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FOUR-PASS QUADRATURE ARRANGEMENT FOR HIGHLY EFFICIENT SECOND-HARMONIC GENERATION

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Four-Pass Quadrature Arrangement for Highly Efficient Second-harmonic Generation

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A four-pass quadrature arrangement was developed to generate green output with high efficiency for pumping an ultrashort pulse laser system. With this scheme, an efficiency from fundamental energy into total second harmonic energy in excess of 80 % was achieved for frequency doubling of 1064-nm in KTP with a low input fundamental laser intensity of 76 MW/cm^2. A total second-harmonic output of 486 mJ was obtained with 607 mJ of the input 1064-nm fundamental laser at 10 Hz.

Keywords: Quadrature Arrangement, Second-harmonic Generation (SHG), KTP, Nd:YAG Laser

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* Hamamatsu Photonics K. K.

4パス矩象波長変換方式による高効率第二高調波発生

日本原子力研究所関西研究所光量子科学研究センター

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(2001年2月20日受理)

Ti:sapphire レーザーに用いる励起光源のエネルギー利用効率の向上を目的として Nd:YAG レーザー光を効率よく第二高調波光に変換する方式を新たに考案した。KTP 結晶を用いた基礎実験において、この方式を用いることにより、76 MW/cm^2 の低い 入射 Nd:YAG レーザー光強度に対して 80 %の高い変換効率が得られた。 607 mJ の入射 Nd:YAG レーザー光に対して 486 mJ の第二高調波出力光が 10 Hz の繰り返し率で得られた。

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1. INTRODUCTION

Green lasers operating at 530 nm have a number of applications in medicine and materials processing as well as serving as useful pumping sources for other systems. The second harmonic output of Nd:YAG or Nd:YLF laser in nonlinear optical crystals such as $KTiOPO_4$ (KTP) is the most attractive for pumping light source of a Ti:sapphire chirped pulse amplifier (CPA) system. For second harmonic generation (SHG) with the 1064-nm Nd:YAG lasers, a commonly employed laser source, conversion efficiencies of around 50 % can be routinely obtained [1-7]. It is desirable to obtain high efficiency SHG to realize high power and compactness in Ti:sapphire CPA system. Also, in many applications, a high second-harmonic conversion efficiency is preferred for the purpose of improving the signal-to-noise ratio or reducing the required power of the laser source.

In order to achieve high conversion efficiency, a quadrature frequency conversion scheme has been proposed [8]. In the quadrature doubling scheme used for SHG, the optical axes of two type II crystals are arranged to be orthogonal and the polarization of input laser beam is rotated to interact in both crystals for efficient conversion. Thus, the input laser beam unconverted in the first crystal can be converted in the second crystal. Also, as the second harmonic output beam generated in the first crystal is not the correct polarization to interact in the second crystal, the beam can be passed through the second crystal without back-conversion.

In this paper, we describe a four-pass quadrature frequency conversion scheme by using polarization rotation and report a total frequency conversion efficiency of above 80 % from fundamental energy into total second harmonic energy with a low input fundamental laser beam intensity of 76 MW/cm^2. The incorporation of quadrature and multi-pass features in this scheme provides a frequency conversion performance superior to that of comparable lasers in its class. This scheme can be easily scaled up by increasing the size of the nonlinear optical crystal to accommodate larger input fundamental laser beam cross-section.

2. EXPERIMENTAL SETUP

The experimental arrangement of four-pass quadrature frequency conversion scheme is shown in Fig.1. The laser source used in this experiment was a Q-switched Nd:YAG laser (Continuum, Powerlite 910), operated at a repetition rate of 10 Hz. The input 1064-nm fundamental laser beam diameter was 8.5 mm and the pulse duration was 15 ns (full width at half maximum (FWHM)). $KTiOPO_4$ (KTP) was chosen as the nonlinear optical crystal because of its high effective nonlinear coefficient, large acceptance angle, large temperature bandwidth, and reasonably high damage threshold. The KTP crystal (Crystal Associates, gray-tracking-resistant KTP) size was 10mm×10mm×10mm. The crystal was oriented for type II phase matching for SHG of input 1064-nm laser radiation at room temperature. The input faces of the crystals were antireflection coated at both 532-nm and 1064-nm. The crystals were mounted on a rotation stage for optimizing the angle between the input beam and the crystals at room ambient without any crystal temperature control.

