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Optical Materials Characterization

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and

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Semi-Annual Technical Report
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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, *Secretary*

Dr. Betsy Ancker-Johnson, *Assistant Secretary for Science and Technology*

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

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OPTICAL MATERIALS CHARACTERIZATION

Abstract

The refractive indices of three prisms of chemical vapor deposited ZnS were measured at room temperature over the wavelength range 540 nm to 1.083 μm. The refractive indices of eight specimens of CaF_2 doped with Er were measured from 404.7 nm to 1.083 μm. The doping range was 0.001% to 3% Er. Interferometric measurements of dn/dT were made over the temperature range −180 °C to 200 °C at the wavelengths 632.8 nm and 3.39 μm on single crystal specimens of BaF_2, CaF_2, reactive atmosphere processed (RAP) KBr, RAP KCl, KCl doped with KI, LiF, NaF and SrF_2, and on chemical vapor deposited (CVD) ZnSe and hot forged CaF_2.

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OPTICAL MATERIALS CHARACTERIZATION

1. Technical Report Summary

1.1 Technical Problem

Windows subjected to high-average-power laser radiation will undergo optical and mechanical distortion due to absorptive heating. If the distortion becomes sufficiently severe, the windows become unusable. Theoretical calculations of optical distortion in laser windows depend on the following material parameters; absorption coefficient, refractive index, change of index with temperature, thermal expansion coefficient, stress-optical constants, elastic compliances, specific heat, thermal conductivity and density. Our program has been established to measure refractive indices, changes of index with temperature, stress-optical constants, elastic compliances, and thermal expansion coefficients of candidate laser window materials.

1.2 General Methodology

Laboratory experiments are conducted for measuring refractive indices, changes of index with temperature, stress-optical constants, elastic compliances, and thermal expansion coefficients.

The refractive indices of prismatic specimens are measured on precision spectrometers by using the method of minimum deviation. Two spectrometers are used. One instrument, which uses glass optics, is used for measuring refractive indices in the visible with an accuracy of several parts in 10^6. The other instrument, which uses mirror optics, is used for measuring refractive indices in the ultraviolet and the infrared to an accuracy of several parts in 10^5. Using both spectrometers we can measure refractive indices over the spectral region 0.2 μm to 50 μm.

We measure the coefficient of linear thermal expansion, α, by a method of Fizeau interferometry. The interferometer consists of a specially prepared specimen which separates two flat plates. Interference fringes are observed due to reflections from the plate surfaces in contact with the specimen. We obtain α by measuring the shift of these interference fringes as a function of temperature. We can measure α from -180 °C to 800 °C.

The change of refractive index with temperature, dn/dT, is measured by two methods. In the first method, we measure the refractive index with the precision spectrometers at two temperatures, 20 °C and 30 °C, by varying the temperature of the laboratory. This provides us with a measure of dn/dT at room temperature. The second method may be used for measuring dn/dT from -180 °C to 800 °C. We obtain dn/dT from a knowledge of the expansion coefficient and by measuring the shift of Fizeau fringes in a heated specimen as a function of temperature. The Fizeau fringes are due to interferences between reflections from the front and back surfaces of the specimens.

We measure piezo-optic coefficients and elastic compliances using a combination of Twyman-Green and Fizeau interferometers. From the shift of fringes in specimens subjected to uniaxial or hydrostatic compression, we obtain the necessary data for determining all the stress-optical constants and elastic compliances.

In materials with small piezo-optic constants or in materials that cannot withstand large stresses, we use interferometers designed to measure fractional fringe shifts. At 10.6 μm we use a modified Twyman-Green interferometer which has a sensitivity of 0.01λ. At 632.8 nm, we use a modified Dyson interferometer which has a sensitivity of 0.002λ. When using these interferometers to measure piezo-optic constants we must know the elastic constants of the material under test.

1.3 Technical Results

The refractive indices of three specimens of chemical vapor deposited (CVD) ZnS were measured at room temperature over the wavelength range 540 nm to 1.083 μm. The refractive indices of eight specimens of CaF_2 doped with Er were measured from 404.7 nm to 1.083 μm. The doping range was 0.001% to 3% Er. The latter measurements were done at the request of Dr. Fontanella of the United States Naval Academy.

