Developments of All Solid-state Laser and Optics for Airborne and Space Lidar Systems

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1.Introduction

Spaceborne lidars have the potential to obtain atomospheric parameters such as the vertical and horizontal distribution of aerosols,cloud top hight,temperature and pressure profiles etc on a global scale.

The lidar system consists of a high power laser , receiving optics, and a detector with elctronics and signal processing. In this system, the laser is the most important device. High peak power laser diode(LD) pumped solid state lasers have been developed for airborne and space lidar systems.[1,2] For these applications,high efficiency with good beam quality and reliability are the most important factors in designing the laser.

In this paper we describe the design and performance of 100-mJ-class laser oscillator and lightweight telescope made of Beryllium.

2. LD pumped Nd:YLF Q-switched Laser

For high efficiency with good beam quality , the laser material with high stored energy and low thermal distortions should be selected. We utilized Nd:YLF as the laser material because of its long upper laser level lifetime, low thermal lensing and natural birefringence. In particular, c-axis Nd:YLF laser rod[3] is suitable for high power operation using laser didode side pumping.

To obtain the reliability for vibrations and shocks, the resonator must be insensitive to misalignment. There are two types of standing wave prism resonators whose misalignment sensitivities for both vertical and horizontal are much lower than those of conventional resonator with a pair of mirrors. One is crossed roof prism-roof prism resonator with polarization coupling optics and the other is mirror-cube corner prism resonator with output coupling mirror. Although the mirror-cube corner prism resonator is simple, three different polarization modes caused by three different bounces in the prism oscillate independently[4]. Thus we selected the crossed roof prism-roof prism resonator.

Figure 1 shows a schematic diagram of the developed Q-switched laser oscillator . The resonator consists of crossed polarization-state maintaining roof prisms (PMRP's),a polarization-state maintaining folding prism (PMFP), a polarizer, an intracavity telescope[5] and a half wave plate 1(HWP1). The polarizer is used as an output coupler with the HWP1 which gives a variable output coupling ratio. In this resonator, the resonant mode is equivalent to that of plane-plane resonator and this resonator acts as the stable resonator using the intracavity positive lens. Using polarization-state maintaining roof prisms,the output coupling ratio can be set continuously from 0 to 1 using the half wave plate. A magnification of the intracavity telescope is set to be 1.8 to use the laser rod itself as a mode selecting aperture and maximizing extraction energy of TEM_{00} mode. The telescope is slightly defocused to compensate the negative thermal lens power of the laser rod as well as to make this resonator as a stable resonator. Designing the g parameter as g_1g_2~0.5 by setting the effective focal length of the intracavity telescope to be about 7m , the

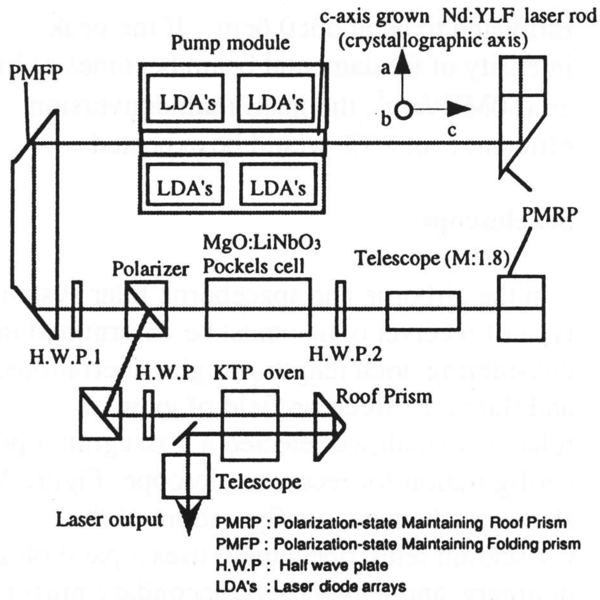


Fig.1 Schematic diagram of the laser diode side-pumped Nd:YLF laser.

spotsize in the rod is nearly constant (1.3mm: HW1/e^{2}M) for the focal length of thermal lens from -∞ to -10m. The MgO:LiNbO$_3$ Pockels cell is used as an Electrooptic Q-switching element. The polarizer and the Pockels cell with a half wave plate 2 (HWP2) and PMRP generate Q-switched pulse when quarter wave voltage is applied to the cell.

The pump module was assembled with a c-axis Nd:YLF laser rod and pumping LDA's. The rod is 4.1mm$^\phi$ ×65mm in size,doped with 1.5atm.% Nd. The rod is pumped by 16 three-bar-stacked LDA's using close-coupled 16-fold symmetrical side-pumping arrangement. These LDA's provide the combined maximum pump power of 2.9kW with 48% electrical efficiency. The combined central emission wavelength of these LDA's is 796nm at heatsink temperature of 25℃ and the emission linewidth is about 5nm. Taking into account π -polarized absorption coefficient of the rod and combined linewidth of the LDA's, absorption efficiency is estimated to be from 75% to 80% according to the central pump wavelength from 792nm to 798nm. This indicates that the fluctuation of the laser output is less than 6% when the heatsink temperature of LDA's changes about 20 ℃. Thus the LDA's do not need severe temperature control.

Type II KTP crystal,which is 5x5x10 mm^3 in size and controled at 60 ℃in the oven,is used as a second harmonic generator.

