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Frequency Conversion of High Peak and High Average Power Lasers

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Abstract

We examine the potential performance of existing materials for frequency conversion of a 10 Hz, 10 ns, 1 kilowatt average power laser.

Frequency Conversion of High Peak and High Average Power Lasers*

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Mercury[1] is an advanced diode pumped laser facility under development at Lawrence Livermore National Laboratory as a 10% scale prototype of a single beamlet of a future inertial confinement fusion driver. The goals of this Yb:S-FAP based laser are 1 kW average power (100 J/pulse, 10 Hz) with a pulsewidth near 10 ns and a 10% wall-plug efficiency. High conversion efficiency (>50%) to the second harmonic (523.5) at the full aperture (3 cm x 5 cm) of the source is desired. We compare the potential of the available frequency conversion materials in the context of the peak and average power constraints using the 'threshold power' and 'thermally limited power' models developed at LLNL.

The threshold power criteria[2], P_{th}, is useful for determining the minimum peak power necessary for efficient frequency conversion (50%) in a given material.

$$P_{th} = \left[\frac{1}{a_r Q^2}\right]\left(\frac{1}{f_2}\right)\left(\frac{\beta_\theta \lambda}{C}\right)^2 \tag{1}$$

C is the nonlinear optical coupling[2], β_θ is the angular sensitivity of the phasematching process, λ is the fundamental wavelength and f_2 is a numerical factor: 1 for doubling and 2 for tripling. Q is a beam quality factor, fixed by the laser resonator (and subsequent thermal degradation) and a_r is an aspect ratio factor determined by the ratio of the thickness (t) of the beam in the angular insensitive phasematching plane, to the width (W) of the beam in the angular sensitive plane ($a_r = t/W$). For face cooled frequency conversion elements, $a_r = 1$. The threshold power, P_{th}, for BBO, LBO, and GdCOB are compared in Table 1. Given that the available peak power of this source greatly exceeds the threshold power of nearly all nonlinear optical crystals, the selection of those examined is based upon the current or near availability of crystals with a minimum aperture of 3 cm x 3 cm and with low optical absorption at the fundamental/harmonic. The last criteria excludes KTP, $LiIO_3$, and $LiNbO_3$ from consideration. The length required for efficient conversion is calculated and also shown in Table 1 assuming a 'drive' (C^2L^2I) ~ 1-3.

The "thermally limited power", P_{av}, figure of merit[3], is analogous to the threshold power limit for efficient frequency conversion. This condition, shown in equation 2, determines the maximum average power that can be tolerated by a given frequency conversion process, to maintain a high conversion efficiency.

$$a_r P_{av} \le \left(\frac{16\, C\, I_D^{0.5} \kappa}{\beta_T \alpha} \right) \qquad (2)$$

κ is the thermal conductivity, I_D is the limiting intensity (limited either by the damage threshold or by nonlinear optical absorption), β_T is the phasematching thermal sensitivity, and α is the linear optical absorption. The thermal average power efficiency limit, P_{av}, is also compared for each crystal. The uncertainties in this calculation are much larger than for the threshold power calculation. Only limited information is available concerning the damage threshold and optical absorption in the available materials. Given the variability of the data, the average power limit is calculated assuming the absorption coefficient is less than 0.25%/cm in LBO and BBO. Currently, insufficient information is available for GdCOB to predict its potential thermal limitations.

From a combined perspective of both the average power limitations, available peak power, and anecdotal information concerning available aperture and parasitic processes, a single Type I BBO plate is the most attractive candidate for frequency conversion of this laser source, requiring only a single plate. Type I BBO crystals with apertures of 2.2 - 2.5 cm^2 can be currently obtained with the required thickness of 3 - 4 mm. Although currently available in slightly larger apertures, the higher thermal sensitivity and smaller nonlinearity of LBO makes it much less attractive than BBO. Due to the lower thermal conductivity, and small nonlinearity, KD*P has the lowest potential for utilization as a *single plate* frequency converter. However, in principle, the average power limitations of a single plate of KD*P, or any crystal, can be circumvented through the use of multiple plates. Large aperture KD*P is readily available, mitigating the need for materials development should larger apertures be required, transferring the challenge to developing a robust, multi-plate, gas cooled frequency conversion architecture.

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Table 1. Threshold power and average power limititations for 1.06 μm doubling

Material / Process	Phasematching Angle (θ,ϕ)	Angular Sensitivity β_θ (cm-rad)$^{-1}$	d_{eff} (pm/V)	Thermal Sensitivity β_T (cm-°C)$^{-1}$	Thermal Conductivity κ (W/(cm-°C))	Nonlinearity C (GW$^{-1/2}$)	**Opt. Length (cm)**	**P_{th} (MW)**	**P_{av} (kW)**
LBO 2ωI T=23 °C	(90,13.3)	1.528×10^3	0.82	0.87	0.035	1.9	**0.53** [A] **0.91** [B]	**7.1**	**0.5**
LBO 2ωII T=23 °C	(22.5,90)	6.08×10^2	0.84	0.69	0.035	1.94	**0.52** [A] **0.89** [B]	**1.1**	**0.63**
LBO 2ωI T=158 °C	(90, 0) NCPM	0	0.84	1.42	0.035	1.94	**0.52** [A] **0.89** [B]	**0**	**0.3**
BBO 2ω Type I	(21.1,90)	8.439×10^3	2.05	0.109	0.016(Z) 0.014(X-Y)	5.19	**0.19** [A] **0.33** [B]	**29**	**4.9**
BBO 2ω Type II	(30.4,90)	5.604×10^3	1.58	0.15	0.016(Z) 0.014(X-Y)	4	**0.25** [A] **0.43** [B]	**21.5**	**2.7**
KD*P 2ωI	(37.6,45)	4.305×10^3	0.215	0.24	0.011(Z) 0.015 (X-Y)	0.60	**4.65** [A] **8.06** [B]	**564**	**0.224**
KD*P 2ωII	(59,0)	2.02×10^3	0.34	0.305	0.011(Z) 0.015 (X-Y)	0.977	**1.02** [A] **1.77** [B]	**46**	**0.287**
GdCOB	(18.1,0)	2.40×10^3	1.23	?	0.014	2.85	**0.35** [A] **0.61** [B]	**7.8**	**?**

[A] optimized length assuming drive ~1

[B] optimized length assuming drive ~3

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