We have measured the linear thermal expansion and dn/dT of the following materials:

BaF_2	LiF
CaF_2	NaF
KBr (RAP)*	SrF_2
KCl (RAP)*	ZnSe (CVD)
KCl doped with KI (KCl:KI)	

*reactive atmosphere processed.

The measurements were made by Fizeau interferometry over the temperature range from -180 °C to 200 °C. We measured dn/dT at 632.8 nm and at 3.39 μm. The thermal expansion data were in good agreement with earlier published data.

In addition to the above measurements on potential laser window materials, we have measured the linear thermal expansion coefficient and dn/dT of Plexiglas 55, a material used in the construction of aircraft windows. This work was done at the request of Captain Hurst of the Air Force Materials Laboratory at Wright-Patterson Air Force Base.

1.4 Department of Defense Implications

The Department of Defense is currently constructing high-power laser systems. Criteria are needed for determining the suitability of different materials for use as windows in these systems. The measurements we are performing provide data that laser system designers can use for determining the optical performance of candidate window materials.

1.5 Implications for Further Research

Measurements of refractive index, dn/dT, thermal expansion, and piezo-optical constants will be continued on candidate laser window materials as well as on other optical materials of interest to the Department of Defense. We shall continue our efforts on measurements at 3.39 μm, which is within the wavelength range of interest to designers of chemical laser systems (2-5 μm range).

The wavelengths of primary interest will shift from the infrared to the ultraviolet. The infrared laser window program is now coming to completion, whereas, interest is growing for optical materials data in the ultraviolet because of the development of powerful new lasers in the ultraviolet. These lasers include the XeF laser operating at 354 nm and the KrF laser operating at 248 nm. Procurement is proceeding for an argon ion laser and a frequency doubler. The laser will be operated in the ultraviolet to obtain radiation at 351 nm which is close to the XeF wavelength. We will double the 514.5 nm line to 258 nm which is near the KrF wavelength. We will then proceed to measure the optical properties of potential uv laser window materials.

At present, we are searching the literature for optical data on uv materials. Preliminary results indicate that very little dn/dT data exists and that photoelastic constant data are almost nonexistant in the uv region of the spectrum.

2. Technical Report

2.1 Refractive Index of CVD Zinc Sulfide and Erbium-Doped Calcium Fluoride

Marilyn J. Dodge and Warren K. Gladden

2.1.1 Introduction

Chemical vapor deposited (CVD) zinc sulfide is a promising candidate infrared laser window material. It is considered to have an useful transmission range from about 0.6 to 13μm with a strong absorption band at 6μm [1][1]. Three samples of this material have been submitted by B. A. de Benedetto of Raytheon Co[2]. The three specimens were identified as "standard", "high-scatter", and "high-temperature", and for the purpose of this report the samples will be designated as S, HS and HT respectively. Preliminary refractive index measurements were made on the S and HS samples of ZnS from 0.5461 to 1.083μm. The measurement of index was not possible on the HT sample below 0.78μm because of almost total absorption, but the refractive index has been determined from 0.7800 to 1.12μm. From visual observations, the S sample exhibited much more scatter than the HS sample.

Eight specimens of erbium-doped calcium fluoride were made available by John Fontanella of the U.S. Naval Academy for index of refraction measurements. The samples were all grown at the Harshaw Chemical Company. The samples were designated as follows:
CaF_2:Er.001%, CaF_2:Er.003%, CaF_2:Er.01%, CaF_2:Er.03%, CaF_2:Er.1%, CaF_2:Er.3%, CaF_2:Er 1%, and CaF_2:Er 3%. The refractive index was determined for each sample at 11 wavelengths from 0.4047μm to 1.083μm.

2.1.2 Experimental Technique

The specimens were in prismatic form and were measured by means of the minimum-deviation method on a Wild precision spectrometer. The index was determined at known emission wavelengths of mercury, cadmium and helium. An infrared image converter was used to facilitate the measurement of the near IR lines.

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1. Figures in brackets indicate the literature references at the end of this paper.
2. The use of company and brand names in this paper are for identification purposes only and in no case does it imply recommendation or endorsement by the National Bureau of Standards and it does not imply that the materials used in this study are necessarily the best available.

