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Development of Cr,Nd:GSGG Laser as a Pumping Source of Ti:Sapphire Laser

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Since efficiency of Cr,Nd doped gadolinium scandium gallium garnet (GSGG) laser is in principle higher than that of Nd:YAG laser, it can be a highly efficient pumping source for Ti:sapphire laser. We have made GSGG laser, and measured its oscillation properties. It was two times more efficient than Nd:YAG laser at free running mode operation. At Q-switched mode operation, fundamental output of 50mJ and second harmonics output of 8mJ were obtained. The developed laser had appropriate spatial profile, temporal duration, long time stability for solid state laser pumping. Ti:sapphire laser oscillation was achieved by the second harmonics of GSGG laser.

Keywords: GSGG laser, Ti:sapphire Laser, DLAP, AVLIS, Chromium, Neodymium

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チタンサファイアレーザー励起用光源としてのCr,Nd:GSGGレーザーの開発

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クロム、ネオジムドープのGSGGレーザーはヤグレーザよりも原理的に効率が高く、チタンサファイアレーザーなどの高効率励起用光源となる可能性がある。そのため、GSGGレーザーを試作しその発振特性を調べた。発振効率はフリーランニングモードでNd:YAGレーザーの2倍であった。Qスイッチモードにおいて基本波で50mJ、第二高調波で8mJを得た。レーザーの空間分布、時間波形、長時間安定性は固体レーザー励起に適したものであった。GSGGレーザーの第二高調波励起によりチタンサファイアレーザーの発振が達成できた。

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1. Introduction

A compact tunable laser light source is desirable as an alternative to conventional dye laser for high resolution spectroscopy[1], remote sensing[2], and isotope separation[3]. Titanium-doped sapphire laser (TSL) is promising because of its advantageous features such as the broad gain region extending over 400nm, easy handling of solid state brick, and stable operation without vibration by dye circulation. Especially, TSL has possibility to become one of the promising light source for atomic vapor laser isotope separation (AVLIS), because some of the requirements of AVLIS light source such as broad tunability, narrow line width, stable operation are achievable by TSL.

The light source for material processing like isotope separation requires high efficiency for the economy of the process. The main pumping source for TSL is frequency doubled Nd:YAG laser. But its efficiency is usually not more than a few percent. Therefore, it is desirable to increase the pumping efficiency. Sensitization of the laser medium is a possible approach to high efficiency. One of the promising materials for the sensitization is Cr^{3+}, Nd^{3+} doped gadolinium scandium gallium garnet (GSGG). Broad absorption band of doped Cr ion well match the emission spectrum of flash lamp spectra and absorb the lamp energy efficiently. The excited energy is non-radiatively transferred from Cr ion to upper level of Nd in GSGG host crystal, although it is slow and inefficient in YAG host crystal due to relatively small lattice parameter[4]. Since the energy transfer rate from Cr ion to Nd is very efficient (0.86), it is almost as efficient as direct Nd pumping[5]. Therefore, it is expected that Cr,Nd:GSGG laser can be a more efficient pump source compared with Nd:YAG laser. Zharikov et al. reported that the differential efficiency of Cr,Nd:GSGG was about 2 times higher than that of Nd:YAG at free running mode operation[6].

Rather large diameter crystal of GSGG up to 2.5-inch with high optical quality can be grown by Czochralski method[7], although it is difficult for YAG bole which generates a center core during the crystal growth. It is desirable feature to scale up the laser for massive material processing which requires large laser medium.

The coexistence of Cr and Nd in GSGG crystal can reduce solarization by radiation. It was reported that GSGG laser output was unaffected to ^{60}Co γ-ray irradiation up to 10Mrad, although Nd:YAG output dropped by an order of magnitude after 1Mrad γ-ray exposure[8]. These properties make GSGG more desirable laser for atomic energy applications or space applications where strong radiation is expected.

As a pump laser of TSL smooth spatial profile to avoid damage to the crystal surface and several J/cm^2 of fluence to oscillate dispersive cavity are required. About 50mJ of fundamental output is desirable to oscillate TSL laser considering SHG efficiency, spatial profile, and losses during optical delivery.

In this study, in order to investigate the possibility of efficient tunable laser system for AVLIS pumped by GSGG laser, Nd, Cr:GSGG laser was developed. Free running and Q-switched mode operations were achieved. TSL oscillation pumped by the second harmonics of GSGG was demonstrated.

2. Apparatus

The goal of our development was to generate green light from GSGG laser that can oscillate TSL resonator. Figure 1 shows schematic diagram of the developed laser system. The laser system consisted of GSGG oscillator (GSGG crystal, mirror, lamp house, E/O Q-switch, polarizer, shutter), SHG crystal, TSL oscillator. The GSGG oscillator cavity consisted of a flat output coupler and a highly reflecting concave mirror, with a lamp house between mirrors. Nd, Cr:GSGG crystal (4mm diameter × 75mm length) was obtained from Tokin Co. Ltd. The concentration of Cr and Nd was

1% and 2%, respectively. The crystal was set in a silver coated lamp house with elliptical shape, which was cooled with purified water. The silver coating has better reflection especially in UV region than the conventional Au coating, which would improve pumping efficiency of flash lamp. A Xe flash lamp light was focused into GSGG crystal. The flash lamp was simmered and driven by a conventional discharge circuit. The half-height pulse width of the current to the flash lamp was 340 μ s. The cavity was supported with 3 invar rod (20 mm ϕ × 1.2 mL) to prevent thermal and mechanical disturbance. An iris of 1.5 mm ϕ was inserted in the resonator in order to limit the number of transverse modes in operation and to investigate its effect to output energy.

3. Results

The designed laser resonator was used as a free running oscillator to optimize the laser system and to compare the oscillation efficiency. The oscillation was in 1.06 μm wavelength range which corresponds to $^4F_{3/2}$-$^4I_{11/2}$ transition of Nd^{3+} ion. Figure 2 shows the laser output energy as a function of electrical input energy to the flash lamp for a Nd, Cr:GSGG rod and a Nd:YAG rod tested in the same resonator. The result shows that in this experiment GSGG was about two times more efficient than YAG laser, although oscillation threshold energy of GSGG was slightly higher than that of YAG.

Figure 3 shows the output energy versus the lamp input at the free running mode operation with output coupler of 50 percent reflectivity and 1m cavity length. The repetition rate was 1Hz. By insertion of iris, the output power decreased considerably, and the oscillation threshold energy increased. On the other hand, the beam size 1.5 m away from the output coupler decreased from 3.6 mm ϕ to 1.7 mm ϕ, and smooth spatial mode close to TEM_{00} mode was obtained.

