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Thermomechanical Properties of Cr:Tm:Ho:Y₃Al₅O₁₂ *

John E. Marion

April 5, 1990

Abstract

The thermomechanical properties of Cr:Ho:Tm:Y₃Al₅O₁₂ have been measured and compared to similar measurements on Nd:Y₃Al₅O₁₂. We find that, in general, the properties are similar, with the single exception being thermal diffusivity. Nd:YAG has substantially higher thermal diffusivity than Cr:Tm:Ho:YAG. Consequently, the intrinsic thermal stress resistance figure of merit R^*_T , which governs a materials resistance to fracture in the presence of a steady thermal gradient is lower in Cr:Tm:Ho:YAG ($3.37 \text{ Wm}^{-1/2}$) than in Nd:YAG ($4.79 \text{ Wm}^{-1/2}$).

1. Introduction

The search for efficient $2\mu\text{m}$ lasers has recently focused on Ho:YAG coactivated with Cr and Tm¹. The broad band absorption of Cr couples well to flashlamps, which efficiently transfer energy to Tm. In high concentrations the Tm fluorescence is quenched and two $^4F_{3/2}$ excitation levels can resonance-couple to the upper laser level of Ho. By this scheme, slope efficiencies in excess of 2% have been achieved.²

While characterized spectroscopically, Cr:Tm:Ho:YAG has not been carefully analyzed with regard to thermomechanical properties. Here we report measurements of thermomechanical properties in the context of fracture resistance in a steady state thermal gradient.

The thermal stress resistance figure of merit³ which characterizes the inherent materials properties governing resistance to fracture from a steady state thermal gradient⁴ is

$$R^*_T = K_{IC} \kappa(1-\nu)/\alpha E \quad (1)$$

where R^*T is the intrinsic thermal stress figure of merit, κ is thermal conductivity, ν is Poisson's ratio, α is thermal expansion coefficient, E is Young's modulus and K_{IC} is fracture toughness. R^*T differs from the commonly used RT in that fracture toughness, the materials' inherent resistance to crack propagation, is substituted for the fracture stress. This is done because fracture stress (strength) is an extrinsic parameter which depends on the flaw size, whereas fracture toughness is an intrinsic parameter.⁴

II. Measurements

a) Elastic Constants

Elastic constants are calculated from acoustic velocities and density. Density is measured by Archimedes method. Acoustic velocities are measured by the pulse echo overlap technique in which the frequency of a transducer attached to the sample is tuned until overlap of pulse and echo occur. For cubic materials, such as the garnets, there are three independent elastic constants; C_{11} , C_{12} and C_{44} .

The samples provided were not oriented as requested; consequently average acoustical velocities were used to get an isotropic approximation for the elastic constant.

$$E = \rho V_s^2 (4-3r^2)/(1-r^2) \quad (2)$$

Where E is Young's modulus, ρ is density, V_s is the average shear velocity and r is the ratio of V_L , the average longitudinal velocity, to V_s . The results, Table I, indicate that Young's modulus of Cr:Tm:Ho:YAG (268.1 GPa) is a little smaller than Nd:YAG (282.9 GPa). In general, these acoustic velocity measurements are limited by the accuracy to which the sample length can be measured. However, both pieces of YAG had some residual stress which retards particularly the shear wave. We note that our Nd:YAG measurement, 282.9 GPa, is similar to the commonly quoted 282 GPa.⁵ We estimate that despite the residual stress, the error is less than 5%.

b) Thermal Conductivity

Thermal conductivity is calculated from the product of the thermal diffusivity, λ , specific heat, C_p , and density ρ : the C_p and ρ are readily measured with high accuracy ($\pm 3\%$). By calculating the thermal conductivity

from these individual measurements, the common problems in direct heat conduction measurements are avoided.

The thermal diffusivity is measured using the pulse method and is performed at room temperature. In this method a small (1cm diameter) oriented disk with opaque coatings is irradiated on one face with a high power (10J) pulsed laser, while the temperature rise on the opposite face is monitored with an IR detector. The characteristic heating curve and the sample thickness give the thermal diffusivity. A standard deviation of 5% is typical for this measurement on glass samples. While there is no NIST (National Institute of Standards and Technology) standard reference material for thermal diffusivity, the absolute accuracy of the measurement was assessed by testing Pyroceram, (Code 9606, Corning Glass), a microcrystalline ceramic that is particularly uniform and is chemically stable. Pyroceram has been used as an informal thermal diffusivity standard for two decades in the physical properties community.