The input laser beam for this scheme, which was *p*-polarized, was relayed and passed through an optical isolator and a thin-film polarizer. The optical isolator (EOT, 12I1064) was placed between the Q-switched Nd:YAG laser and the frequency conversion part in order to provide sufficient optical isolation between the two sections. This scheme consists of a thin-film polarizer, a high-reflection mirror, two dichroic mirrors, a half-wave plate, two type II KTP crystals and a quarter-wave plate. The input beam was injected into the two KTP crystals in quadrature frequency conversion scheme by dichroic mirror M_1, which was high-reflection coated at 1064-nm and anti-reflection coated at 532-nm, and then converted, after rotating the polarization by 45° in a half-wave plate for correct polarization to the crystals for efficient conversion. Furthermore, the polarization of the input beam was rotated by 90° after a round-trip pass through the quarter-wave plate before retracing its path. As the input beam was passed through two KTP crystals and then half-wave plate, the input beam was rotated to *s*-polarized and reflected by thin-film polarizer for further two more passes. Thus, the input beam was passed through the two KTP crystals in quadrature frequency conversion scheme a total of four times and the second-harmonic output generated was extracted through the dichroic mirrors M_1 and M_2. A dual-output scheme was used to avoid back-conversion of second harmonic output beam. The typical application of the second harmonic dual output beams generated by this scheme is to pump Ti:sapphire amplifier. Figure 2 shows the pumping geometry of Ti:sapphire amplifier. The second harmonic output beams on each direction (total in four), which are elliptically polarized, will be separated into two linear polarized beams (*p*-polarized and *s*-polarized beams) by a thin-film polarizer. The two linear polarized beams will be rotated in half-wave plates for correct polarization to the Ti:sapphire amplifier for efficient absorption.

3. RESULTS

Figure 3 shows the 532-nm second-harmonic output energy as a function of the input 1064-nm fundamental laser energy for energy emitted through each mirror M_1 and M_2 and total energy emitted through both mirrors M_1 and M_2. The second-harmonic output and the fundamental laser energy were measured by a calibrated power meter (OPHIR, ATN). There were no compensation for optical losses such as reflection, absorption and scattering of the crystals, and transmission losses of the dichroic mirrors. From Fig. 3, it is seen that the 532-nm second-harmonic output energy emitted through M_2 is about ten times as much as that emitted through M_1. For pumping Ti:sapphire amplifier as shown in Fig.2, all the four second harmonic output beams incident on the Ti:sapphire amplifier at small angle to Ti:sapphire laser beam generate uniform gain profile with axial gradient in the gain distribution. The Ti:sapphire laser beam path will cross the gain gradient and each part of the beam will have the same gain history because the Ti:sapphire amplifier is pumped through the faces. The gain will then be the same for each part of the beam, and the beam will be amplified uniformly. A total second-harmonic output energy of 486 mJ was obtained with an input 1064-nm fundamental laser energy of 607 mJ.

Figure 4 shows the 532-nm second-harmonic conversion efficiency as a function of the input 1064-nm fundamental laser intensity for individual efficiency emitted through each mirror M_1 and M_2 and total efficiency emitted through both mirrors M_1 and M_2. The intensity was calculated from the measured pulse duration, the measured energy, and measured beam diameter. As can be seen from this figure, a total maximum second-harmonic conversion efficiency of above 80 % was achieved with a low input laser intensity of 76 MW/cm^2. The high efficiency enables efficient use of energy and hardware. The low input laser intensity enables the use of a smaller laser source, and ensures no photochromic damage (gray-tracking) [9,10] in KTP. Though the threshold of gray-tracking depends on the repetition rate of the laser and the growth technique of the crystal, laser damage thresholds ranging from 100 MW/cm^2 to about 10 GW/cm^2 have been reported.

