

Optical Absorption Measurements in Monocrystalline Sapphire at 1 micron

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ABSTRACT

Measurements are reported on the optical absorption of various samples of monocrystalline sapphire from various manufacturers, at 1 μm wavelength. The lowest observed absorption coefficient was 3.1 ppm/cm comparable to the best optical glass materials. The absorption coefficient showed variations within samples $\sim 30\%$ and was not correlated with metal impurity concentration.

Introduction

Advanced optical techniques, and particularly interferometers for gravitational wave detection, require extremely low loss optical materials. The test masses in laser interferometer gravitational wave detectors need to combine excellent mechanical and acoustic properties, with superb optical performance [1]. Due to its high sound velocity and very low acoustic losses, sapphire appears to be an ideal candidate material. Its thermal noise amplitude can be expected to be between one and two orders of magnitude better than silica. If its optical performance was satisfactory, sapphire would be an ideal material for test masses and beamsplitters in interferometers. Due to its high thermal conductivity (about 17 times higher than silica) it is less susceptible to thermal lensing. Some preliminary data [2] indicates that the optical absorption in sapphire at 1 μm is comparable to good quality samples of pure silica. For this reason we undertook a series of measurements on various samples of sapphire, made by different techniques, to assess their optical absorption. Measurements were made using the mirage effect as described below.

Measurements were made using the same apparatus as described in Baures and Man [2]. A single mode NdYAG laser giving stabilised power of about 26W was chopped at about 500Hz and focussed inside the sample to be measured. This is the pump beam. Optical absorption causes heating, and through the temperature dependence of refractive index, creates a refractive index gradient near to the pump beam. A probe beam, provided by a HeNe laser passes through the heated region, and experiences a deflection (at the chopper frequency) proportional to the absorbed power. The probe beam deflection is measured with a quadrant photodiode, and detected using a lock-in amplifier referenced to the chopper signal.

As first shown by Jackson *et al.*[3], for high modulation frequency, the maximum deflection angle is given by

$$\theta_{max} = (L/20a^3n) \cdot dn/dT \cdot (\alpha P_o/v\rho c). \quad (1)$$

Here L is the interaction length of the two beams in the sample (which depends on the beam geometry); a is the waist size of the pump laser, n is the refractive index of the medium, dn/dT is the temperature coefficient of refractive index of the medium, α is the absorption coefficient of the medium, P_o is the pump power, v is the chopper frequency, ρ is the density of the medium and c the specific heat of the medium.

Due to the difficulty in calibrating the signal it is highly advantageous to use relative measurements as long as at least one reference sample is available. In our case several reference samples were available. In this case calibration is avoided and the absorption coefficient is obtained from the relation:

$$\alpha = \alpha_{ref} \cdot (V/V_{ref}) \cdot (dn/dT_{ref}) / (dn/dT) \cdot (\rho c) / (\rho c)_{ref}. \quad (2)$$

Here ref refers to the reference sample. To use this calibration procedure it is essential that the beam geometry be unaltered between measurements.

Results

The HeNe probe beam and the NdYAG beam were adjusted so as to cross near the centre of the samples. The relative angle between the two beams was 7 degrees. For the beam size $\sim 100 \mu\text{m}$, the interaction length was about 1 mm, substantially smaller than the samples, which varied in length from 8 mm to 90 mm. Care was taken to ensure that the interaction region was within the samples. Through small adjustments of the NdYAG beam direction it was possible to probe a substantial volume within the sample to determine the homogeneity of the sample absorption coefficient.

Five samples of sapphire were tested, and compared with several silica samples of known absorption. All measurements were relative to the known samples. Frequent remeasurements of the known samples were made to ensure the stability of the measurement system. Care was taken to ensure that all surfaces were clean, since surface absorption can create a spurious signal if the interaction region approaches the absorption site. Care was also taken to verify the expected phase inversion as the pump beam was moved from one side to the other of the probe beam. The pump beam was directed so that residual transmission did not impinge on the quadrant photodiode to minimise the feedthrough signal arising directly from the pump. This signal is 90 degrees out of phase from the mirage signal, and is typically $\sim 0.3 \mu\text{V}$ compared to the smallest signal in any sample $\sim 6 \mu\text{V}$. When the lock-in amplifier phase is correctly adjusted, the measurement is insensitive to this effect.