Figure 2 shows the Q-switched laser output characteristics of the fundamental beam. At the PRF of up to 50Hz, the maximum output pulse energy of more than 100mJ in less than 25ns pulse width was obtained. The

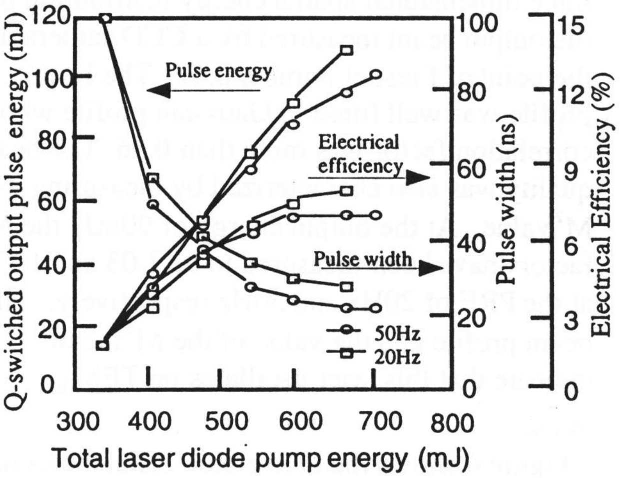


Fig.2 Q-switched output pulse energy, pulse width and electrical efficiency in TEM$_{00}$ mode of the laser oscillator.

corresponding peak power was more than 4.5MW and the electrical efficiency was more than 7%. The fluctuation of the output average power was measured to be ±0.5% or less for 50,000 shots operation when the coolant temperature was set to be constant and ±2.3% for the coolant temperature from 10 ℃ to 30 ℃.

The near field spatial energy distributions of

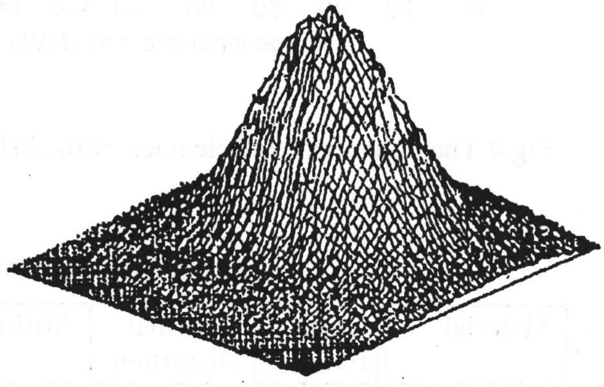


Fig.3 The spatial energy distribution of the output beam at the point of Fresnel number 0.67.

the output beams were slightly modulated by the edge diffractions at the laser rod. But the spatial energy distributions become well fitted to Gaussian profiles as the Fresnel number become smaller than 1.0. Figure 3 shows the typical three dimensional spatial energy distribution of the output beam measured by a CCD camera at the point of Fresnel number 0.67. The beam profile was well fitted to Gaussian profile whose correlation factor was more than 0.96. The beam quality was also characterized by measuring its M^2 value. At the output energy of 90mJ, the M^2 factors have been measured to be 1.03 and 1.17 at the PRF of 20Hz and 50Hz respectively. The beam profile and the value of the M^2 factor indicate that this laser oscillates on TEM_{00} mode.

Figure 4 shows the conversion efficiencies of the SHG. The conversion efficiencies of the SHG were approximately 55% at the PRF of up to 50Hz . Taking into account the peak intensity of fudamental beams of 50MW/cm^2 and the experimental conversion efficiency, phase mismatch of the KTP crystal was estimated to be about 0.6cm^{-1}. If the peak intensity of fundamental beam becomes as high as 150MW/cm^2, the maximum conversion efficiency of 80% would be expected.

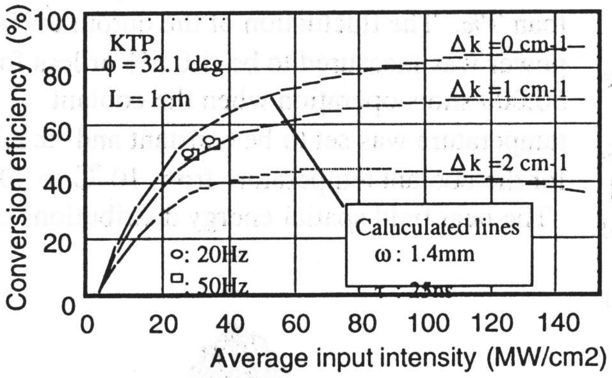


Fig.4 The conversion efficiencies of the SHG.

3.Telescope

In the airborne and spaceborne lidar systems, type of receiver optics must be determined in considering total length ,weight, aberrations, and flare etc. Because field of view is relatively small,we selected a Cassegrain optical configuration for receiver telescope. Figure 5 shows a schematic configuration of the Cassegrain telescope which uses a paraboloid praimary and a hyperbolic secondary mirror. Both mirror are comparatively easy to manufacture and test.

For the spaceborne lidar ,there are several materials of light weight mirror such as Fused Sillica, ultra low expansion glass(ULE),Zerodur, Beryllium, and Silicon Carbide(SiC) etc. These materials have been used for spaceborne optics. We make a comparison of these materials

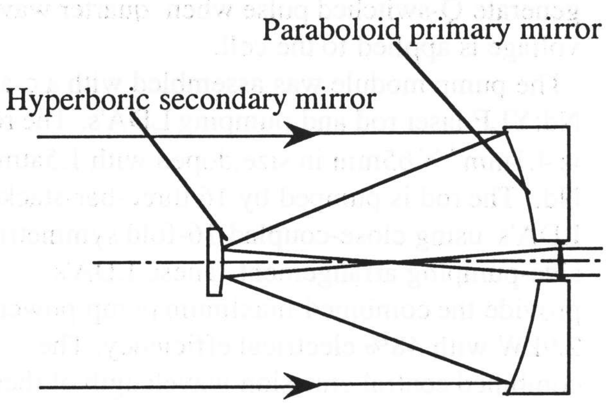


Fig.5 The Cassegrain telescope for the reciever optics.

