is lack of water-solubility. Nevertheless, its optical damage threshold is very low and this forbids its application in middle and high power laser.

Crystalline $Nd:La_3Ga_5SiO_{14}$ (Nd:LGS) was first reported by Kaminskii in 1982 [3] as a crystal with piezoelectricity, E-O characteristics and optical activity. As a E-O material, it is only 2 or 3 years since it is introduced for fabricating an E-O switch. LGS has all the requisite properties required for making E-O Q-switch. Tables 1 and 2 provide the damage threshold and thermal expansion coefficients of several crystals [4]. LGS's transparency range is 190–2400 nm and optical damage threshold, according to Table 1, is 9.5 times as high as LN's. And its thermal expansion coefficient is also considerably low (Table 2). In the field of fabracating LGS E-O switches, much work has been reported [5–7]. Based on the former work, we proposed a novel $La_3Ga_5SiO_{14}$ E-O Q-switched Nd:YLF laser with a Cassegrain unstable cavity.

Experimental results indicate us this laser's good output performance. Since each end of the Nd:YLF rod was cut at Brewster's angle, even without antireflection coating, oscillation at 1.053 μm is ensured while the other at 1.047 μm is well restrained, which facilitates the stable polarized output [8,9].

The laser transition of Nd:LiYF at 1053 nm matches well to the peak gain of Nd doped phosphate and fluorophosphates glasses. As a result, it is currently being used in master oscillators for amplifier chains using these glasses. If the two surfaces of the LiYF rod are cut according to the Brewster angle at 1047, 1047 nm polarized light also can be obtained which is suitable for the pump source for $Tm^{3+}$ doped fiber amplifier and laser crystal. In this work, LiYF rod is cut at the Brewster angle of 1053 nm ordinary light, which sufficiently exert LiYF crystal's large natural birefringence [10]. Compared with usual YAG laser, this design saves the need for Glam prism or polarizor and anti-reflection coating, which simplifies the laser's structure.

## 2. Experimental setup

The schematic diagram of Nd:YLF laser cavity is showed in Fig. 1. A Cassegrain unstable cavity with the length of $L = 600$ mm is employed in this Nd:YLF laser [11]. The rear mirror is concave mirror with $R_1 = 2650$ mm and the output coupler is convex mirror with $R_2 = -1500$ mm which is a variable reflectivity mirror (VRM) [12]. The rate of lateral magnification $M$ is experimentally set as 1.8. The LiYF rod with 1% $Nd^{3+}$ doping was water cooled and pumped with double Xenon lamp. The size of the a-cut Nd:YLF rod in our experiment is $\phi^5 \times 80$ mm. The refractive index at 1053 nm (σ, ordinary) $n_0 = 1.448$ [13] (1047 nm, extraordinary, π, $n_e = 1.4704$). As shown in Fig. 2, it is obvious that [14]

Table 1
Optical damage threshold of several crystals

| Samples | Damage threshold ($MW/cm^2$) | Ratio with LN |
|---|---|---|
| $LiNbO_3$ | 100 | 1 |
| DKDP | 3260 | 32.6 |
| LGS | 950 | 9.5 |

Table 2
Thermal expansion coefficients

| Crystals | $\alpha_{11}$ ($10^{-6}$/°C) | $\alpha_{33}$ ($10^{-6}$/°C) |
|---|---|---|
| LGS | 5.8 | 3.9 |
| KDP | 24.9 | 4.4 |

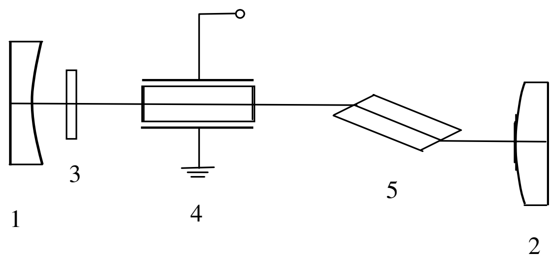


Fig. 1. Schematic of Nd:YLF laser Q-switched with LGS, (1) All-reflection mirror (2) Output coupler (3) 1/4 $\lambda$ plate (4) LGS E-O Q-switch (5) Nd:YLF laser rod.