2.1.3 Experimental Results

The refractive index of the standard ZnS sample ranges from 2.3881 at 0.5461μm to 2.2869 at 1.083μm. The index of the hi-scatter sample was lower than the standard specimen by about 3×10^{-4}, and the hi-temperature sample has an index in the near IR of 2×10^{-4} higher than the standard sample. The dispersion curve for ZnS is shown in fig. 1. The experimental index values are considered accurate within 3×10^{-5}.

The index of refraction of the Er-doped CaF_2 increases with the increase in percentage of dopant. The index of CaF_2:Er.001% is compared with a recently studied sample of hot-forged CaF_2 [2] in Table 1. The increase in refractive index of each subsequent sample over the one preceding it is also shown in Table 1. As the percent of dopant increases to greater than .003% the increase in refractive index is almost predictable. The average change in refractive index over the wavelength range studied is 2.12×10^{-3} per 1% increase of erbium. There appears to be a slightly higher change in the blue than in the red region of the spectrum. Figure 2 shows index plotted as a function of wavelength for CaF_2:Er.001%, CaF_2:Er.1%, CaF_2:Er 1% and CaF_2:Er 3%. Refractive index values are plotted as a function of percent of erbium at five wavelengths in Figure 3. These values of refractive index are accurate within 1×10^{-5}.

2.1.4 Conclusions

The results discussed in this report are preliminary and for the visible and near IR regions of the spectrum only and should not be used in an attempt to predict the behavior of the refractive index in the infrared region of the spectrum for ZnS or in the IR or UV regions for CaF_2:Er. Index determinations are planned for all three samples of the CVD ZnS out to the IR absorption edge. Representative samplings of the erbium-doped CaF_2 will be measured from 0.2μm or, the UV absorption edge if higher than 0.2μm, to the IR limits of transmittance.

2.1.7 References

[1] B. A. de Benedetto, Private communication.

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TABLE I - CHANGE IN REFRACTIVE INDEX OF CaF_2:Er WITH INCREASE IN PERCENTAGE OF Er

λ(μm)	n HOT-FORGED CaF_2	n CaF_2(A)[a]	$\Delta n \times 10^5$							
			A-HF	B-A	C-B	D-C	E-D	F-E	G-F	H-G
0.4047	1.441509	1.441506	-0.3	2.6	1.0	4.5	14.4	43.9	160.5	478.3
0.4358	1.439492	1.439493	0.1	1.9	1.2	4.4	14.7	43.8	158.5	477.4
0.4678	1.437840	1.437841	0.1	1.7	1.4	4.3	14.4	43.7	158.3	475.0
0.4800	1.437297	1.437301	0.4	1.6	0.9	4.2	14.8	43.5	157.4	473.9
0.5086	1.436170	1.436174	0.4	1.2	1.3	4.4	15.0	43.6	157.2	472.0
0.5461	1.434959	1.434957	-0.2	1.6	1.3	4.2	15.3	42.7	156.8	471.3
0.5876	--	1.433867	--	1.8	1.2	4.2	15.2	42.5	156.8	469.7
0.6438	1.432701	1.432699	-0.2	1.7	1.6	3.8	14.6	43.4	155.5	466.9
0.6678	--	1.432297	--	0.5	1.3	3.8	15.8	42.1	156.0	468.5
0.7065	--	1.431703	--	1.2	1.3	3.7	15.2	41.9	158.0	463.4
1.014	1.428811	1.428823	1.2	1.7	1.5	4.8	15.6	39.6	156.0	462.1
1.083	1.428384	1.428400	1.6	1.6	1.2	3.3	15.7	41.8	155.2	460.7
AVG $\Delta n \times 10^5$	--	--	0.47	1.59	1.27	4.13	15.06	42.70	157.18	469.93
Δn/1%Er $\times 10^3$	--	--	4.70	7.95	1.8	2.06	2.15	2.14	2.24	2.35