Based on these investigations about the optical components such as mirror reflectivity, mirror curvature, the influence of iris, etc., the oscillator configuration was optimized. The optimized laser resonator consisted of a concave total reflector with 3 m radius of curvature and a plane mirror of 20 percent reflectivity separated by 65 cm. The reflectivity and the curvature of the selected mirrors maximized the output energy among several available mirrors. After these optimizations, the slope efficiency increased form 0.2 % to 1 %, and a smooth spatial mode close to TEM_{00} was obtained without iris.

Figure 4 shows the temporal profile of GSGG fundamental output at the free running mode operation detected with a PIN photo diode. The repetition rate was 10 Hz, and the electrical input to the flash lamp was 12.2 J/pulse. The GSGG laser pulse appeared as a series of short spikes. The duration of the pulse envelope was 120 μ sec. Figure 5 shows the spatial profile of fundamental output detected with CCD camera (Hitachi Co. KP-140).

A Q-switched mode oscillation was performed, which was achieved with a Pockel cell and a polarizer in the cavity. Figure 6 shows the temporal profile of generated laser pulse measured with photomultiplier at the repetition rate of 10Hz. Post lasing caused by the residual distortion of E/O Q-switch observed 0.7-several μ sec after the main oscillation was reduced sufficiently by adjusting optical alignment. The output beam from the resonator was vertically polarized. Figure 7 shows spatial profile of the fundamental output. The observed transverse mode profile was close to TEM_{00} mode, and it was appropriate for TSL pumping without intense spot that would cause crystal damage. The beam size was 2.5 mm ϕ and the beam divergence was 2.4 mrad.

Figure 8 shows the fundamental output of Q-switched laser versus flash lamp input energy at a repetition rate of 10Hz. In this case, the laser output was proportional to the flash lamp input power. The maximum fundamental output of 50 mJ was obtained. The conversion efficiency from electric power to laser output was 0.4 percent, and the slope efficiency was 1percent.

The thermal properties of GSGG host crystal is poor compared with that of YAG crystal. In order to examine the thermal effect to GSGG output, long time operation for over 60 minutes was measured at the repetition rate of 1Hz and 10Hz. Figure 9 shows the laser output energy as a function of operation time. At a repetition rate of 1Hz, the output power did not change considerably in time. On the other hand, at a repetition rate of 10Hz, the output power decreased by 6 percent within the initial 1 minute after the start of oscillation, and stabilized. Therefore, within these repetition rates, stable operation for daily operational time was possible without serious thermal effect to the output power.

The second harmonics of the fundamental output was generated with a nonlinear crystal, deuterated L-Arginine Phosphate Monohydrate (DLAP) which was obtained from Creveland crystal Co. The size of the crystal was 10 mm×10 mm×15 mm length. It was reported that LAP has better SHG conversion efficiency than KDP and the damage threshold is two times higher than that of KDP[9], which were desirable for efficient laser operation. Figure 10 shows the temporal profile of the generated second harmonics. The half-height temporal duration was 12 nsec. The profile was smooth and appropriate for TSL pumping. The divergence was 1.8 mrad. Figure 11 shows SHG output fluence versus fundamental laser fluence. The maximum SHG energy of 8 mJ was obtained at the fundamental input of 50 mJ, which corresponds to conversion efficiency of 16 percent. In this experiment, the SHG conversion efficiency was low, which was caused mainly by several nm of broad spectral line width of GSGG oscillator and rather low fluence of the fundamental output. It is possible to improve the conversion efficiency by narrowing the line width with a dispersive element, or intensify the fundamental fluence.

In order to investigate the acceptable temperature range of the laser when it was operated at a high repetition rate or at high power, the temperature dependence of the laser output was measured. Figure 12 shows the SHG output as a function of DLAP house temperature. In this experimental setup, the acceptable temperature range was about 5degree. Figure 13 shows the relative SHG output versus tuning angle of DLAP. In this case, the acceptable tuning angle was about ±1mrad.

The generated second harmonics was then introduced to TSL oscillator. The TSL oscillator consisted of a plane total reflector, a plane output coupler of 95 percent reflection, and a TSL crystal (Union Carbide Co., 5 mm×5 mm×12 mmL). The Ti concentration was 0.15 wt%, and FOM was 90. The pump laser was focused with a lens (f=50cm) before the crystal surface, and longitudinally pumped the crystal. Figure 14 shows the temporal profile of the generated TSL pulse which was 50 nsec delayed from the pump beam. The temporal duration of TSL was 12 nsec. Figure 15 shows the laser output as a function of incident pump energy. The threshold fluence of oscillation was 2.0 J/cm^2. The slope efficiency was 6.7 %. Figure 16 shows the vertical and horizontal beam profile of generated laser. The beam divergence was 1.8 mrad. The beam profile of the obtained TSL was smooth, and was appropriate for various applications.

We have developed Nd,Cr:GSGG oscillator that had sufficient output power and spatial profile to oscillate TSL. Although at this stage, the conversion efficiency of the total system is low, and further optimizations of the laser system are required, it is demonstrated that the GSGG laser is potentially more efficient pump source for TSL than YAG laser.

Since the thermal properties of GSGG crystal is not good, the influence of the thermal lensing or thermally induced birefringence might be larger compared with that of YAG. However, these influence can be reduced by using a slab type resonator with zigzag optical path[10] or a flow cooled multiple disk type resonator[11], which make high average power GSGG laser system possible.

4. Conclusions

Cr,Nd doped GSGG laser has been developed. It was about two times more efficient than Nd:YAG laser at the free running mode operation. At the Q-switched mode operation, fundamental output of 50 mJ, and SHG output of 8 mJ were obtained. Appropriate spatial profile, temporal duration, and long time stability for TSL pumping were achieved. Oscillation of TSL was demonstrated by the second harmonics of GSGG laser.

