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Demonstration of Quadrature Arrangement using $CsLiB_6O_{10}$ Crystals

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The ability of $CsLiB_6O_{10}$ (CLBO) crystals for high power second-harmonic generation (SHG) of a 1064-nm Nd:YAG laser in a quadrature arrangement was experimentally demonstrated. A 532-nm second harmonic output pulse energy of 2.25 J was obtained with 3.21 J of an input 1064-nm fundamental pulse energy at a repetition rate of 10 Hz, corresponding to a power conversion efficiency in excess of 70 %.

Keywords: Quadrature Arrangement, Second-Harmonic Generation (SHG), $CsLiB_6O_{10}$ (CLBO) Crystal, Nd:YAG Laser

* on leave from Hamamatsu Photonics K. K.

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$CsLiB_6O_{10}$結晶を用いた矩象波長変換

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（２００１年２月８日受理）

高出力 Nd:YAG レーザーの第二高調波光発生に対して $CsLiB_6O_{10}$（CLBO）結晶を用いた矩象波長変換方式の可能性について実験的に評価した。3.21 J の入射 Nd:YAG レーザー光に対して 2.25 J の第二高調波光出力が繰り返し率 10Hz で得られた。このときのパワー変換効率は 70 ％以上に相当する。

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1. INTRODUCTION

Several high power near-infrared solid-state laser systems such as the popular Nd:YAG laser system have been developed and operated efficiently for many years. High power green lasers using these systems are effective tools in material processing, remote sensing and as a pumping source of Ti:sapphire lasers. In a solid-state laser, a green laser beam is typically generated by a second-harmonic generation (SHG) scheme based on the use of nonlinear optical crystals [1], [2]. At present, there are many crystals available for SHG of the Nd:YAG laser : $KTiOPO_4$ (KTP), LiB_3O_5 (LBO), β-BaB_2O_4 (BBO), KD_2PO_4 (DKDP) and $CsLiB_6O_{10}$ (CLBO). KTP, LBO and BBO have been widely used due to their large nonlinear coefficients [1]-[4]. However, the small crystal sizes are not suitable for the SHG of high power lasers for which large laser beam diameter is typical. Both DKDP and CLBO can be grown to large sizes in a relatively short period. The CLBO crystal offers some attractive nonlinear parameters compared with DKDP crystal [5]. For type II phase matching at a pump wavelength of 1064-nm, the nonlinear coefficients (d_{eff}) for CLBO and DKDP are 0.95 pm/V and 0.40 pm/V, respectively. DKDP has a wide angular acceptance bandwidth of 5.0 mrad-cm compared with 1.7 mrad-cm for the CLBO crystal. However, the temperature acceptance bandwidths for CLBO and DKDP are 43.1 ℃-cm and 6.7 ℃-cm, respectively. The walk-off angles and spectral acceptance bandwidths of CLBO and DKDP are rather similar. For high-power and high repetition rate second harmonic generation, the small nonlinear coefficient and narrow temperature acceptance bandwidth limit the use of DKDP crystal. Also, it has been shown experimentally that the performance of the CLBO crystal for SHG of the Nd:YAG laser is superior to that of the DKDP crystal [5]. For these reasons, CLBO crystal is suitable for high power and high repetition rate SHG of the Nd:YAG laser.

Eimerl proposed a quadrature frequency conversion scheme using of two crystals [6]. In this scheme, the optic axes of two type II crystals in series are arranged orthogonally. The input fundamental laser beam unconverted in the first crystal can be reused for further frequency conversion in the second. This scheme provides for a wide input intensity range over which conversion efficiency is high and a relatively high tolerance to angle and thermal misadjustment compared with a single crystal scheme. Furthermore, back-conversion can be minimized because the second-harmonic output produced in the first crystal is not at the correct polarization for interaction in the second. Eimerl has described in detail the quadrature SHG conversion efficiency for the Nd laser with numerical calculations for DKDP, KTP and BBO, and measurement for DKDP.