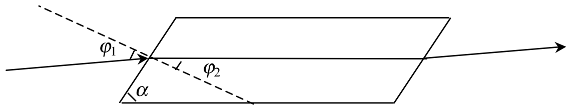


Fig. 2. Each end of Nd:YLF rod was cut according to the Brewster angle at 1053 nm.

$$\varphi_1 = \varphi_B = \arg\tan\left(\frac{n_0}{n_1}\right) = 55.37^\circ. \quad (1)$$

A crystal of LGS was cut and polished to form a Pockels cell with dimensions of $8 \times 8 \times 38$ mm$^3$ $(X, Y, Z)$. Laser travels along the optical axis ($Z$). By applying an electric field parallel to $X$-axis, we utilized the transverse E-O effect of LGS crystal to make it a Q-switch and the half-wave voltage $V_\pi$ can be expressed as follows:

$$V_\pi = \frac{\lambda}{2n_0^3\gamma_{11}(l/d)}, \quad (2)$$

where $\lambda$, $n_0$, $l$ and $d$ are the laser wavelength, the refractive index of LGS for the ordinary light, the optical path length and the thickness along the applied electric field direction of LGS crystal. $\gamma_{11} = 2.3 \times 10^{-12}$ m/V is the E-O coefficient. $l/d$ is the aspect ratio of LGS crystal(length/thickness). It is obvious we can adjust the half-wave voltage by changing $l/d$. It is calculated that the $V_\lambda/4$ voltage is 3600 V. The output profile is measured with a MRD500 PIN and a TEKTDS620B oscilloscope. Output energy and power is measured with EPM-2000 energy meter. We employ a rotatable Glam prism to measure the polarization rate.

## 3. Results and discussion

### *3.1. The characteristics of input–output*

When there is no voltage applied on the LGS E-O Q-switch, the LGS does not affect the polarized vector as the polarized light travels through the LGS forth and back two times. Because of the 1/4 $\lambda$ plate, the total rotated angle of the polarization plane is $\pi/2$ and to the moment the light meets the largest loss on the LiYF's cut surface. Oscillation failing to build up, there is no laser output. When quarter-wave voltage $V_\lambda/4$ (3600 V) is applied on the Pockels cell, the LGS rotates the polarized vector 90°. Taking the effect of 1/4 $\lambda$ plate into account, the total rotated angle of the polarization plane is 180°. The loss on the LiYF's cut surface is the least and an output pulse is generated.

The 1/4 $\lambda$ plate used in the experiment is an extremely thin quartz plate, both sides coated for high transmission at 1053 nm. The insertion loss of the LGS $\delta = 1 - E_2/E_1 = 2\%$, in which $E_1$ and $E_2$ represent the output energy without and with LGS crystal in free running. When pump energy is 121 J with 3 Hz repetition rate, the output single pulse energy is measured to be 275 mJ and the dynamic to static ratio $G = E_3/E_2 = 76\%$, where $E_3$ is the LGS E-O Q-switched output energy. The output pulse profile is shown in Fig. 3 and the pulse width is 10 ns. When incident energy is changed, the input–output characteristics is shown in Fig. 4.

