single-photon absorption (SPA). On the other hand, we have to operate reasonably near the band edge to minimize the free carrier absorption (FCA) induced in the material.

Since we are using high input powers and operating at the band tail, we expect TPA to dominate over SPA. The z-scan signature for the TPA is opposite to SPA. For TPA, the transmitted power decreases with increasing incident power and is minimum at the beam focus as shown in Figure 3, whereas for SPA the transmitted power increases with increasing incident power (absorption saturation).

Here we neglected the loss of carriers due to recombination and diffusion because these processes occur on longer time scales than the femtosecond pulses used in the experiments.

For the measurements we use low-temperature-grown GaAs (LT-GaAs) samples. One sample is 1.5-µm thick grown at 270°C and rapid thermal annealed for 30 s at 700°C and the other is 1.07-µm thick grown at 220°C and rapid thermal annealed for 30 s at 900°C. The TPA coefficients for these samples were measured to be equal to ~ 35 cm/GW and ~ 30 cm/GW, respectively.[4] The laser pulse repetition rate was reduced to 4 kHz to minimize any possible thermal problems.

In Figure 4 we show how the beam spot size is evaluated and as can be seen changing the fitted value by approximately ± 10% will result in inaccurate fitting to the measurements.

Conclusion

The open aperture z-scan technique can be used to measure small laser beam spot sizes. It is a simple and inexpensive method to measure the laser beam spot sizes. We have shown that by using this method one can measure small laser beam spot sizes with uncertainty less than 10%.

Acknowledgments

We would like to thank David Thompson and Brad Robinson at McMaster Univ. for growing the LT-GaAs samples, P. Mascher of McMaster Univ. for the AR coatings, and H.E. Ruda of the Univ. of Toronto for annealing the samples. We acknowledge research support from the Photonics Research Ontario, and the Natural Sciences and Engineering Research Council of Canada.

References

1. Photon Inc., BeamScan manual for model 1180 optical profiler.
2. M. Sheik-Bahae *et al.*, "Sensitive measurement of optical nonlinearities using a single beam," IEEE J. Quantum Electron. **26,** 760–769 (1990).
3. E.W. Van Stryland and M. Sheik-Bahae, "Z-scan technique for nonlinear materials characterization," Critical reviews of optical science and technology, SPIE **CR69,** 501–524 (1997).
4. H.S. Loka *et al.*, "Two-photon absorption coefficient and refractive index changes in low-temperature-grown GaAs," Proc. CLEO '98 **6,** 536 (1998).

Thermal Expansion of Borosilicate Glass, Zerodur, Zerodur M, and Unceramized Zerodur at Low Temperatures

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Abstract

Current plans for space exploration are calling for more information about materials—at ever lower temperatures. The University of Arizona is making a 2-m prototype mirror for the Next Generation Space Telescope (NGST) to operate at 35 K.[1] Previous low temperature measurements of thermal expansion have been limited to temperatures down to 77 K, except for the very low temperature studies of White *et al.*[2,3,4]

We present here some new thermal expansion measurements of materials useful for optical engineering, made over the temperature range 10–300 K, and compare these with existing data for other materials. In particular, we present new low temperature data on borosilicate glass, Schott's recently manufactured Zerodur, Zerodur M, and unceramized Zerodur.

Of special interest are the thermal expansivity zero-crossings, which occur near 32 K for borosilicate glass and near 83 K for unceramized Zerodur. The former is close to the desired operating temperature for the NGST; the latter is close to the convenient boiling temperature of liquid nitrogen.

The experimental method has been described previously.[5] It involves configuring a Fabry-Perot resonator with the sample as mirror spacer, locking a tunable HeNe laser to the Fabry-Perot resonant frequency, which depends on spacer length, and comparing this laser's frequency with that of a frequency-stabilized HeNe laser.