a. A≡.001%Er; B≡.003%Er; C≡.01%Er; D≡.03%Er; E≡.1%Er; F≡.3%Er; G≡1%Er; H≡3%Er

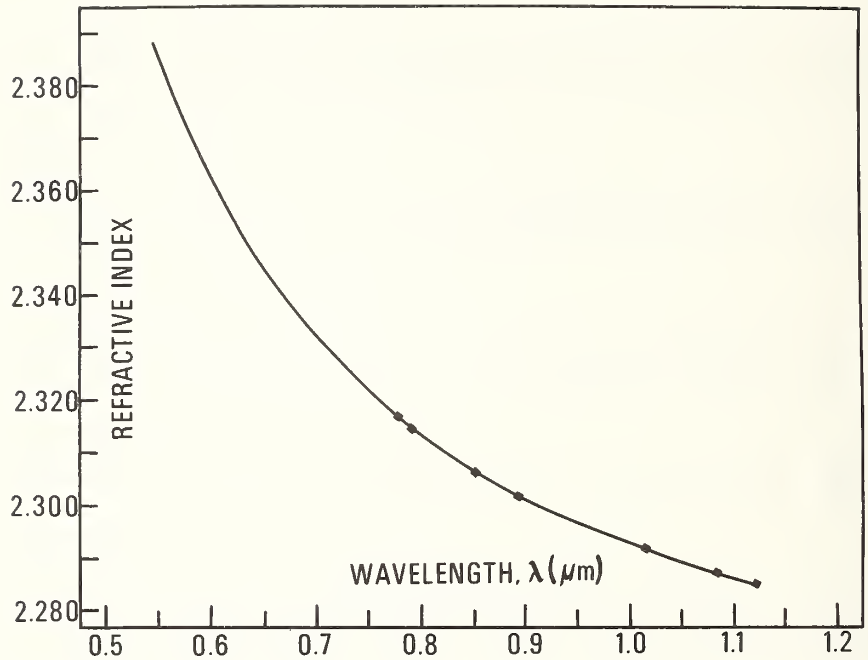

Fig. 1 - The refractive index of CVD ZnS as a function of wavelength. The data points represent the index of a sample of hi-temperature CVD ZnS.

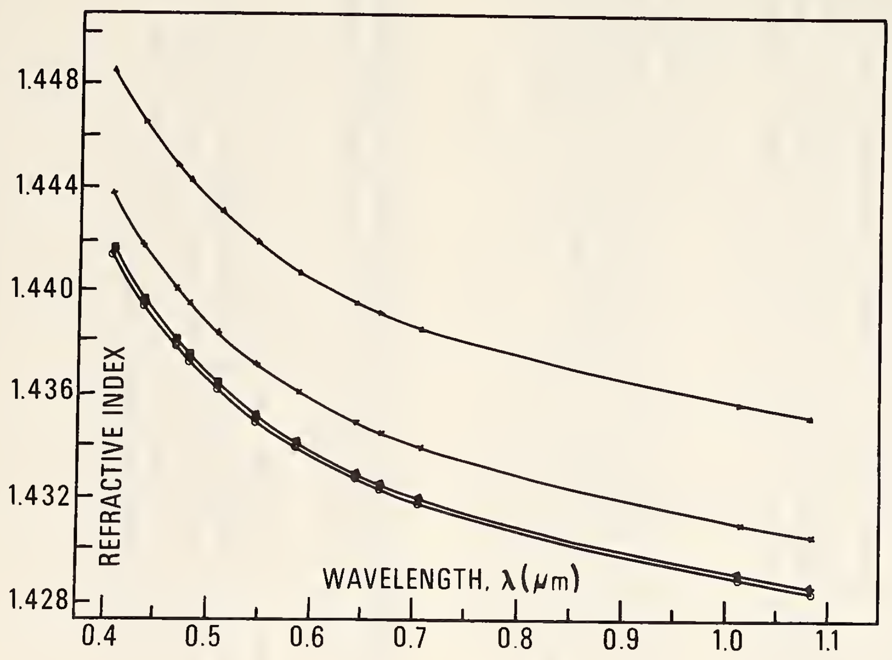

Fig. 2 - The refractive index of Er-doped CaF_2 as a function of wavelength; o— CaF_2:Er.001%; ■— CaF_2:Er.1%; x—CaF_2:Er 1%; ▲—CaF_2:Er 3%.