Table 2. Trade-off for Primary Mirror Material

Material	Surface Finish	Thermal Distortion	Stiffness	Light weighting	Antiradiation	Achievment	Total
Beryllium	○	△	◎	◎	◎	◎	◎
SiC	◎	○	◎	◎	◎	△	◎
ULE	◎	◎	△	○	○	◎	○
Fused Silica	◎	◎	△	△	◎	○	△
Zerodur	◎	○	△	△	△	○	△

◎:Excellent,○:Good,△:Fair

whether to be suitable for primary mirror of lidar optics. Items for the comparison are surface finish, thermal distortion,stiffness, lightweighting,antiradiation,and achievment. The result is shown in Table 1. Beryllium or SiC is the best material. However Beryllium is more desireble than SiC in respect of achievement.

Telescope with Beryllium primary mirror was fablicated for airborne lidar and optical characteristics was measured. Figure 6 shows the external view of the fabricated telescope. Table 1 shows the performance of the telescope. The experimental results was in good agreement with the calculated value.

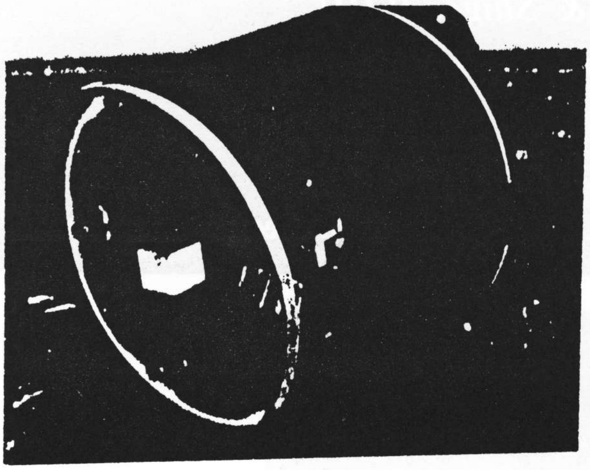


Fig. 6 External view of the fabricated telescope.

Table 1. Performance of Telescope

Item	Specifications
Clear Aperture	200mm
System F-number	3.2
Field of view	1.25mrad
Typical Focus Spot Diameter	40 μ m
Overall Transmittance	54%
Overall Length	270mm
Overall Diameter	264mm
Total Weight	6kg
Primary Mirror Material	Beryllium

4.Summary

We have developed the 100-mJ-class LD pumped Q-switched laser for airborne lidar systems using c-axis Nd:YLF rod and the crossed prism resonator. At the PRF of up to 50Hz, the electrical efficiency of more than 7% has been obtained in TEM_{00} mode which has the M^2 factor of less than 1.17. The conversion efficiency of the SHG using KTP was 55%.

Considering the relative low stimulated cross section of σ -polarized lasing at 1053nm ($1.34\times 10^{-19}cm^2$ was estimated), long lifetime (350 μ s at $5kw/cm^2$ pump condition was measured) and low thermal lensing effect of c-axis Nd:YLF, the output energy of one Joule and the electrical efficiency of more than 10%, which are required in the space lidar systems, would be easily obtained using a master oscillator power amplifier configuration (MOPA).

We have also developed the lightweight telescope with Beryllium primary mirror. Telescope with diameter of 1m, which is required in the spaceborne lidar systems, would be performed using a Beryllium mirror.

The airborne lidar systems using the 100mJ - Nd:YLF laser and 200mm-Beryllium telescope was developed and a flight test is planed in next year.

References

1. L.E.Holder, C.Kennedy, L.Long and G.Dube, IEEE J. Quantum Electron.,28, 986 (1992)
2. J.J.Kasinski, W.Hughes, D.DiBiase, P.Bournes and R.Burnham, IEEE J. Quantum Electron., 28, 977 (1992)
3. N.Sims,Jr.,N.P.Barnes,in technical digest of ASSL'93,41 (1993)
4. N.Hodgson,C.Rahlff,H.Weber and Wei Guang-hiu,in technical digest of CLEO'91 ,CThR18 (1991)
5. D.C.Hanna,S.G.Sawyers and M.A.Yuratich, Opt. Quantum Electron., 13, 493 (1981)