In this paper, we describe the efficient SHG performances for high power Nd:YAG laser by combining the advantages of CLBO crystal and the quadrature frequency conversion scheme. This scheme can be easily scaled up by increasing the sizes of the nonlinear optical crystals to accommodate larger input fundamental laser beam cross-section.

2. EXPERIMENTAL SETUP

A schematic of the experimental setup is shown in Fig.1. A SHG experiment was carried out using a high power 1064-nm Q-switched Nd:YAG laser system, operated at a repetition rate of 10 Hz [7]. In this experiment, we used one of two beam lines in the system. The laser system was injection seeded to provide a single axial-mode output. The seeded temporal profile of the laser pulse was observed to be smooth and near Gaussian. The spatial profile was near flat-top. The beam diameter was 10.9 mm and the pulse duration was about 13 ns at full width at half maximum (FWHM). Each CLBO crystal (KOGAKUGIKEN Co., Ltd) had a cross section of 18 mm×18 mm and length of 10 mm and had no antireflection coatings. Each crystal was oriented for type II for SHG of the input 1064-nm fundamental laser and was housed in a heater with a proportional integral derivative (PID) controller. The crystals were maintained constantly at 160 ℃ with an accuracy of 0.1 ℃ and were argon gas purged in order to avoid their degradation due to stresses introduced by crystal hydration, cutting, polishing, and thermal shock owing to laser power absorption [8]. The temperature-ramping rate was fixed at 2.3℃/min. The windows of the heaters were antireflection coated for both 1064-nm and 532-nm. Each heater was mounted on a rotation stage to optimize the angle between the input beam and the crystal.

The input 1064-nm fundamental laser beam, which was linearly polarized, was passed through an optical isolator and relayed. The optical isolator provides sufficient optical isolation between the Q-switched Nd:YAG laser system and the frequency conversion part. The image-relay telescope was used to transport the input laser beam to the CLBO crystals with the flat-top spatial profile while avoiding damage to the optics. The two CLBO crystals were placed close to each other. Polarization of the input laser beam was adjusted with a half-wave plate for correct orientation to the crystals for efficient frequency conversion. A dichroic mirror was placed after the CLBO crystals to separate the 1064-nm fundamental laser beam and the generated 532-nm second-harmonic output beam.

3. RESULTS

Figure 2 shows the 532-nm second-harmonic output pulse energy as a function of the input 1064-nm fundamental pulse energy. A maximum second-harmonic output pulse energy of 2.26 J was obtained with an input fundamental pulse energy of 3.21 J at a repetition rate of 10 Hz, corresponding to an average second-harmonic output power of 22.6 W. There was no compensation for optical losses such as reflection, absorption and scattering of the crystals. No power saturation was observed within the investigated power range. Figure 3 shows the 532-nm second-harmonic conversion efficiency as a function of the input fundamental laser intensity. As can be seen in this figure, a high conversion efficiency of over 70 % for SHG was achieved with an input laser intensity of 317 MW/cm^2. This result indicates that the high efficiency enables an efficient use of energy as well as hardware. The ability of CLBO crystals for high power SHG of the Nd:YAG laser in a quadrature arrangement was clearly demonstrated.

Using the numerical calculation method [1], [6], the performance at optimized crystal length was estimated. The calculation assumed a beam divergence of 1.0 mrad at a repetition rate of 10 Hz, and also assumed a Gaussian temporal profile and flat-top spatial profile. Crystal length was assumed to be 10 mm (first crystal) and 10.8 mm (second crystal), respectively, and there were losses for Fresnel reflections. The calculation indicates that a second-harmonic conversion efficiency exceeding 75 % could be achieved with the input laser intensity of about 360 MW/cm^2.

4. CONCLUSION

W have demonstrated experimentally the ability of CLBO crystal for high power frequency doubling of the Nd:YAG laser in a quadrature arrangement. A high second-harmonic conversion efficiency of over 70 % was achieved with an input fundamental laser intensity of 317 MW/cm^2. A second-harmonic output pulse energy of 2.25 J was obtained with 3.21 J of input fundamental pulse energy at 10 Hz. The results clearly indicate that CLBO crystal can be attractive for high power second-harmonic generation with large beam diameter.