Acknowledgment

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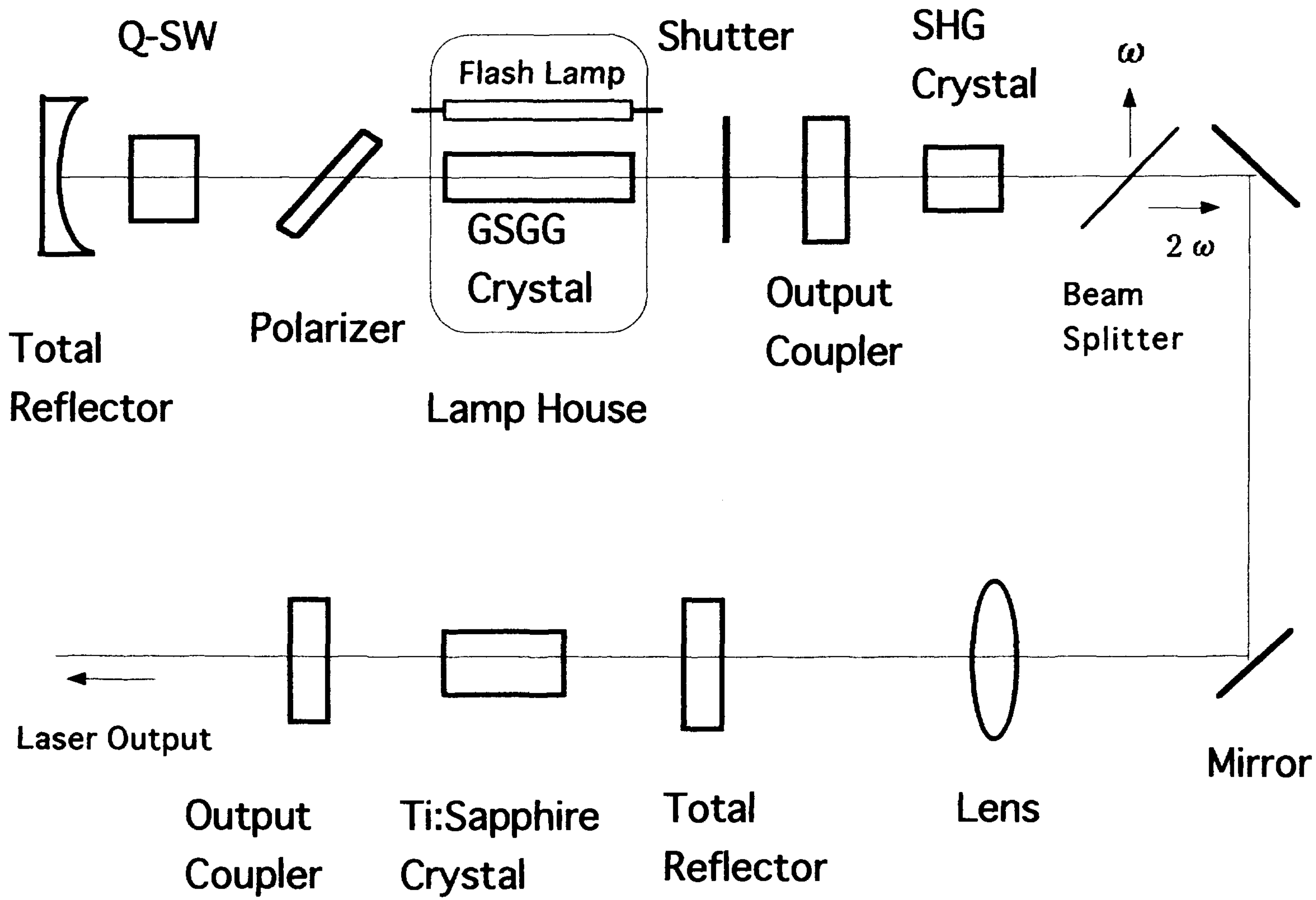

Figure 1. Configurations of GSGG laser and Ti:sapphire resonator.

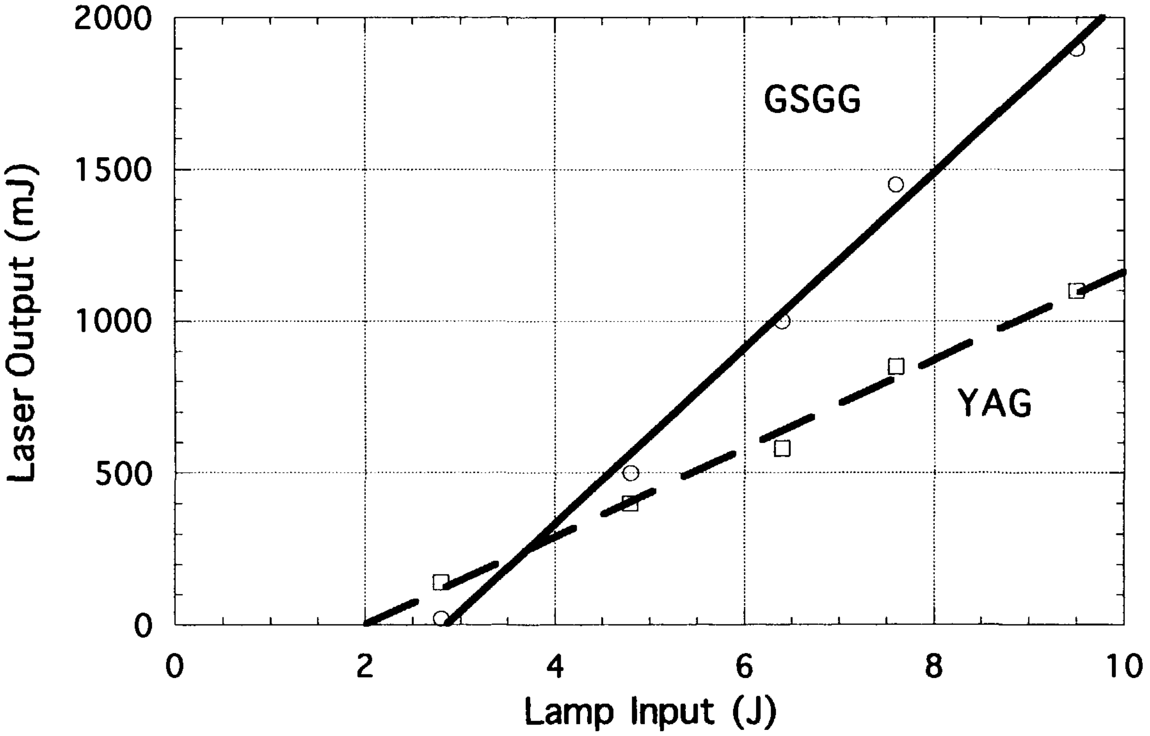

Figure 2. The output energy of GSGG and YAG resonator as a function of lamp input energy.