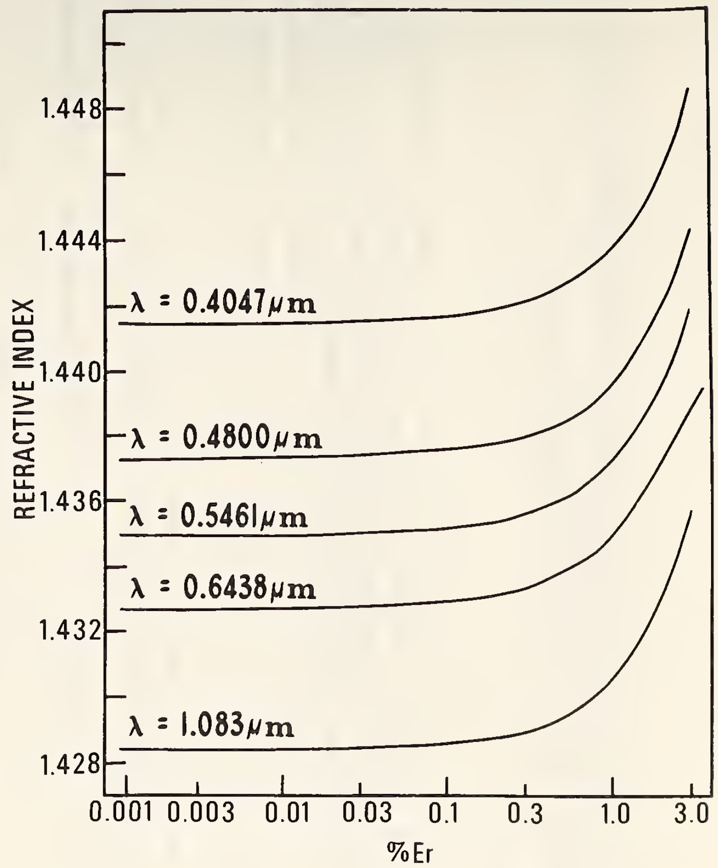

Fig. 3 - The refractive index at specific wavelengths of Er-doped CaF_2 as a function of percent Er (logarithmic scale).

2.2 Effect of Temperature on the Refractive Indices of Window Materials

Albert Feldman, Deane Horowitz and Roy M. Waxler

2.2.1 Introduction

When high-power radiation propogates through a laser window, the residual absorption causes a temperature rise in the window. The temperature distribution is, in general, nonuniform and hence, will distort the wavefront of the beam. The distortion arises from: the change of refractive index with temperature; the change of thickness with temperature; the change of refractive index and thickness caused by stresses produced by thermal gradients. If the distortion is sufficiently severe, the laser window becomes unusable. In order to predict the distortion of a laser beam wavefront from the laser energy deposited in a window, one requires certain material parameters. These include the absorption coefficient, the refractive index n, the change of index with temperature dn/dT, the piezo-optic constants q_{ij}, the thermal expansion coefficient α, and the elastic constants s_{ij} or c_{ij}. It is the purpose of the Optical Materials Characterization Program at the National Bureau of Standards to measure n, dn/dT, q_{ij} and if necessary, α and s_{ij}.

In this report, we present data of dn/dT obtained on BaF_2, CaF_2, KBr (RAP), KCl (RAP), KCl nominally doped with 1% KI (KCl:KI), LiF, NaF, SrF_2 and ZnSe (CVD). Data were obtained at 632.8 nm and 3.93 µm over the temperature range -180 °C to 200 °C. The data were obtained by the method of Fizeau interferometry which requires a knowledge of the thermal expansion coefficient. We measured the linear thermal expansion coefficients of all the above specimens and found the results to be in good agreement with published values. We used the published values in our computations.

In addition, we have measured the linear thermal expansion and dn/dT over the temperature range -160 °C to 60 °C of Plexiglas 55, a material used for aircraft windows. The measurements were made at the request of Captain Hurst of the Air Force Materials Laboratory for determining the effect of heating caused by a nuclear explosion on the optical properties of aircraft windows.

2.2.2 Apparatus

The thermal expansion and dn/dT were measured by the method of Fizeau interferometry. The general method for making these measurements has been described in the literature [1].