4. CONCLUSION

We have demonstrated efficient SHG in four-pass quadrature frequency conversion scheme for pumping an ultrashort pulse laser system. A high second-harmonic conversion efficiency from fundamental energy into total second harmonic energy of 80 % has been achieved with low input laser intensity of 76 MW/cm^2. The successful operation of the scheme demonstrates that it is applicable and scalable to the design of a high power laser system with high efficiency.

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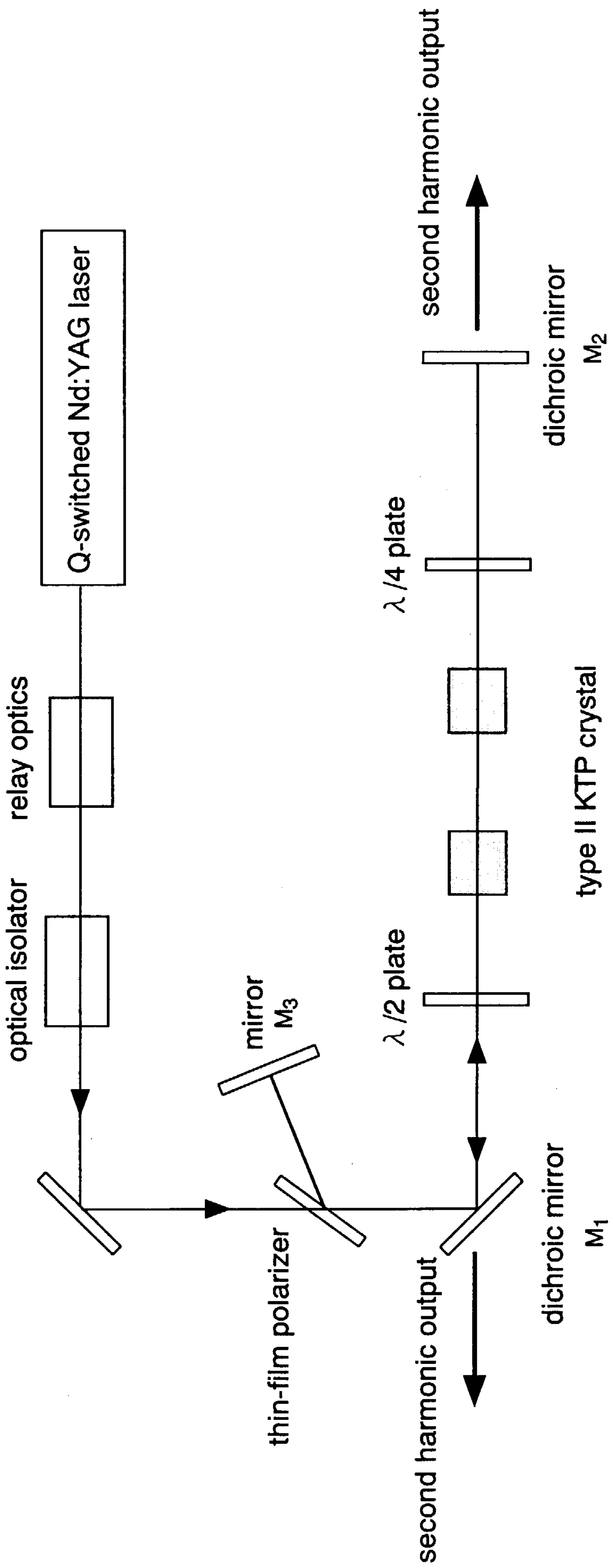

Fig.1　　Experimental arrangement of four- pass quadrature scheme.