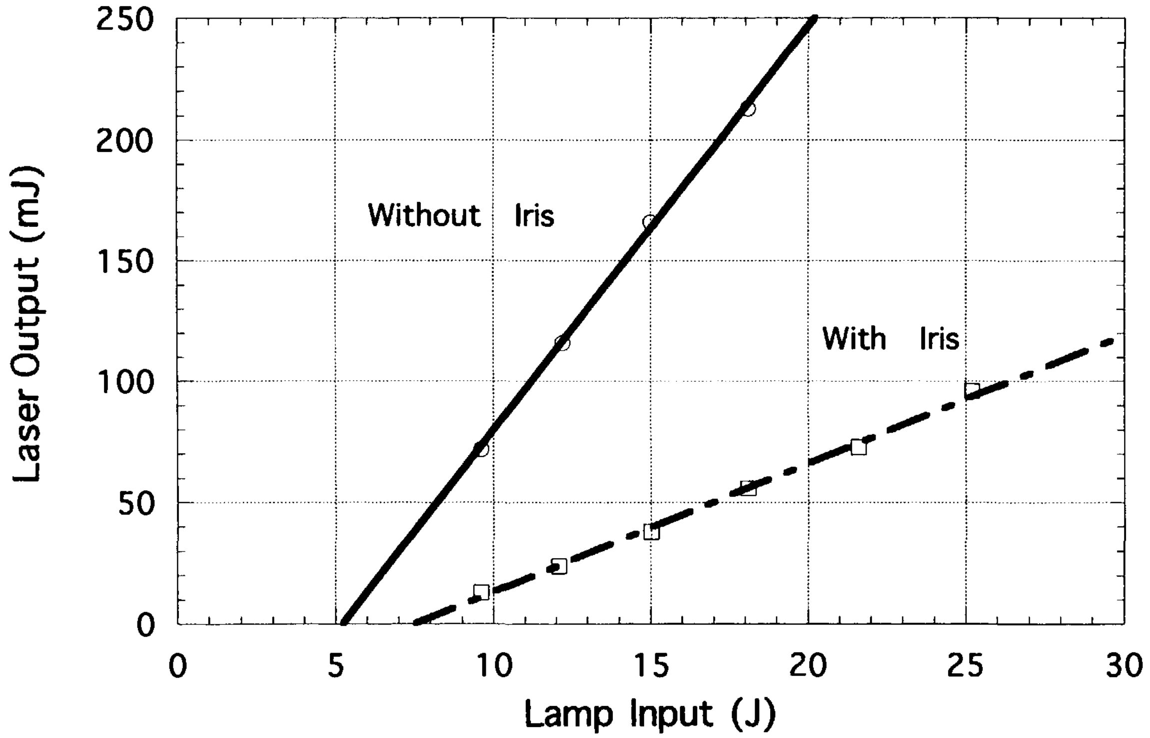

Figure 3. The output energy of GSGG laser as a function of lamp input energy with and without iris.

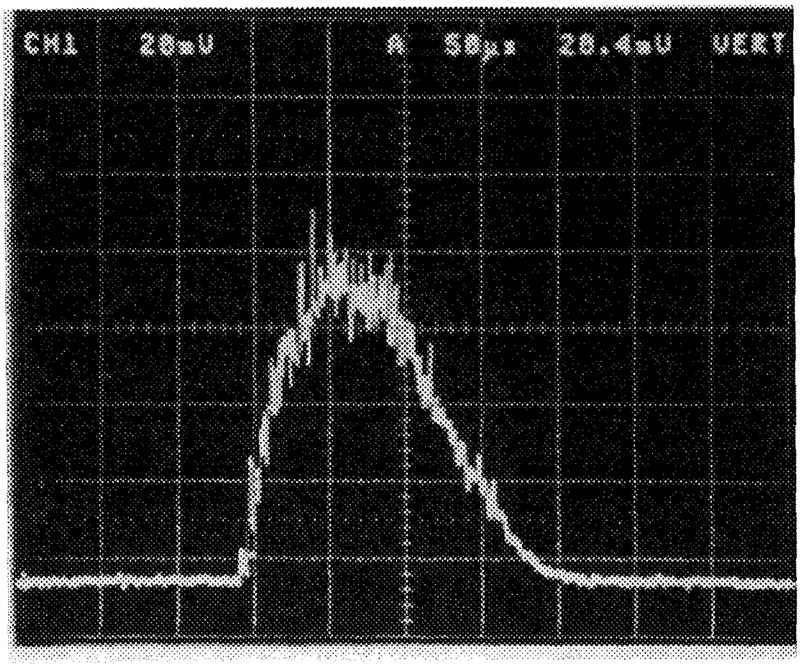

Figure 4. Temporal profile of GSGG fundamental output at a free running mode operation.

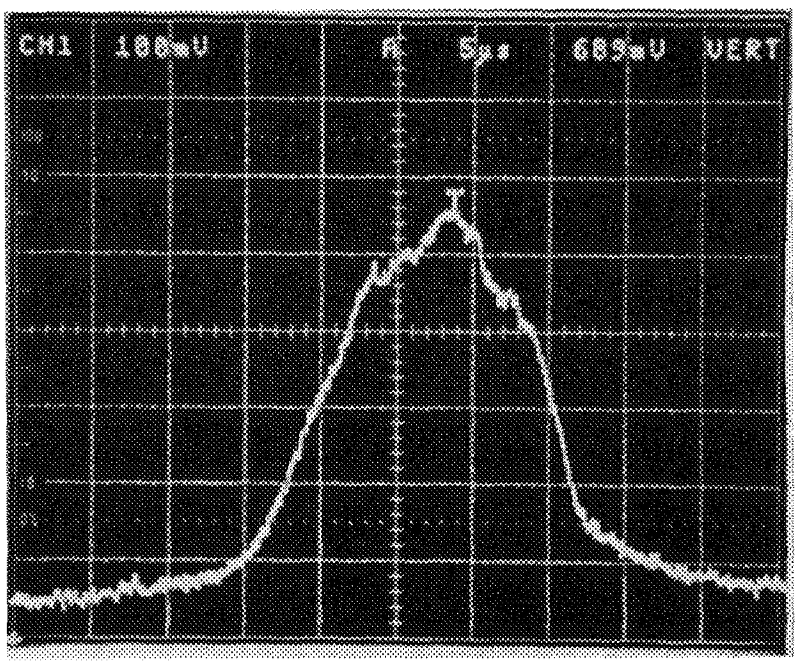

Figure 5. Spatial profile of GSGG fundamental output.

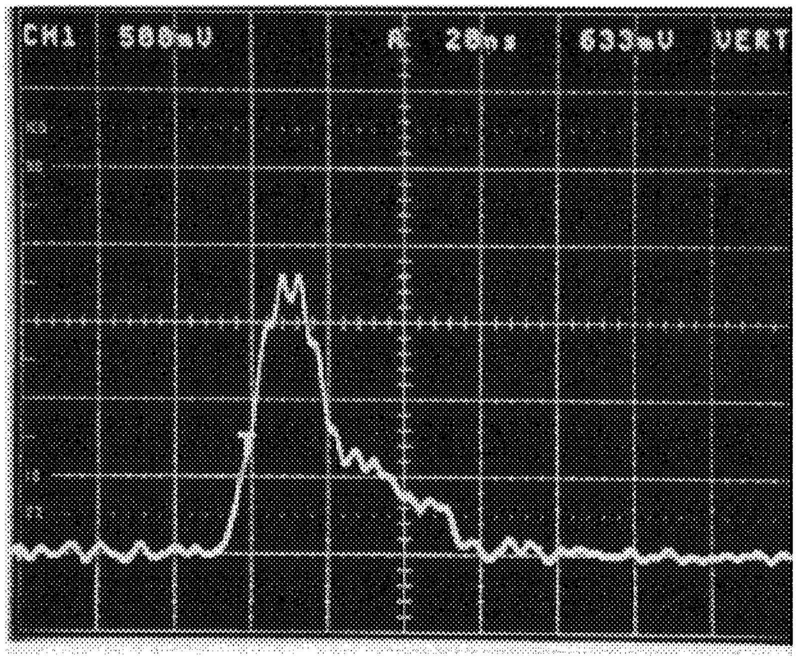

Figure 6. Temporal profile of GSGG fundamental output.