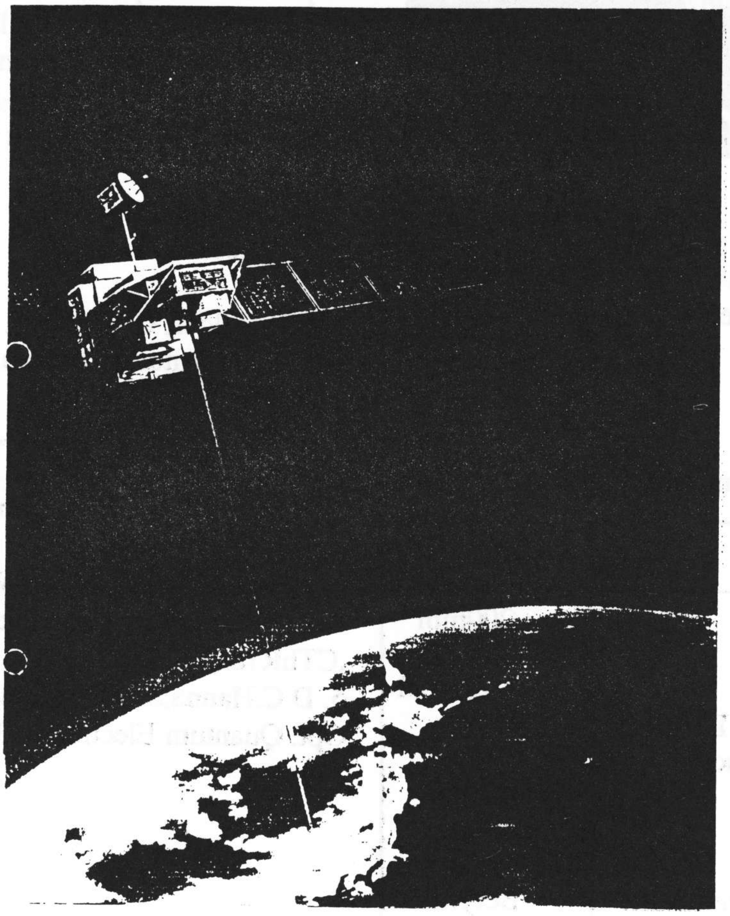
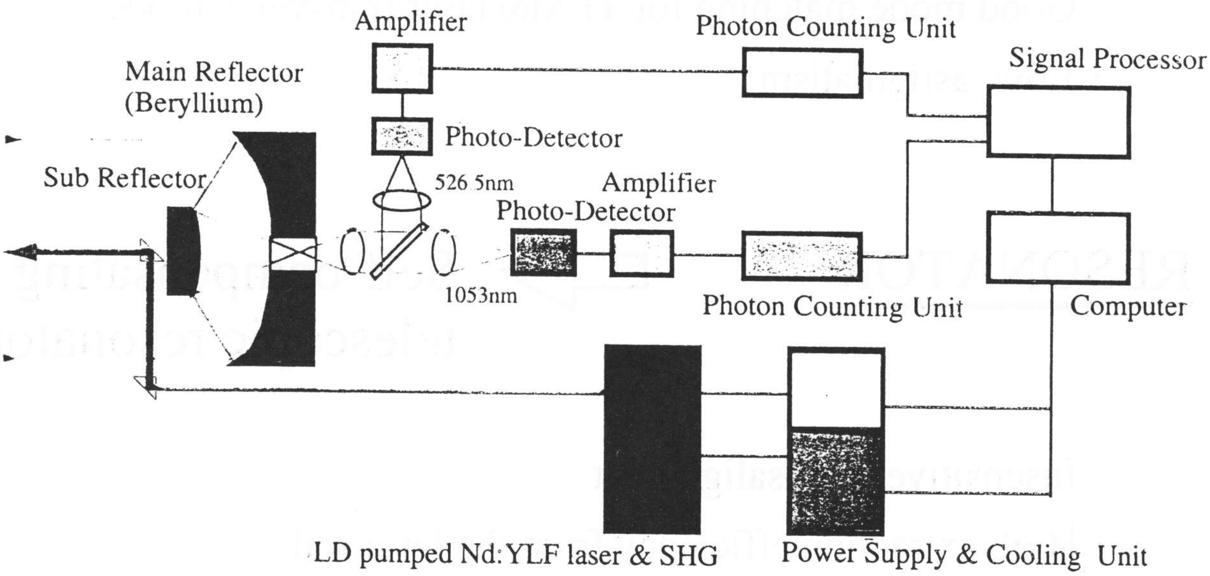


図　衛星搭載大気観測ライダ構想図
Space Lidar Systems

SYSTEM PARAMETERS for AIRBORNE LIDAR

ITEM	SPECIFICATION
WAVE-LENGTH	1053nm and 526.5nm
OUTPUT ENERGY	≧100mJ/pulse
REPETITION FREQUENCY	20～50Hz
SPATIAL RESOLUTION	≦1km (Horizontal) ≦100m (Vertical)
OBJECT for MEASUREMENT	Aerosol, Cloud
MEASUREMENT RANGE	0～10 km (Down looking)
RESOLUTION of the TOPHIGHT of the CLOUD	≦10m (Air,Water vapor)
TELESCOPE	200mm ϕ



SCHEMATIC DIAGRAM of AIRBORNE LIDAR

MITSUBISHI | DESIGN FEATURE

LASER MATERIAL ⇨ c-axis Nd:YLF

- Low thermal lens & Astigmatism
- High stored energy & Saturation fluence
- High absorption efficiency using LDA's side-pumping