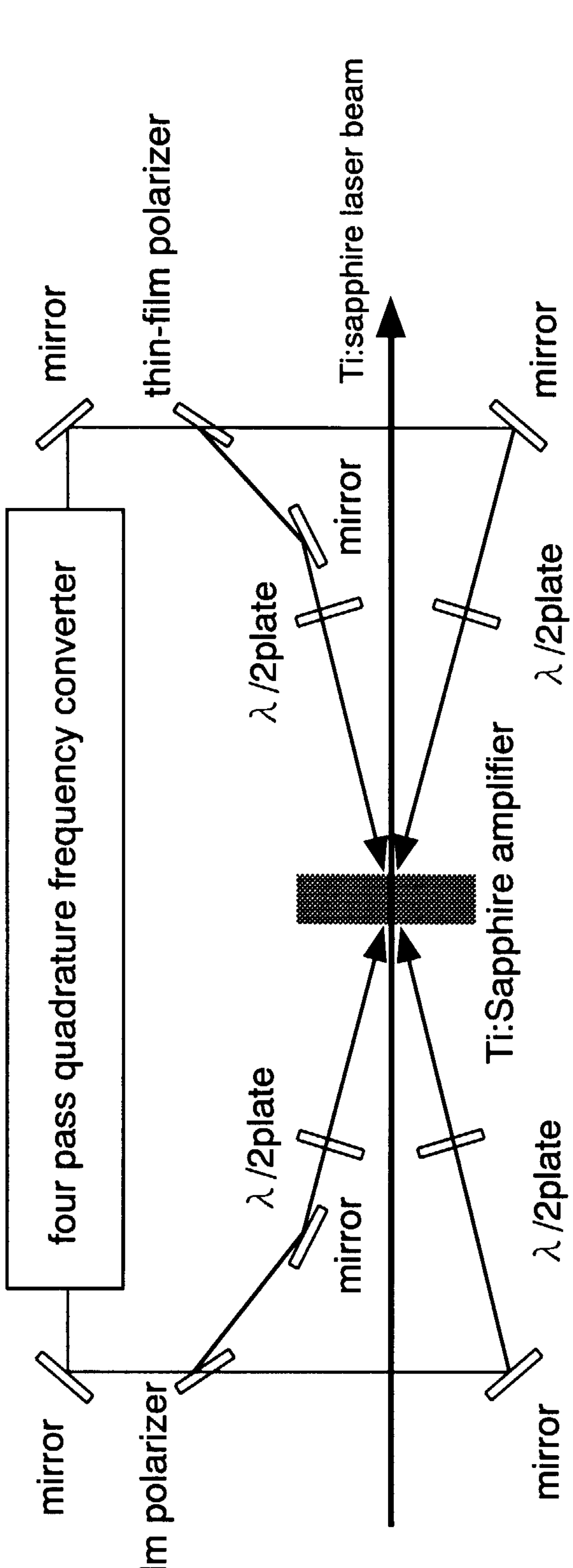

Fig.2 Pumping geometry of Ti:sapphire amplifier.