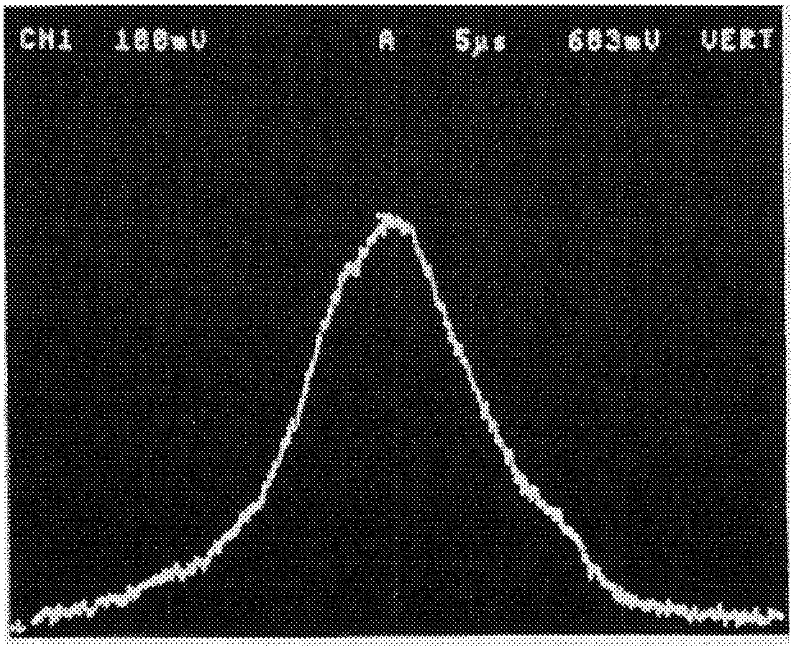

Figure 7. Spatial profile of Q-switched GSGG fundamental output.

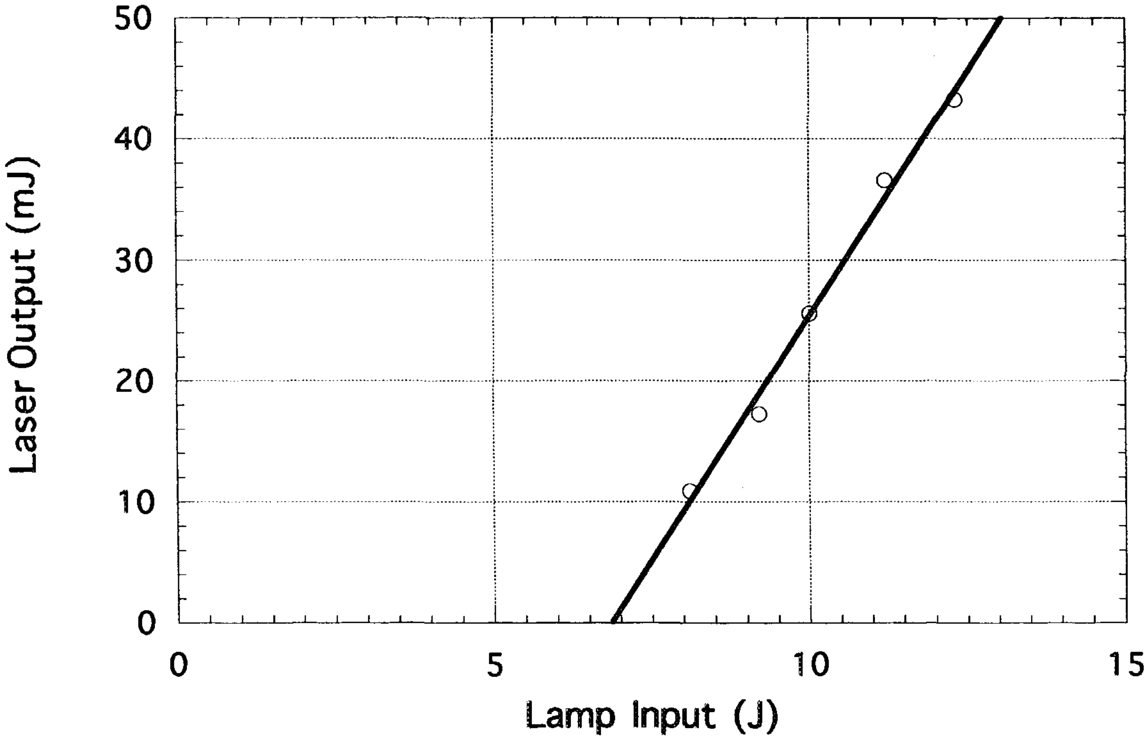

Figure 8. Fundamental output of Q-switched GSGG laser as a function of lamp input energy.