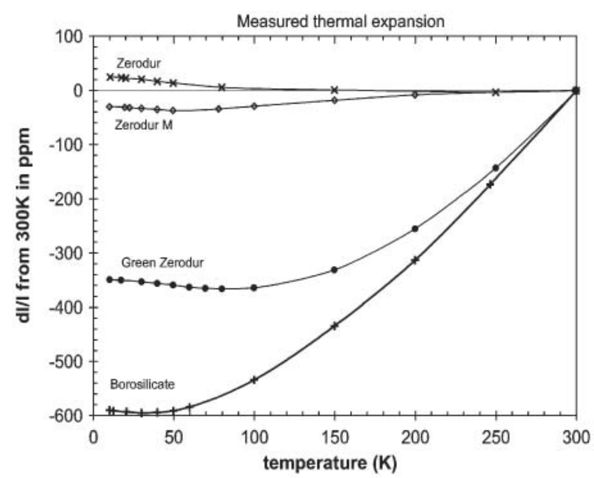

Figure 1. Measured thermal expansion of four materials –300 to 10 K.

Experimental details

The samples were configured as cylinders 99.75 mm long and 25.40 or 31.25 mm in diameter. A hole was bored down the symmetry axis. The ends of the samples were polished flat and parallel so that mirrors could be optically contacted to form confocal Fabry-Perot resonators. Temperature rates of change were less than 5 K/h. Details about the samples are as follows:

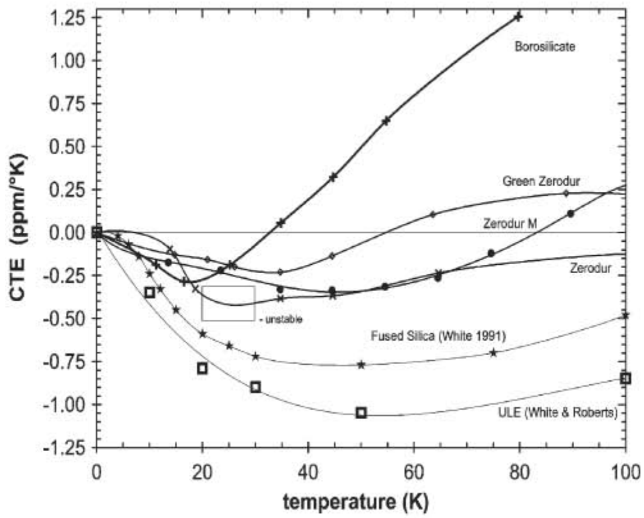

Figure 2. *CTE of six materials –300 to 10 K.*

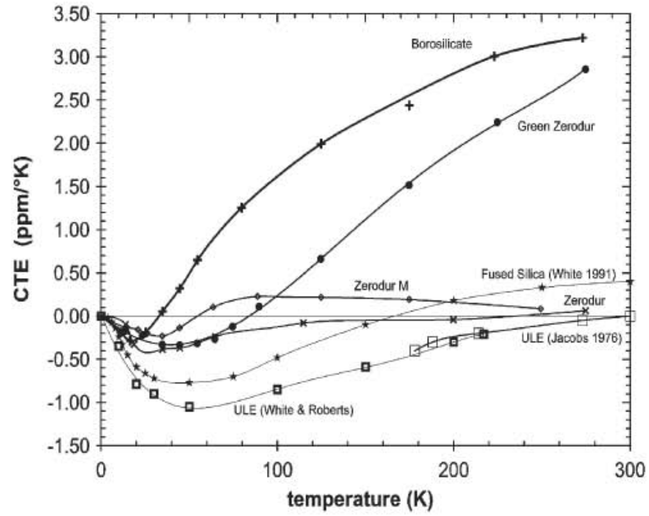

Figure 3. *CTE of six materials, –300 to 10 K, showing region of Zerodur instability.*