Results are given in Table 1 below. The measurements on the known samples are all internally consistent. Most measurements on the sapphire samples were scaled relative to the EQ reference sample which has an absorption coefficient of 125 ppm/cm. However the results could have been scaled relative to any other reference sample without affecting the results. The results for sapphire were scaled according to equation (2) using the

following data for sapphire and silica respectively: dn/dt , 1.3×10^{-5} , 1.2×10^{-5} /deg C; density, 3.98, 2.2 g-cm⁻³; specific heat, 0.77, 0.79 Jg⁻¹.

TABLE 1

Sample	Characteristics	Measured Absorption	Comments
PC reference	1940 ppm/cm		
EQ reference	125 ppm/cm	129 ± 10	relative to PC reference
Herasil 1	56 ppm/cm	58 ± 3	relative to EQ reference
Suprasil 312	6.2 ppm/cm	6.2 ± 0.5	relative to EQ reference
#1 UC sapphire [4]	Cr ~ 1 ppm	max 22 ± 2 min 16 ± 2 mean: 20 ± 6	rel to EQ one bad spot 25 ppm/cm
#2 CS Hemex Ultra sapphire [5]	Very low metal content. Cr~1-10 ppb	55 ± 4	rel to EQ. One region ~ 0.5 mm ³ ~100 ppm/cm
#3 RISC sapphire [6]	Cr > 1 ppm	200 ± 20	rel to EQ
#4 Melles-Griot [7]	Flame fused	max 16 ± 2 min 11 ± 2	rel to EQ
#5 CSI White [5]	High purity	max 3.5 min 3.1	rel to PC

The results in Table I show that there is substantial variability in sapphire absorption at 1 μm wavelength. It was also notable that samples appeared to be somewhat inhomogeneous. Variability as the interaction region was moved within the sample was reproducible, and could not be attributed to surface absorption. Two samples made by the heat exchanger method, #2 and #3, were inferior to the UC sample made by the Czochralski method. However, the third heat exchanger sample from Crystal Systems (#5 CSI White) gave the best results. The lowest absorption observed was 3.1 ppm per centimetre.

It was notable that the sample with the lowest Cr content (#2), and with the lowest metal content was not the sample with lowest absorption. The UC sapphire was one of a batch of 5 manufactured by Union Carbide in 1986. Three of them were used in cryogenic sapphire oscillators very sensitive to the total Cr⁺⁺⁺ content.[8] These measurements

showed no significant differences between samples. Another of this batch was tested previously, and showed 5ppm/cm absorption.[2] [9]

Three of the samples were examined under a few watts of 532 nm argon ion laser power to probe the homogeneity of the chromium impurities. The red fluorescence of Cr+++ was easily visible in all samples when viewed with the naked eye through a red filter. Unfortunately, no quantitative measurement scheme was available. Very strong fluorescence was visible in the Chinese sample. Strong fluorescence was visible in the UC sample. Clear bands of inhomogeneity could also be observed in this sample, emphasising that the Cr impurities are inhomogeneously distributed. The bands were longitudinal and slightly spiralled, on one side of the sample only, and of ~1 mm width. No localised point fluorescence sites could be detected.

Weak fluorescence could also be observed in the CS Hemex Ultra sample. Allowing for the logarithmic sensitivity of the eye it could be guessed that the Cr concentration in the Chinese sample was 10-50 ppm, relative to the known ~1 ppm level in the UC sample. Then the SC sample would be about 10-100 ppb.

The strong chromium inhomogeneity in the UC sample did not correlate with the inhomogeneity of the absorption. In addition the sample with the lowest Cr did not have the lowest absorption. We conclude that the metal content and particularly the Cr content is only weakly related to the absorption at 1 μ m. Other impurities such as hydroxide may be responsible. At 1 μ m wavelength hydroxide contributes absorption of .01 ppm/cm per part per million hydroxide concentration.

Conclusion

The best sapphire sample tested here has absorption about 70% of the absorption of the best bulk sample of silica reported and about 2 times that of the total losses in the best optical fibres, (1.8 ppm/cm including a contribution of about 0.4 ppm/cm from Rayleigh scattering). Only two samples had absorption similar to the single previously reported measurement at this wavelength while others were substantially worse. Absorption appear to be only weakly correlated with metal impurity concentrations.

Combined with the fact that sapphire has much reduced thermal noise compared with silica makes sapphire look extremely advantageous for demanding applications such as laser interferometer gravitational wave detectors. However the losses are highly variable from sample to sample, and inhomogeneous within samples. The inhomogeneities could lead to difficulties. In particular, it will be difficult to obtain high power recycling factors

in interferometers in which a substantial amount of power must pass through a component with inhomogeneous losses. It is very important to understand the nature of the observed losses, to allow improvements in the manufacturing process.

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