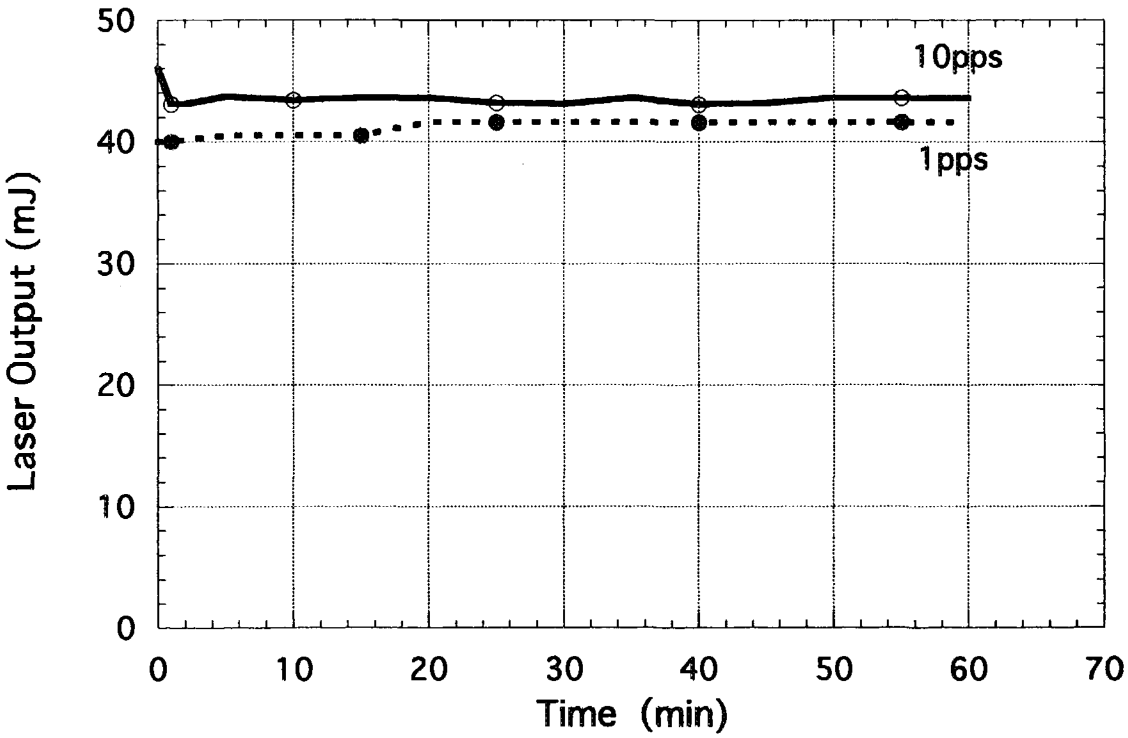

Figure 9. Laser output energy as a function of operation time at repetition rates of 1Hz and 10Hz.

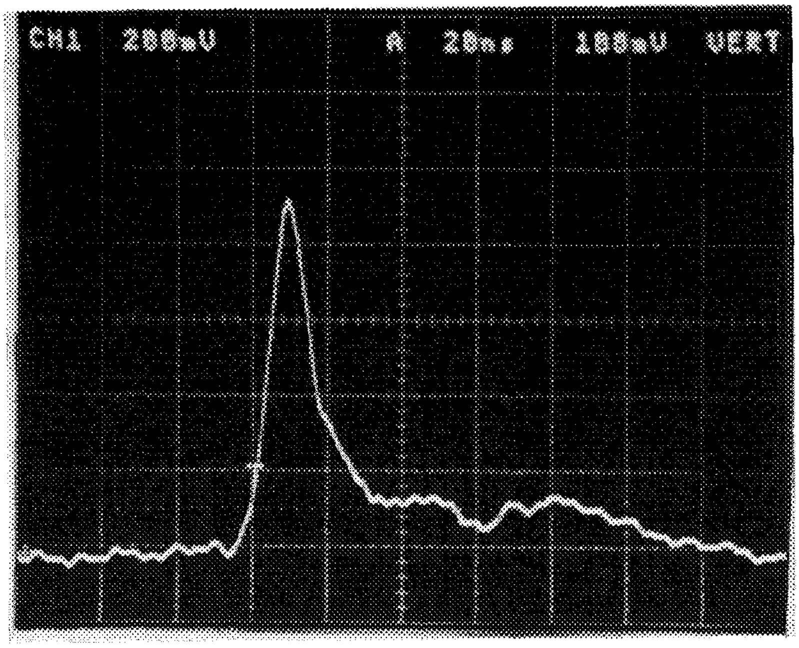

Figure 10. Temporal profile of second harmonics of GSGG laser.

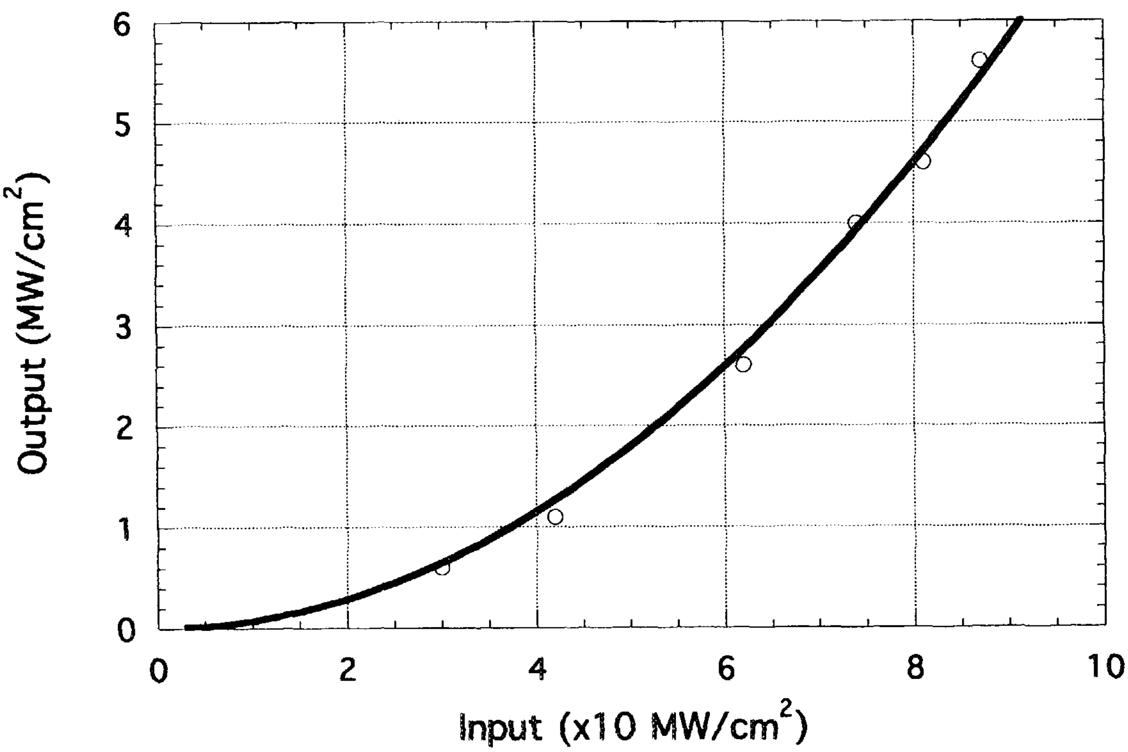

Figure 11. Second harmonics fluence as a function of fundamental fluence.