Thermal diffusivity of Cr:Tm:Ho:YAG ($2.59 \text{ cm}^2/\text{s}$) is much lower than Nd:YAG ($4.18 \text{ cm}^2/\text{s}$). Phonon scattering due to the larger fraction of high atomic mass ions (Tm doping) is the probable cause. Heat capacity was determined using differential scanning calorimetry using sapphire as a NIST secondary reference standard. The results are directly traceable to NIST and accuracy is typically $\pm 3\%$. Heat capacity of the two crystals was similar (Cr:Ho:Tm:YAG = 0.548 J/gmK ; Nd:YAG = 0.536 J/gmK).

The thermal conductivity is calculated to be 6.64 W/mK for Cr:Tm:Ho:YAG and 10.2 W/mK for Nd:YAG. Our previous measurement on YAG (9.8 W/mK)⁵ is within the collective errors of the three measurements ($\rho C_p \lambda$).

c) Thermal Expansion

Thermal expansion was measured using a differential push rod dilatometer. Samples were surrounded by an inert environment of nitrogen and measured with respect to NIST fused silica. The absolute accuracy of the measurement was tested by measuring four NIST secondary reference standards nominally 1 cm in length and with expansion coefficients ranging from 0.5×10^{-6} to $20 \times 10^{-6} \text{ K}^{-1}$ from room temperature to 300°C . The errors ranged from $\pm 7\%$ for expansion coefficients at the low end of the range to $\pm 2.5\%$ for expansion coefficients at the high end.

Our measurements of thermal expansion indicate that these two crystals are similar: Cr:Tm:Ho:YAG had a thermal expansion of 6.62K^{-1} and Nd:YAG was 6.78K^{-1} at 300°C . This two percent difference is within the absolute error with respect to NIST standards. However, the provided samples, 5 cm in length, are expected to give 0.3% reproducibility for our dilatometer.

d. Fracture Toughness

Fracture toughness is measured using the indentation method.⁶ A Vicker diamond pyramidal indenter is lowered onto the sample under a known load. Cracks emanating from the indentation are related to the fracture toughness by

$$K_{IC} = b (E/H)^{1/2} P/C_0^{3/2} \quad (3)$$

where b is an empirical constant (0.016), E is Young's modulus, H is hardness, P is the load in Newtons and C_0 is the indenter center to crack tip length.⁶

This fracture toughness measurement is poor from an absolute scale ($\pm 30\%$), but is fairly reproducible ($\pm 10\%$) on materials in which the fractures around the indenter are well behaved. In both samples indentation loads between 5 and 10 Newtons produced straight cracks emanating from the corners of the indentation that were long enough for the far field stress approximations to be valid (i.e., greater than twice the indentation width). Loads in this range also did not produce undesirable lateral cracks under the indentation. Fracture of both samples can be classified as "well behaved".

The fracture toughness results gave $K_{IC} = 1.2\text{ MPam}^{1/2}$ for both materials. This is in the same range as other garnets.⁴

III. Conclusions

Most of the thermomechanical properties are about the same for these two materials, however, the thermal diffusivity is much lower in triply doped YAG. The calculated intrinsic stress resistance parameter, R^*_T , illustrates that Cr:Tm:Ho:YAG has about 70% of the fracture resistance from thermal stress as does Nd:YAG. Consequently, the triply doped rods will fracture at 70% of the thermal power of Nd:YAG, if the fabrication of the rods has resulted in identical depth of machining defects.

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Table I.

Thermomechanical Properties of Doped YAG

	<u>Cr:Tm:Ho:YAG</u>	<u>Nd:YAG</u>
Density, gm/cm ³	4.68	4.56
Longitudinal velocity, m/s	8548	8562
Shear velocity, m/s	4732	4998
Young's modulus, GPa	268.1	282.9
Poisson's ratio	0.25	0.25
Specific heat, J/gmK	0.548	0.536
Thermal diffusivity, cm ² /s	2.59	4.18
Thermal conductivity, W/mK	6.64	10.21
Fracture toughness, MPa m ^{1/2}	1.2	1.2
Thermal expansion, K ⁻¹	6.62	6.78
<hr/>		
Intrinsic thermal stress resistance figure of merit, R^*_T , Wm ^{-1/2}	3.37	4.79

$$R^*_T \text{ Cr:Tm:Ho:YAG} / R^*_T \text{ Nd:YAG} = 0.70$$

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