### *3.2. Linear polarization ratio*

The output laser is measured to be linear polarized by a polarized prism with linear polarization ratio >99%, for LiYF has much larger natural birefringence than thermal induced birefringence. The incisions at LiYF's double ends according to the Brewster angle at 1053 nm efficiently restrain the oscillation at 1047 nm. This is one of merits of this laser – single polarized light is

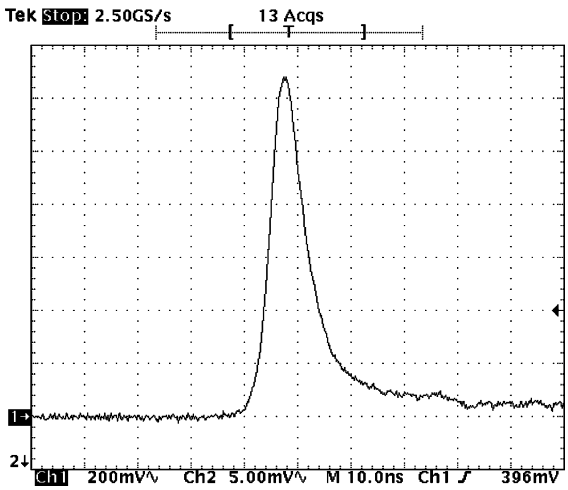


Fig. 3. Pulse profile of the laser output.

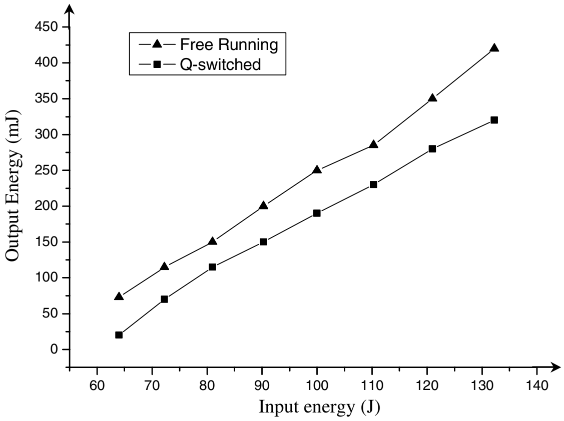


Fig. 4. Input–output performance (output energy vs. input energy).

obtained and the loss is extremely low even without transmission coating. (Compared with this, when YAG is used as laser crystal, both a polarizor and the transmission coating are necessary.)

What is worth noting is with $V_\lambda/4 = 3600$ V applied on the LGS E-O switch, LGS crystal shows both E-O properties and optical activity. When polarized light travels through the LGS crystal back and forth two times, what we are penetrating into is whether the rotated angle caused by polarization $\Delta\theta$ equals to 0 or not. But under such experimental conditions and running mode, a high polarization ratio as 99% indicates that the application of E-O properties has not received any obvious influence.

In addition, in the experiments the tolerance of the Brewster angle is large. When the LiYF crystal's ends are cut at Brewster angle precisely, the output single pulse energy is

$$E_{\text{out}} = \frac{1}{\gamma} Slh\nu(\Delta n_{\text{i}} - \Delta n_{\text{f}}) \frac{\ln \frac{1}{R}}{\ln \frac{1}{R} + L_\alpha}, \tag{3}$$

where $h\nu$, $S$, $l$, $\ln(1/R)$, $R$, $L_\alpha$ $\Delta n_{\text{i}}$ and $\Delta n_{\text{f}}$ are output photon energy, transverse area of the laser crystal, length of the laser crystal, output coupling loss, average reflectivity, forth-and-back loss, the initial density and the final density of inverted population respectively. If the cut surface of LiYF crystal departs from the exact $\theta_{\text{B}}$ with a small angle, the reflecting surface would develop additional reflectivity $R'$ which is a function of the incident angle $\theta_{\text{i}}$. Now the output single pulse energy is expressed as [15]

$$E'_{\text{out}} = \frac{1}{\gamma} Slh\nu(\Delta n_{\text{i}} - \Delta n_{\text{f}}) \frac{\ln \frac{1}{R}}{\ln \frac{1}{R} + L_\alpha + 2\ln(\frac{1}{1-R'})}, \tag{4}$$