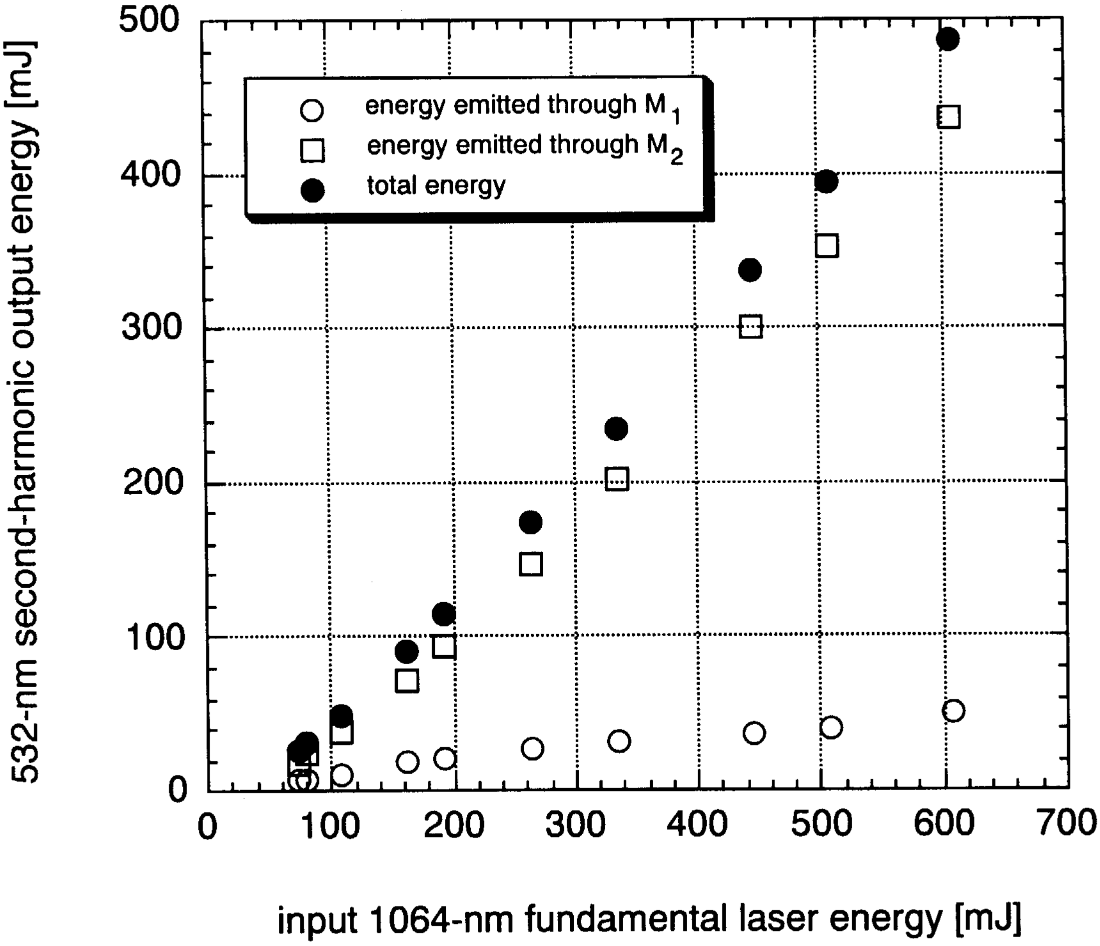

Fig.3 532-nm second harmonic output energy as a function of the input 1064-nm fundamental laser energy for energy emitted through each mirror M_1 and M_2 and total energy emitted through both mirrors M_1 and M_2.