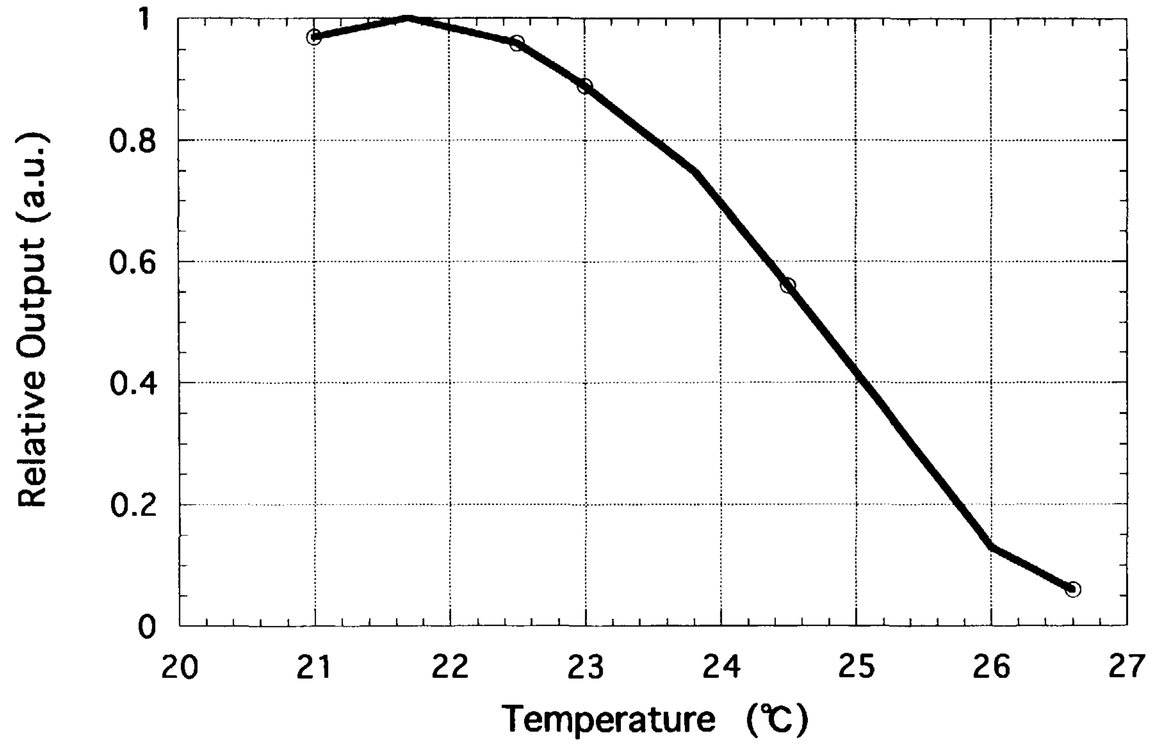

Figure 12. Relative SHG output as a function of the crystal temperature.

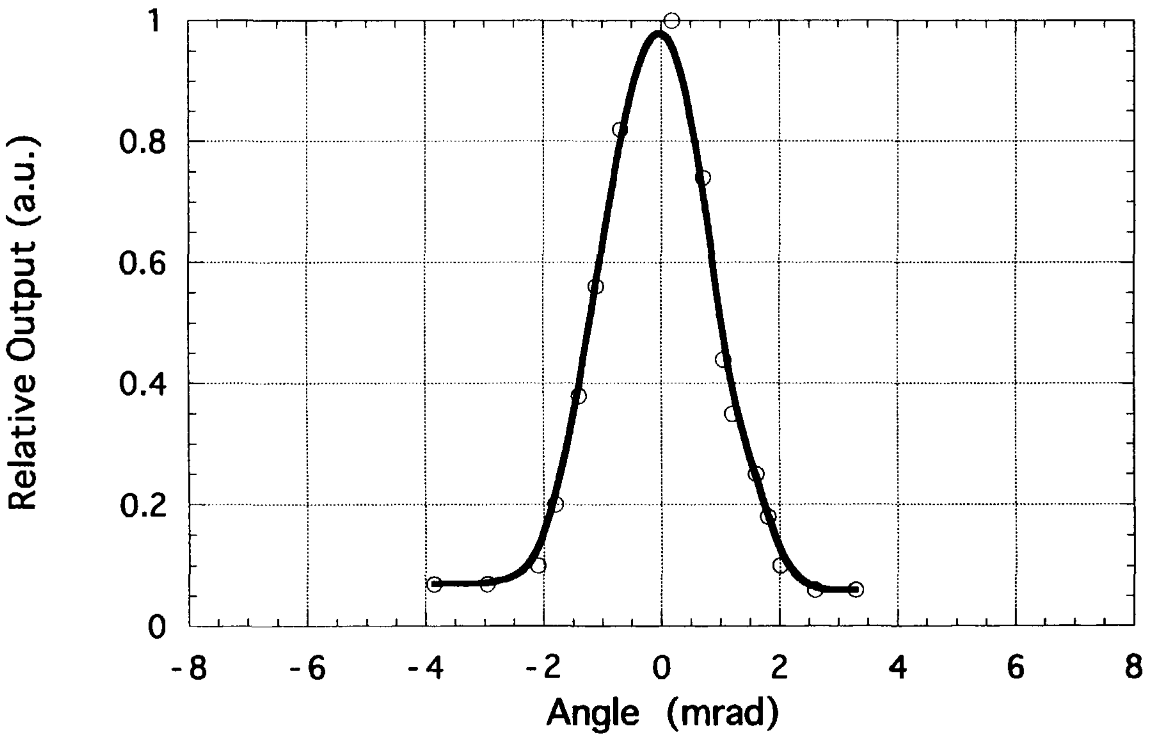

Figure 13. Relative SHG output as a function of the tuning angle.

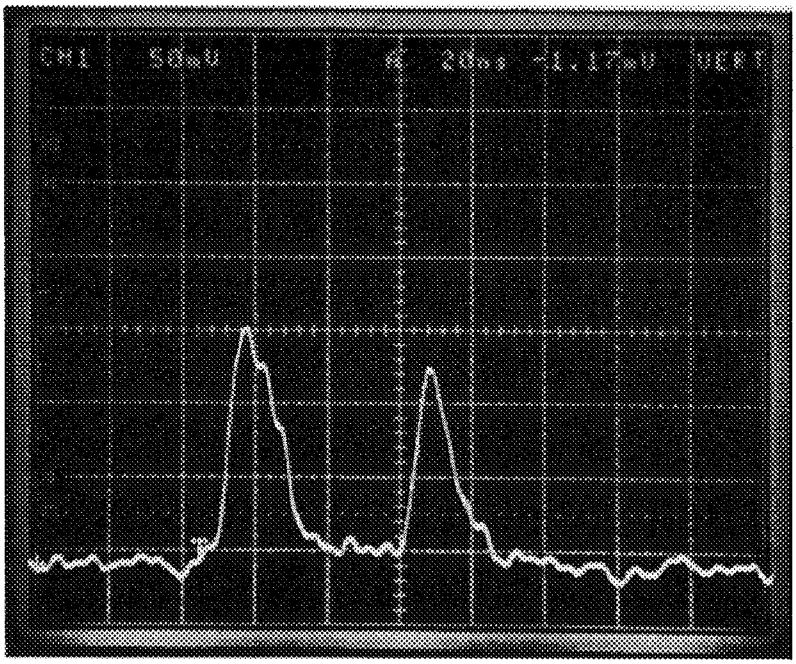

Figure 14. Temporal profile of GSGG laser and generated TSL.