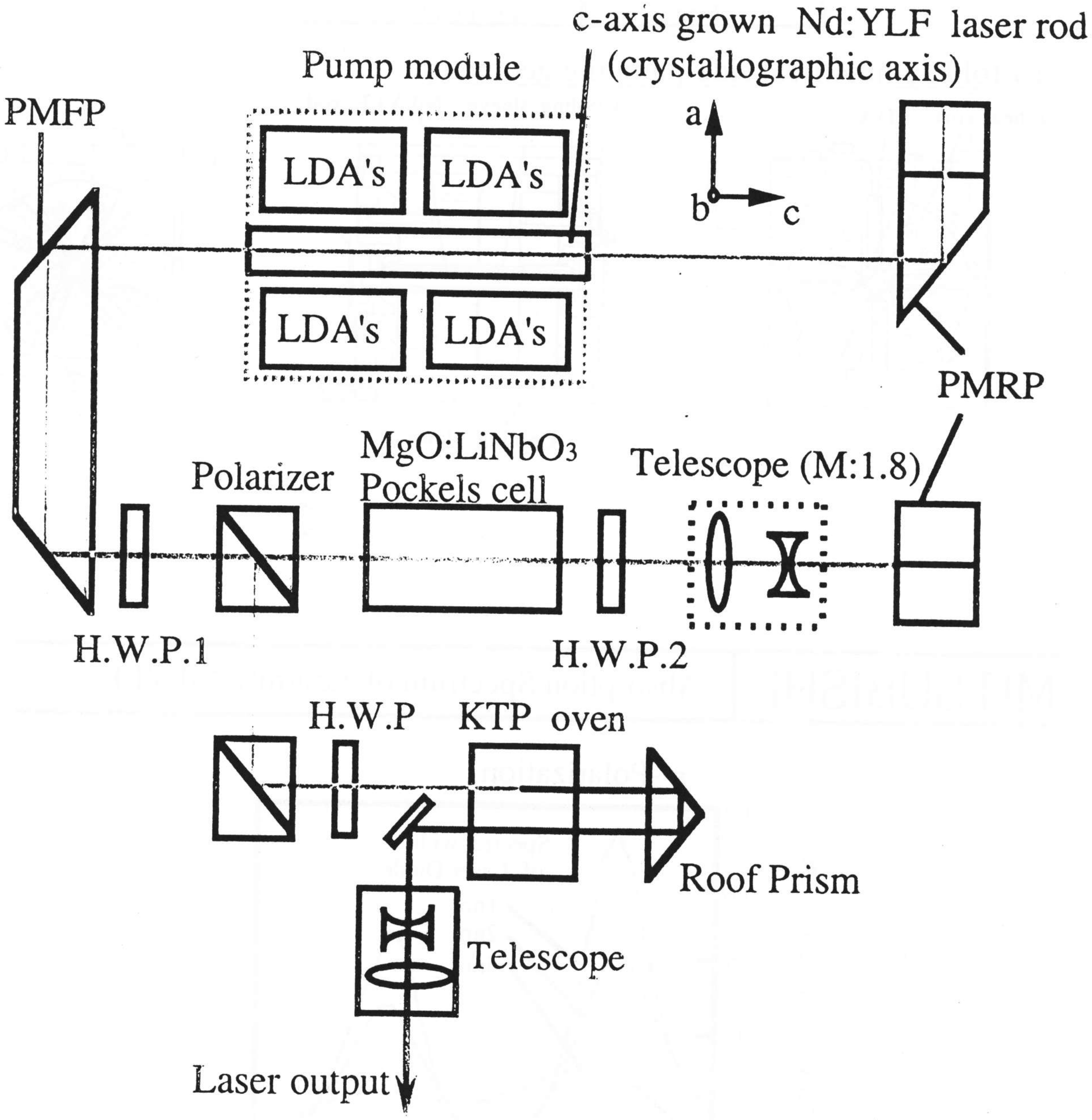
PUMPING ARRANGEMENT ⇨ 16-fold symmetrical side-pumping

- Good mode matching for TEM_{00} laser transverse mode
- Low astigmatism

RESONATOR ⇨ Self-compensating telescopic resonator

- Insensitive to misalignment
- High extraction efficiency from the laser rod
- Insensitive to thermal lens of the laser rod

MITSUBISHI | Configuration

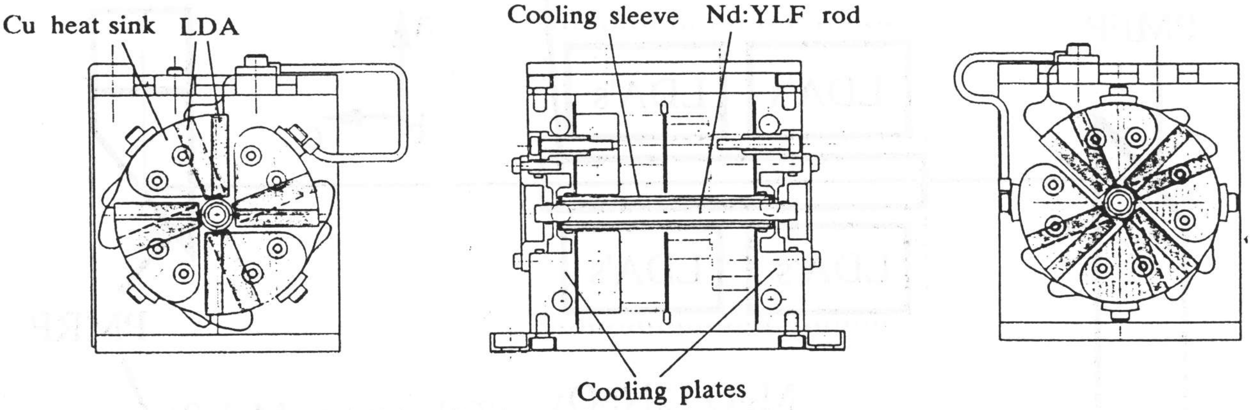


PMRP : Polarization-state Maintaining Roof Prism
PMFP : Polarization-state Maintaining Folding prism
H.W.P : Half wave plate
LDA's : Laser diode arrays

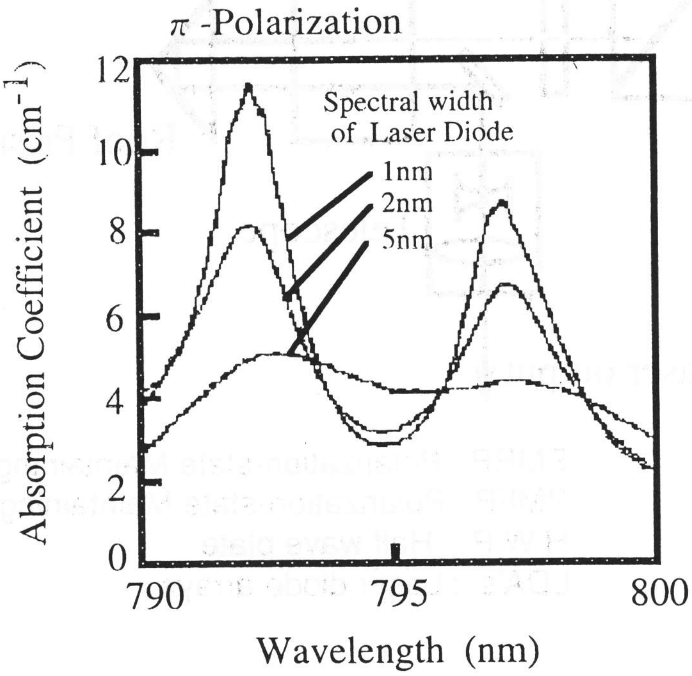
MITSUBISHI | Pump Module

LDA	SDL3230-TZB(3-bar stacked)
Number of LDA	16
Peak pump power	2.9kW
Laser material	c-axis Nd:YLF
Nd concentration	1.5 atm%
Size	φ4.1mm×65mm