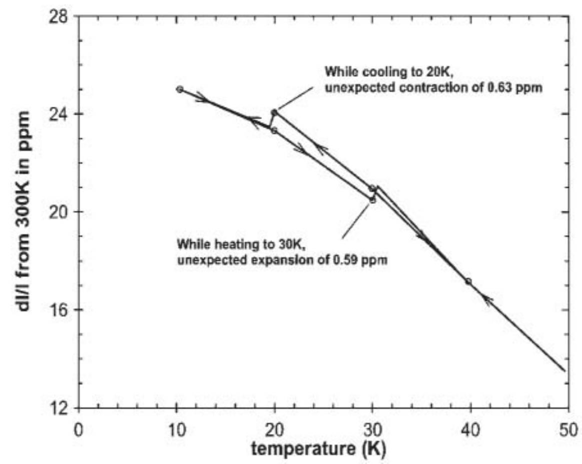

Figure 4. *Details of Zerodur instability.*

Zerodur

Zerodur is a glass-ceramic manufactured by Schott and designed to have near-zero expansion coefficient at room temperature. As noted by Roberts *et al.*,[3] Jacobs *et al.*,[6] and White,[2] Zerodur has been evolving, so that the date of production is important. The Zerodur described here reached us via R. Dyer of Composite Optics Inc. It was produced by Schott Duryea, Penn. in June of 1996. Melt # F9028/1 LK5471.

Zerodur M

Zerodur M is a variation of Zerodur with reduced MgO, designed to decrease relaxation effects (hysteresis) that have been observed in Zerodur at the level of l ppm.[6] The Zerodur M reached us via R. Dyer of Composite Optics Inc.

Unceramized Zerodur

This material was investigated because of its possible availability in large, uniform disks.

Borosilicate glass

The particular borosilicate glass investigated was Schott Borofloat, which is available in large, uniform sheets.

Results

Figure 1 (previous page) shows the normalized displacement dl/l versus temperature, between 300 and 10 K, for the four materials we have just measured. Figure 2 shows the data of Figure 1 in terms of cte versus temperature and including cte of fused silica and Corning 7971 ULE for comparison.

We found a region of temperature (see Fig. 3) where Zerodur showed instability amounting to 0.6 ppm. This is shown in Figure 4, which is an enlarged view of Figure 1. At low temperatures, Zerodur normally expands upon cooling. As sample temperature decreased from 30 K and was approaching 20 K we observed sample length steadily increasing (about .06 ppm/h). This abruptly (10 min.) changed to a steady decrease (about .06 ppm/hr). Further cooling produced "normal" length increase upon cooling. When sample temperature was then increased, we observed "normal" shrinking for temperatures up to 30 K. However, as sample left 30 K equilibrium for higher temperatures sample length decreased about .5 ppm and then increased.

Note that endmirrors could not have slipped since they were optically contacted Zerodur that remained in contact. Zerodur has exhibited hysteresis in two other temperature ranges: near 250 K and near 420 K.[6] No instability was observed in Zerodur M.

References

1. J.H. Burge et al., "Lightweight Mirror Technology Using a Thin Facesheet With Active Rigid Support," Proc. SPIE **3356** (SPIE Press, Bellingham, WA, 1998) (in press).
2. G.K. White, "Thermal expansion at low temperatures of glass-ceramics and glasses," Cryogenics **16,** 487 (1976).
3. R.B. Roberts et al., "Thermal properties of Zerodur at low temperatures," Cryogenics **22,** 566 (1982).
4. S.J. Collocott and G.K. White, "Heat capacity and thermal expansion of Zerodur and Zerodur M at low temperatures," Cryogenics **31,** 102 (1991).
5. S.G. Jacobs et al., "Thermal expansion uniformity of materials for large telescope mirrors," Appl. Opt. **23,** 4237 (1984).
6. S.G. Jacobs and D. Bass, "Improved dimensional stability of Corning 9600 and Schott Zerodur glass ceramics," Appl. Opt. **28,** 4045 (1989).