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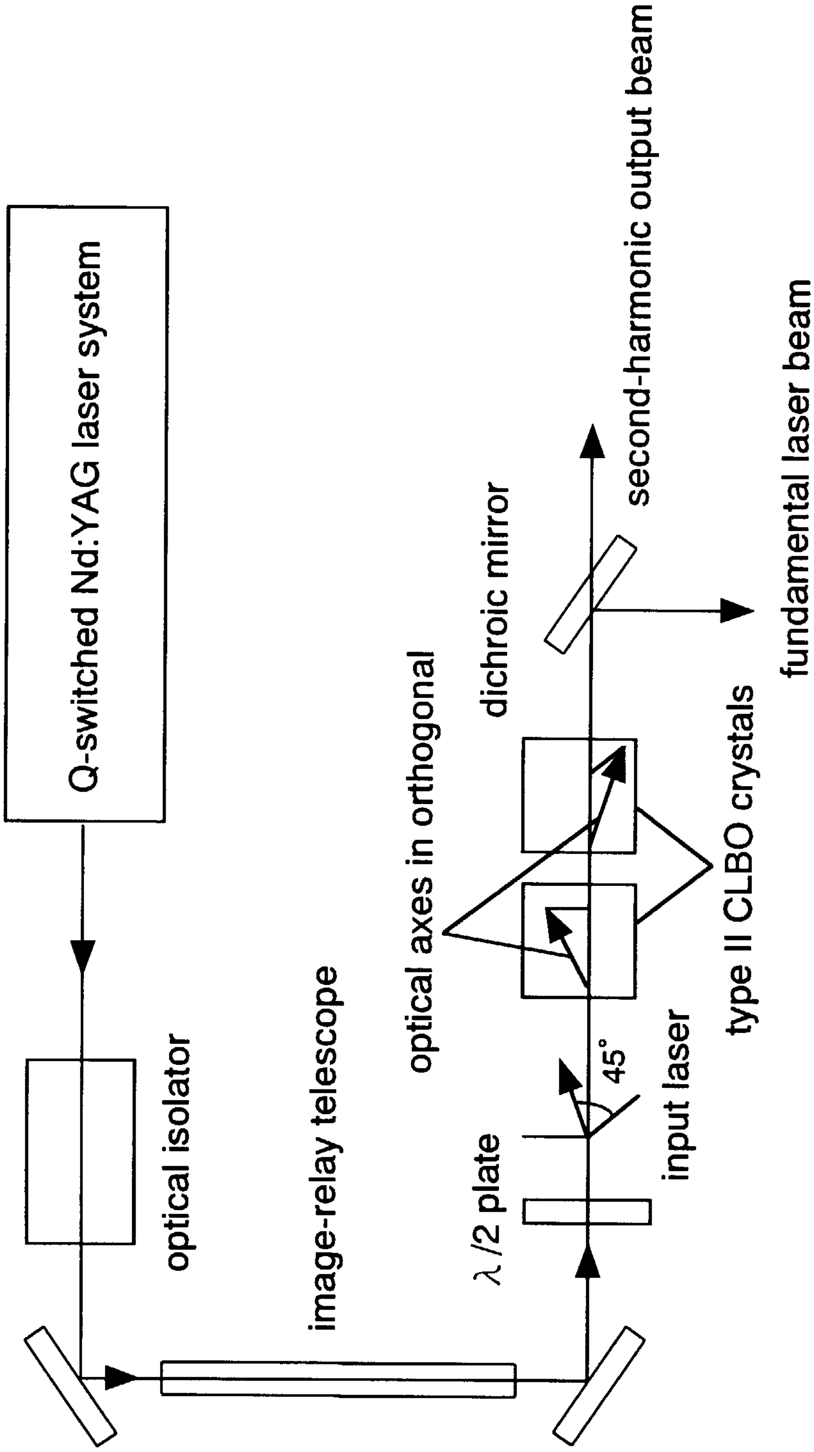

Fig.1 Schematic of the experimental setup.