16-fold symmetrical side-pumping geometry

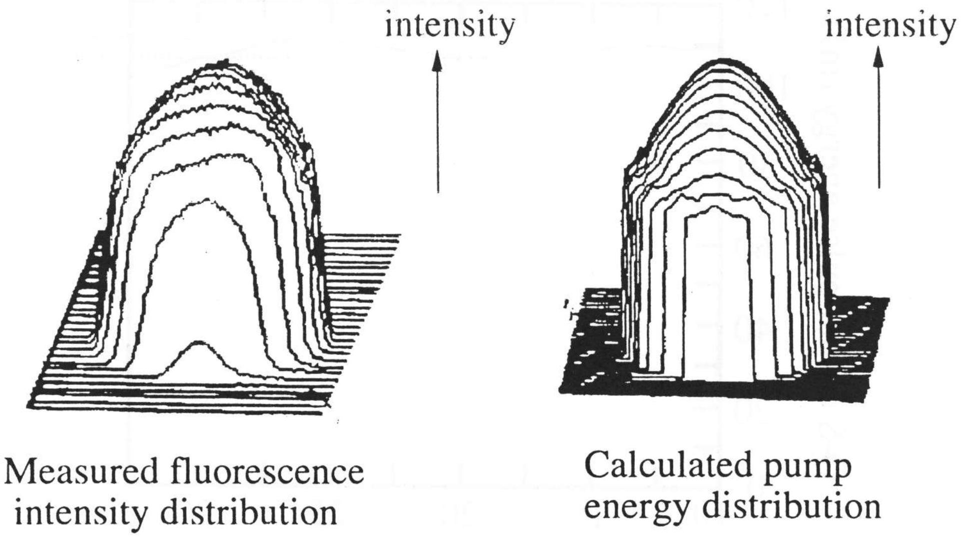


MITSUBISHI | Absorption Spectrum of 1.5atm% Nd:YLF



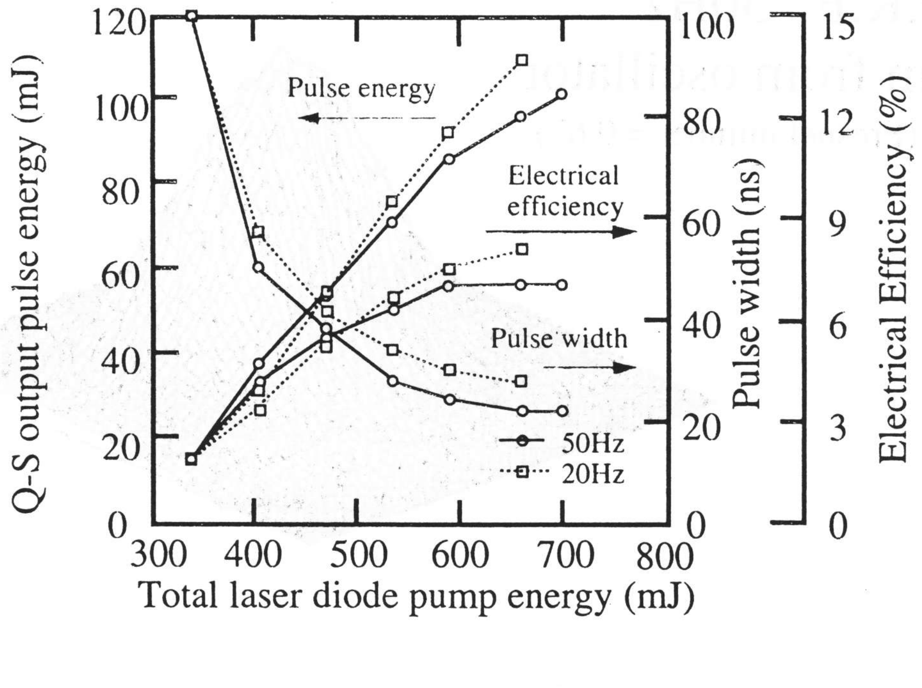
MITSUBISHI | Pump energy distribution

16-fold symmetrical side-pumping

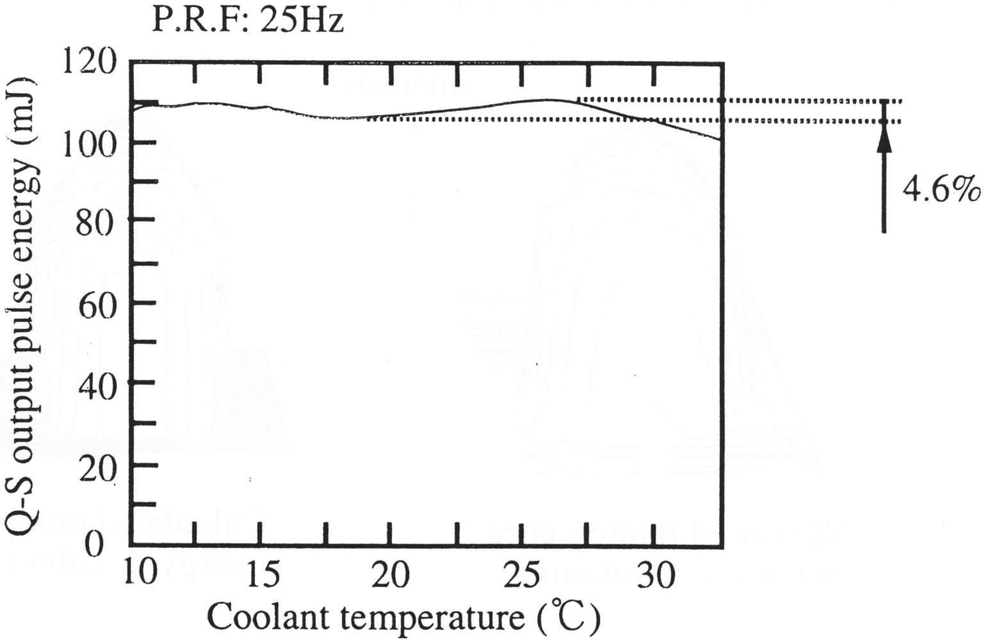


MITSUBISHI | Laser output characteristics