where,

$$R' = \left[ \frac{n_0^2 \cos\theta_{\text{i}} - \sqrt{n_0^2 - \sin^2\theta_{\text{i}}}}{n_0^2 \cos\theta_{\text{i}} + \sqrt{n_0^2 - \sin^2\theta_{\text{i}}}} \right]^2, \tag{5}$$

where $n_{\text{o}}$ is the refractive index, $\theta_{\text{i}} = \pi/2 - \varphi_{\text{B}}$. In Eq. (4) $2\ln(\frac{1}{1-R'})$ is the additional loss. The relationship between $E'_{\text{out}}$ and $\theta_{\text{i}}$ has been shown in Fig. 5. According to the $E'_{\text{out}} \sim \theta_{\text{i}}$ curve, when the angle with which the incident angle $\theta_{\text{i}}$ depart from $\theta_{\text{B}}$ is within several degrees, there is no much effect on $E'_{\text{out}}$.

### 3.3. Design of Cassegrain unstable cavity and the divergence angle

The Cassegrain unstable cavity has powerful ability of mode-distinguish and can efficiently restrain high-order modes. It can keep only $TEM_{00}$ mode in oscillation when YAG and LiYF act as

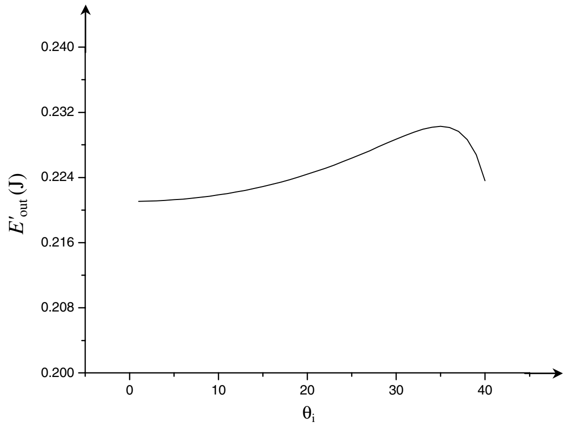


Fig. 5. Relationship between $E'_{\text{out}}$ and incident angle $\theta_{\text{i}}$, with $\gamma = 1$, $L = 0.1$, $R = 24.2\%$, $S = 19.6$ mm$^2$, $l = 80$ mm, $h\nu = 1.89 \times 10^{-19}$ J.

the laser crystals. The reflectivity profile of VRM is described as [16]

$$R(r) = R_{\max} \exp[-2(r/\omega)^2] \quad (r \leqslant \omega), \tag{6}$$

where $\omega$ is the radial distance on the mirror at which the reflectivity falls to $1/e^2$ and $R_{\max}$ is the peak reflectivity of the VRM. The lateral magnification rate $M$ is an important factor. It is defined as

$$M = D/d,$$

where $D$ is the diameter of the rod and $d$ equals to $2\omega$ [16].

The structure of unstable cavity is designed according to the method of geometric optics [17] and it exists

$$R_1 = \frac{2ML}{M-1}, \quad R_2 = -\frac{2L}{M-1}. \tag{7}$$

In addition, when the thermal focus distance $f$ of the laser crystal is considered, we have

$$\frac{1}{f} + \frac{1}{R_1'} = \frac{1}{R_1}, \tag{8}$$

where $R_1'$ is actual radius of curvature of rear mirror with $f$ taken into account. When $dn/dT > 0$, $f$ is positive and larger $R_1'$ is needed to compensate the thermal lensing effect of the rod. When $dn/dT < 0$, $f$ is negative and $R_1'$ should be reduced. In fact, LiYF crystal has large thermal conductivity 6.0 W/m · °C, which permits fast heat release and thus shows small thermal lens effect. In addition the rate with which LiYF's refraction index changes with temperature is negative. It means compensating LIYF's thermal focus with some components that the rate $dn/dT$ is positive is feasible. Actually, LiYF's thermal lensing focus distance is much larger than that of Nd:YAG [12–14]. So $R_1'$ is almost the same as $R_1$. The parameters were set experimentally as $R_1 = 2650$ mm, $R_2 = -1500$ mm, $L = 600$ mm and $M = 1.8$. Ordinary hard-edge output coupler makes the light power distribution at near and far field not uniform. However, when VRM is applied, those disadvantages can be overtaken, which makes light power distribute uniformly in near field and well concentrated in far field. The radial distance on the mirror, at which the reflectivity falls to $1/e^2$ was designed to be 1.35 mm. Thanks to the work of Cassegrain unstable cavity, the divergence angle is measured to be as small as 0.7 mrad.