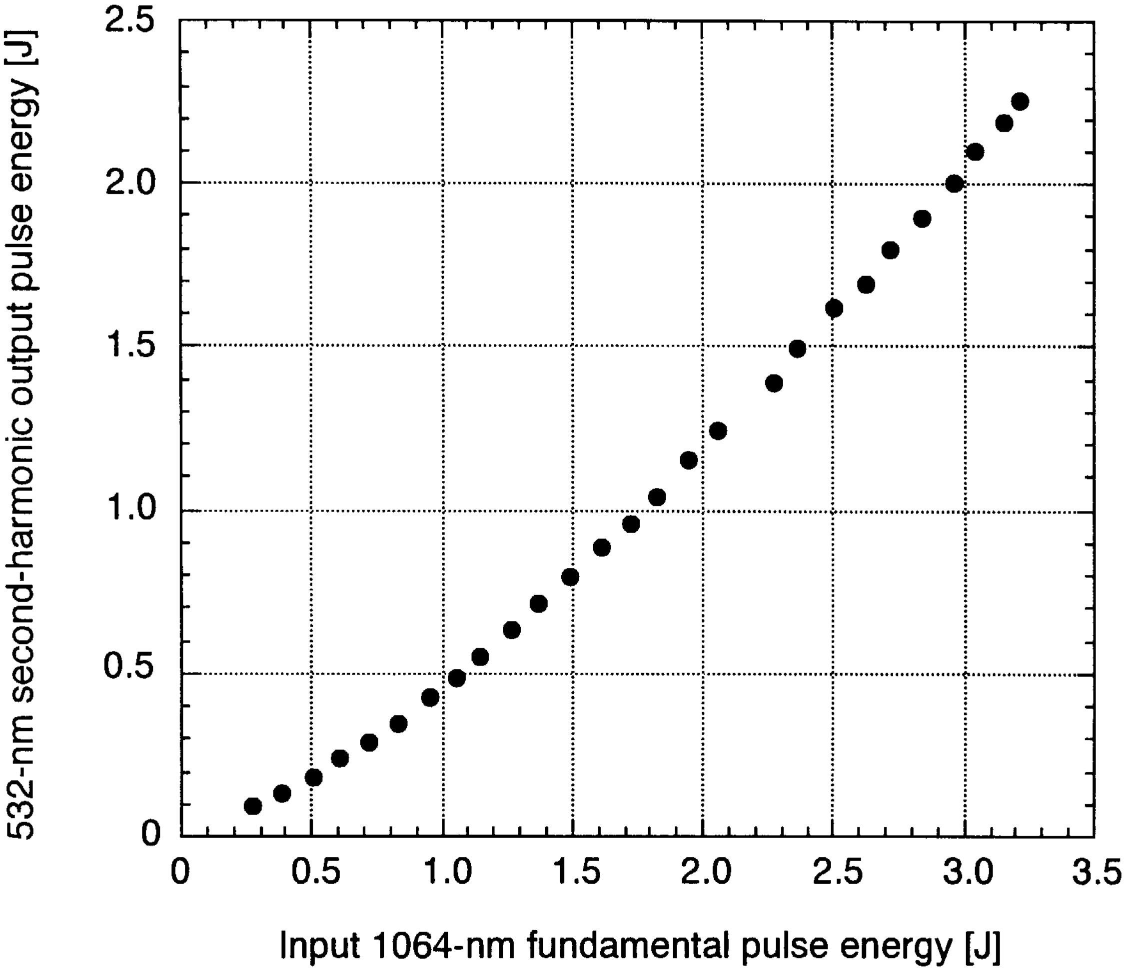

Fig.2 532-nm second harmonic output pulse energy as a function of the input 1064-nm fundamental pulse energy.