Q-switched TEM_{00} mode operation

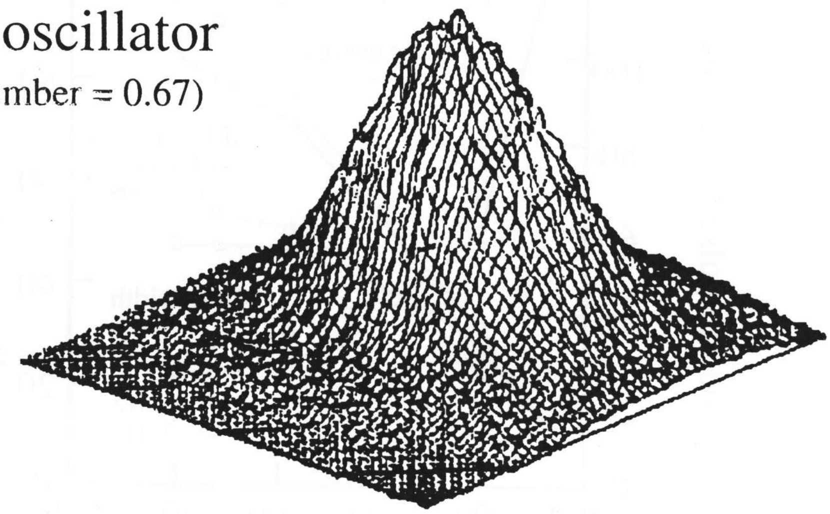


MITSUBISHI | Fluctuation of the output energy

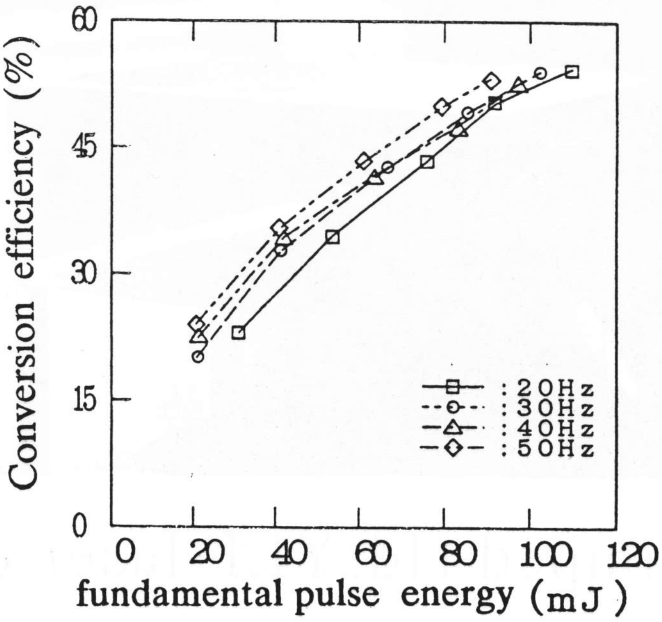


MITSUBISHI | Spatial energy distribution

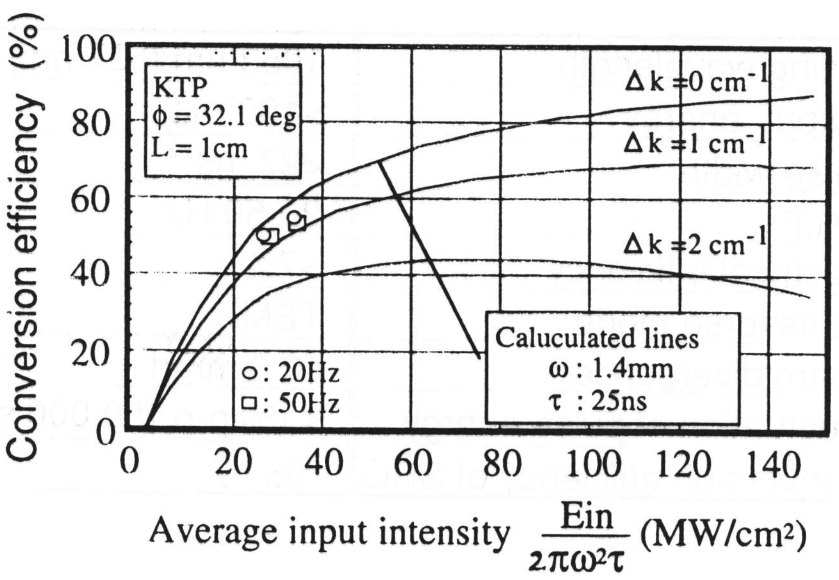
P.R.F : 50Hz
6m from oscillator
(Fresnel number = 0.67)