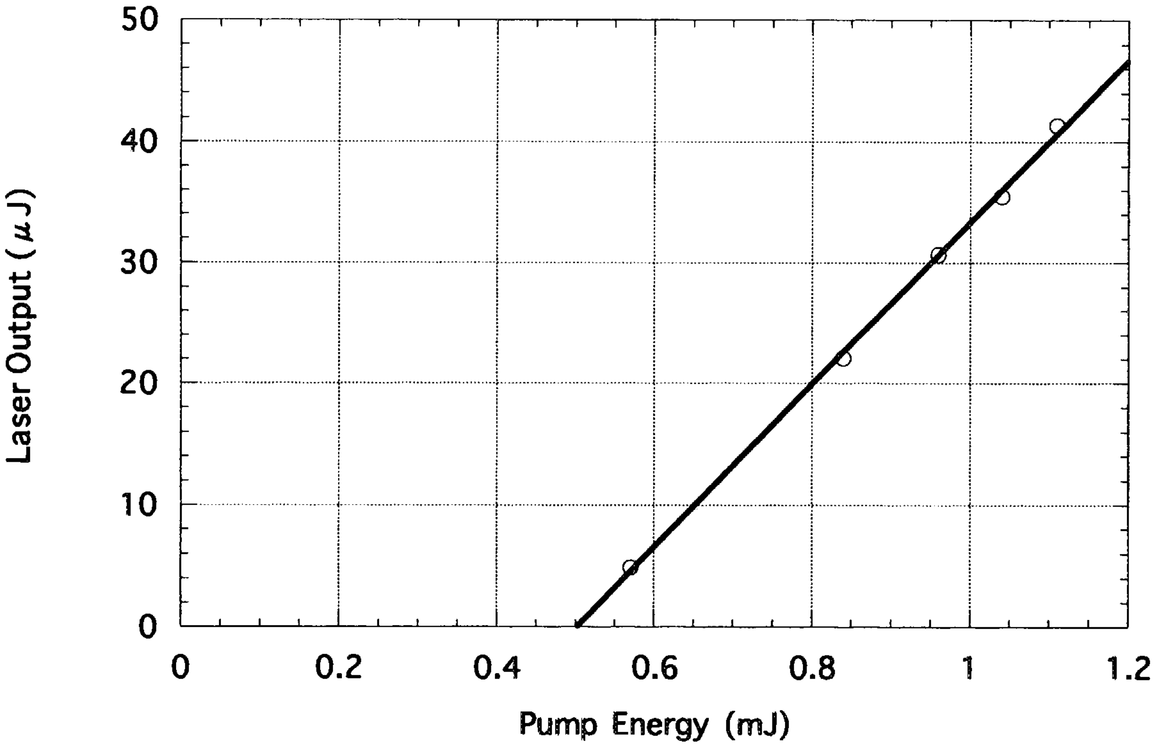

Figure 15. TSL output energy as a function of GSGG input energy.

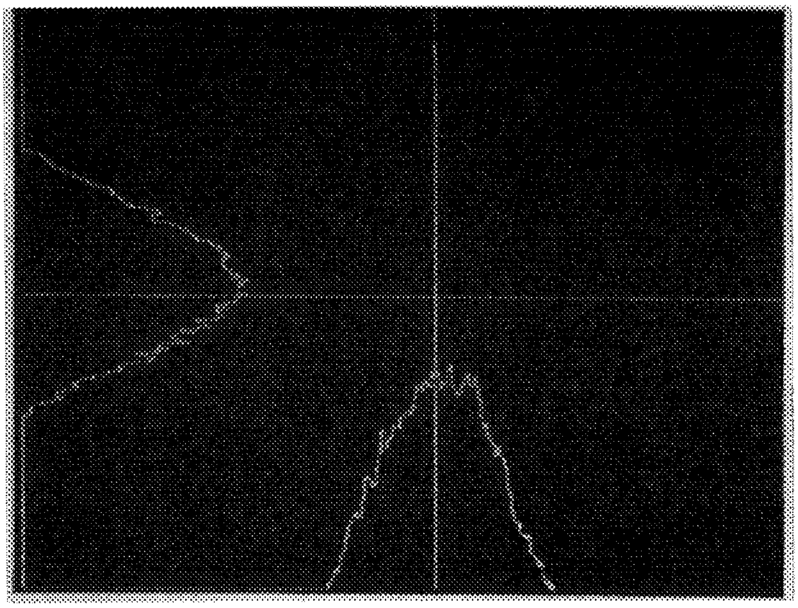

Figure 16. Vertical and horizontal beam profile of TSL.

国際単位系 (SI) と換算表

表1 SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表2 SIと併用される単位

名称	記号
分, 時, 日	min, h, d
度, 分, 秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

1 eV = 1.60218×10^{-19} J
1 u = 1.66054×10^{-27} kg

表5 SI接頭語

倍数	接頭語	記号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表3 固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m\cdot kg/s^2$
圧力, 応力	パスカル	Pa	N/m^2
エネルギー, 仕事, 熱量	ジュール	J	N·m
工率, 放射束	ワット	W	J/s
電気量, 電荷	クーロン	C	A·s
電位, 電圧, 起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表4 SIと共に暫定的に維持される単位

名称	記号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

1 Å = 0.1 nm = 10^{-10} m
1 b = 100 fm^2 = 10^{-28} m^2
1 bar = 0.1 MPa = 10^5 Pa
1 Gal = 1 cm/s^2 = 10^{-2} m/s^2
1 Ci = 3.7×10^{10} Bq
1 R = 2.58×10^{-4} C/kg
1 rad = 1 cGy = 10^{-2} Gy
1 rem = 1 cSv = 10^{-2} Sv

(注)

1. 表1—5は「国際単位系」第5版, 国際度量衡局 1985年刊行による。ただし, 1 eVおよび1 uの値はCODATAの1986年推奨値によった。
2. 表4には海里, ノット, アール, ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. barは, JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令ではbar, barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換算表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘度 1 Pa·s($N\cdot s/m^2$) = 10 P(ポアズ)(g/(cm·s))

動粘度 1 m^2/s = 10^4St(ストークス)(cm^2/s)

圧力	MPa(=10 bar)	kgf/cm^2	atm	mmHg(Torr)	lbf/in^2(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J (計量法)
= 4.184 J (熱化学)
= 4.1855 J (15 °C)
= 4.1868 J (国際蒸気表)

仕事率 1 PS (仏馬力)
= 75 kgf·m/s
= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

DEVELOPMENT OF CR, ND : GSGG LASER AS A PUMPING SOURCE OF TI : SAPPHIRE LASER