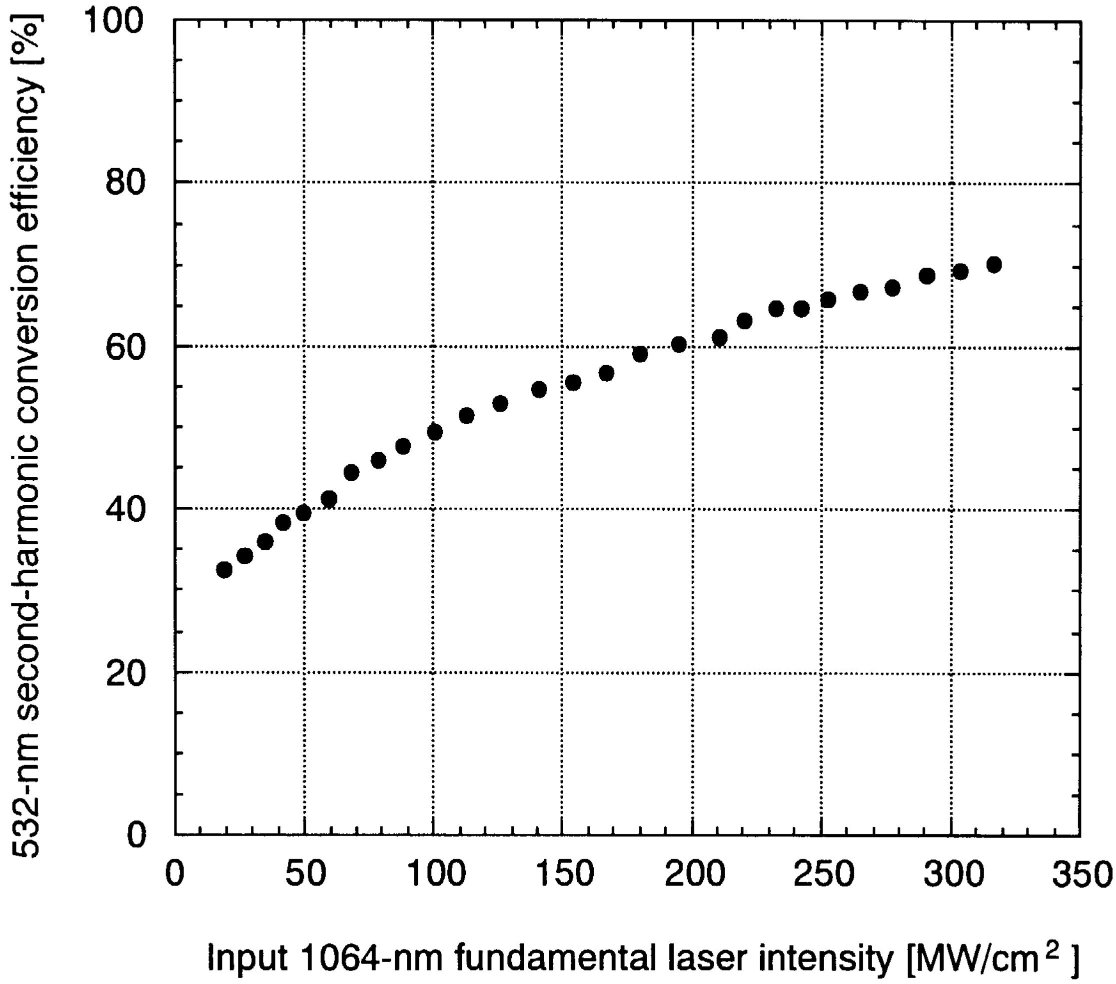

Fig.3 532-nm second-harmonic conversion efficiency as a function of the input 1064-nm fundamental laser intensity.

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

$1\ eV = 1.60218 \times 10^{-19} J$
$1\ u = 1.66054 \times 10^{-27} kg$

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
線量等量	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

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

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

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

動粘度　$1 m^2/s = 10^4 St$（ストークス）(cm^2/s)

圧力	MPa(=10bar)	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($=10^7$ erg)	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＝ 4.18605J（計量法）
＝ 4.184J（熱化学）
＝ 4.1855J（15℃）
＝ 4.1868J（国際蒸気表）

仕事率　1 PS（仏馬力）
＝ 75 kgf·m/s
＝ 735.499W

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）

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