## 4. Conclusion

A Nd:LiYF (Nd:YLF) laser which is actively E-O Q-switched with a $La_3Ga_5SiO_{14}$ single crystal has been designed. Each end of the Nd:YLF rod was cut at Brewster's angle and the orientation of the two surfaces with respect to the crystal's optic axis was such as to ensure operation at 1.053 $\mu$m ($\sigma$), which has saved the need of polarizor. By applying the transverse E-O effect of LGS crystal, we can adjust the half-wave voltage by changing $l/d$. LGS is lack of water-solubility in air and has low insertion loss and high optical damage threshold. When the pump energy is 121 J, the energy of single pulse output has been measured to be 275 mJ with the repetition rate of 3 Hz and the beam divergence angle of 0.7 mrad. The degree of polarization has been measured as more than 99%. It is a good middle power laser and fit for high power, large energy laser's oscillator.

## Acknowledgements

The research is supported by the National Natural Science Foundation of China (Grant No. 69978009), the Natural Science Foundation of Shandong Province (Grant No. Y2002G06) and Research Fund for the Doctoral Program of Higher Education of China (Grant No. 2002022048).

## References

[1] Degnan, IEEE J. Quant. Electron. 25 (1989) 214.
[2] Xingyu Zhang, Shengzhi Zhao, Qingpu Wang et al., IEEE J. Quant. Electron. 35 (1999) 1912.
[3] A.A. Kaminskii, S.E. Sarkisov, Rep. USSR Acad. Sci. 264 (1982) 93.
[4] Haikuan Kong, Jiyang Wang, Huaijin Zhang et al., J. Cryst. Growth 254 (2003) 360.
[5] Xin Yin, Jiyang Wang, Shaojun Zhang, Chin. Opt. Lett. 23 (2003) 1484 (in Chinese).

[6] Yin Xin, Wang Jiyang, Zhang Huajin et al., Jpn. J. Appl. Phys. 41 (2002) 7419.
[7] Yin Xin, Wang Jiyang, Zhang Shaojun, Appl. Opt. 42 (2003) 7188.
[8] T.M. Pollak, W.F. Wing, R.J. Grasso, IEEE J. Quant. Electron. 18 (1982) 159.
[9] G.T. Maker, A.I. Ferguson, Appl. Phys. Lett. 54 (1989) 403.
[10] J.E. Murray, IEEE J. Quant. Electron. 19 (1983) 488.
[11] R.L. Herbst, H. Komine, R.L. Byer, Opt. Commun. 21 (1977) 5.
[12] Zhang Fang, Zhang Pinglei, Zhou Shouhuan, Chin. Opt. Lett. 16 (1996) 1400 (in Chinese).
[13] C. Pfistner, R. Weber, H.P. Weber, S. Merazzi, IEEE J. Quant. Electron. 30 (1994) 1605.
[14] Max Born, Emil Wolf, Principle of Optics, Pergaman Press Ltd, 1964.
[15] Qingpu Wang, Xingyu Zhang, Zejin Liu, Laser Physics, Shandong University Press, 2003.
[16] Walter Koechner, Solid-State Laser Engineering, Springer-Verlag, Berlin, Heidelberg, 1999.
[17] A.E. Siegman, Appl. Opt. 13 (1974) 353.