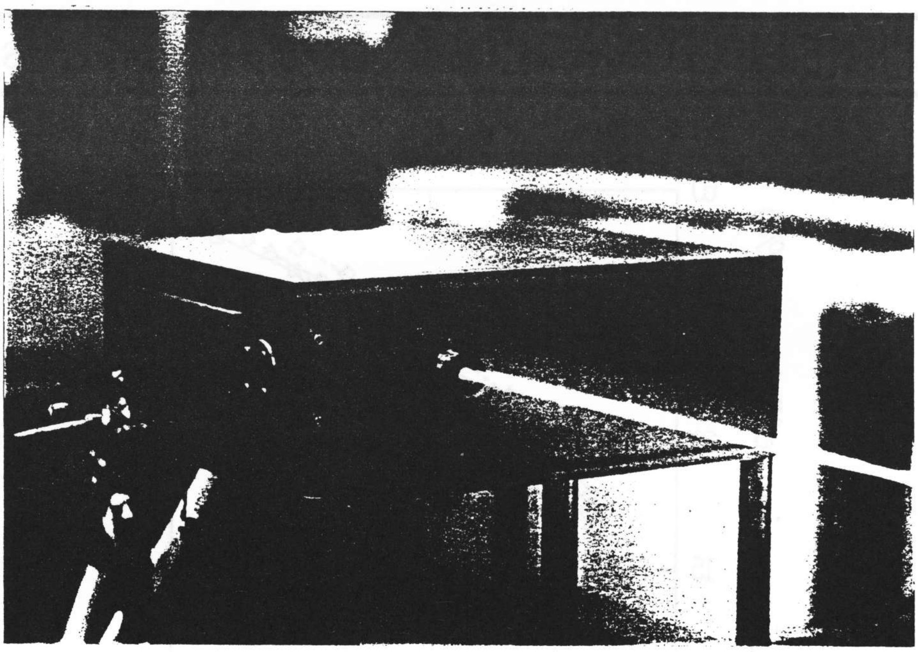


MITSUBISHI | Frequency conversion efficiency of KTP-SHG



MITSUBISHI | Input intensity dependence of SHG



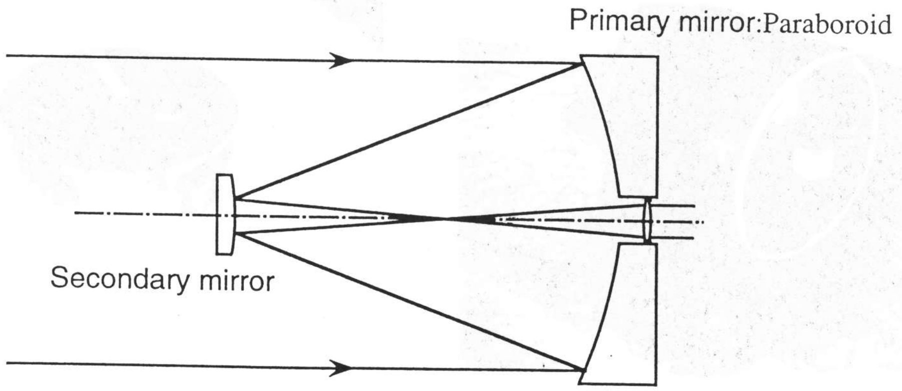


LD pumped Nd: YLF laser & SHG

MITSUBISHI | Performance

Lasing wavelength	1053 nm (527 nm)
Output energy	>100 mJ
Pulse width	<27 ns
P.R.F	20-50 Hz
Electrical efficiency	>7%
Transverse mode	TEM_{00}
Beam divergence	<0.8 mrad
Fluctuation of pulse energy	<1% p-p (50,000 shots)
Conversion efficiency of SHG	55 %

MITSUBISHI | Telescope

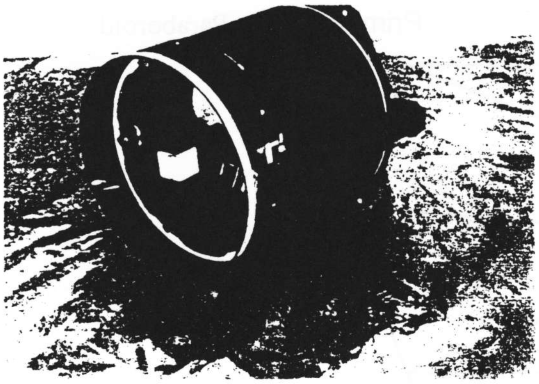


MITSUBISHI | Trade-off for Primary Mirror Material

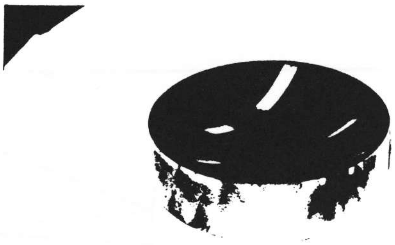
Material	Surface Finish	Thermal Distortion	Stiffness	Light weighting	Antiradiation	Achievment	Total
Beryllium	○	△	◎	◎	◎	◎	◎
SiC	◎	○	◎	◎	◎	△	◎
ULE	◎	◎	△	○	○	◎	○
Fused Silica	◎	◎	△	△	◎	○	△
Zerodur	◎	○	△	△	△	○	△

◎:Excellent,○:Good,△:Fair

MITSUBISHI | TELESCOPE



(A) Telescope



(B) Primary Reflector (Beryllium)

MITSUBISHI | Performance of Telescope

Item	Specifications
Clear Aperture	200mm
System F-number	3.2
Field of view	1.25mrad
Typical Focus Spot Diameter	40 μm
Overall Transmittance	54%
Overall Length	270mm
Overall Diameter	264mm
Total Weight	6kg
Primary Mirror Material	Beryllium