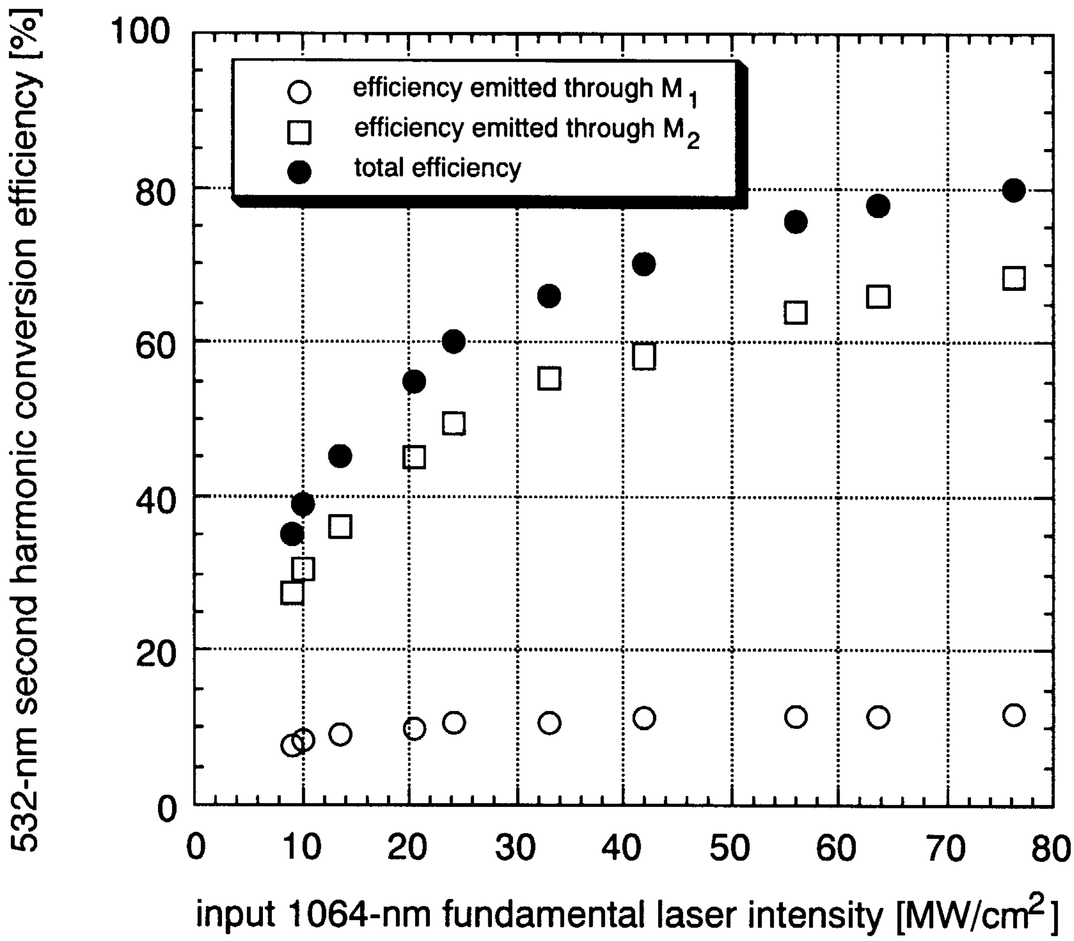

Fig.4 532-nm second-harmonic conversion efficiency as a function of the input 1064-nm fundamental laser intensity for individual efficiency emitted through each mirrorM_1 and M_2 and total efficiency emitted through both mirrors M_1 and M_2.

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

$1\ \mathrm{eV} = 1.60218 \times 10^{-19}\ \mathrm{J}$

$1\ \mathrm{u} = 1.66054 \times 10^{-27}\ \mathrm{kg}$

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

$1\ \text{Å} = 0.1\ \mathrm{nm} = 10^{-10}\ \mathrm{m}$

$1\ \mathrm{b} = 100\ \mathrm{fm}^2 = 10^{-28}\ \mathrm{m}^2$

$1\ \mathrm{bar} = 0.1\ \mathrm{MPa} = 10^5\ \mathrm{Pa}$

$1\ \mathrm{Gal} = 1\ \mathrm{cm/s^2} = 10^{-2}\ \mathrm{m/s^2}$

$1\ \mathrm{Ci} = 3.7 \times 10^{10}\ \mathrm{Bq}$

$1\ \mathrm{R} = 2.58 \times 10^{-4}\ \mathrm{C/kg}$

$1\ \mathrm{rad} = 1\ \mathrm{cGy} = 10^{-2}\ \mathrm{Gy}$

$1\ \mathrm{rem} = 1\ \mathrm{cSv} = 10^{-2}\ \mathrm{Sv}$

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

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

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	$J(=10^7 erg)$	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 = 4.18605 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)

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