To measure thermal expansion, we measure as a function of temperature the shift of Fizeau fringes formed between two optic flats separated by a specimen. To measure dn/dT, we measure as a function of temperature the shift of Fizeau fringes formed from the reflections from the front and back surfaces of a specimen polished plane parallel.

We vary the temperature by placing the specimens in a furnace that can be cooled to -180 °C. We then heat the furnace electrically which permits us to reach all temperatures between -180 °C and 200 °C. The details of the experimental method were presented in our previous report [1].

2.2.3 Data Analysis

The thermal expansion data is obtained in the form of a fringe count as a function of temperature. The linear thermal expansion coefficient, α, is defined by

$$\alpha = \frac{1}{t_o} \frac{dt}{dT} \qquad (1)$$

where t_o is the room temperature specimen thickness, and t is the specimen thickness at temperature T. In terms of a fringe count N_i at a temperature T_i we calculate $\alpha(T)$ by the formula

$$\alpha(T) = \frac{\lambda}{2t_o} \frac{N_i - N_{i-1}}{T_i - T_{i-1}} \qquad (2)$$

where λ is the wavelength of the laser used in the experiment and $T = (T_i + T_{i-1})/2$. A graph is then made of α as a function of T. On this graph we also plot either the accepted handbook values of $\alpha(T)$ when they are available, or else values from the literature. A curve is then visually drawn through the data and from this curve, we abstract a set of data points. These points are then fitted by computer to a tenth degree polynominal. The purpose of the fit is to obtain an analytical expression for $\alpha(T)$. This expression is needed for computing dn/dT as a function of temperature.

The change of index with temperature is also obtained in the form of a fringe count M_i at a particular temperature. The change of index from room temperature to temperature T_i is given by

$$\Delta n(T_i) = \left[\frac{M_i \lambda}{2t_o} - n_o \frac{\Delta t}{t_o} \right] \left(1 + \frac{\Delta t}{t_o}\right)^{-1} \qquad (3)$$

where n_o is the refractive index at room temperature and $\Delta t/t_o$ is computed at temperature T_i. We obtain dn/dT from

$$\frac{dn(T)}{dT} = \frac{\Delta n(T_i) - \Delta n(T_{i-1})}{T_i - T_{i-1}} \qquad (4)$$

The values of dn/dT are then fitted to a third degree polynominal in temperature and tabulated in 20 °C increments.

2.2.4 Results and Discussion

The linear thermal expansion and dn/dT were measured on specimens of BaF_2, CaF_2, KBr (RAP), KCl (RAP), KCl:KI, LiF, NaF, SrF_2 and ZnSe (CVD). All the specimens used were of single crystal material except for the ZnSe which was polycrystalline. We also made measurements on hot forged CaF_2 and these data agreed with the single crystal data.

The values we obtained for the linear thermal expansion agreed well with values from the literature, hence, they are not presented here. However, references to the linear thermal expansion are listed in Table 2, which contains the data used for computing dn/dT.

In figures 4-9, we plot dn/dT as a function of T for the above materials. The points in each of the figures are the experimentally determined values. Through each set of points, we draw a line visually. This line agrees quite well with a third degree polynominal least squares fit to the data of dn/dT as a function of temperature. The results of the fit are tabulated in Tables 3-11. The errors in the tables are the standard deviation of the experimental data to the least squares fit.

In figure 10 we show plotted the linear thermal expansion coefficient of Plexiglass 55 as a function of temperature. Figure 11 is a plot of dn/dT of Plexiglass 55 as a function of temperature.

In a recent article, R. J. Harris, et al. [2] presented dn/dT data on a series of materials including BaF_2, CaF_2, KCl, and ZnSe. At first glance, there appears to be some disagreement between their data and ours; however, if we correct their results by using our values for n and α, we find good agreement in the data for BaF_2, CaF_2, and KCl. There still remains a discrepancy between our values for ZnSe and theirs. We are in the process of measuring dn/dT of ZnSe at 632.8 nm using an immersion technique similar to the technique used by Harris, et al. in order to further compare our data.

2.2.5 References

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Table 2. Data Used in Computation of dn/dT

Material	Refractive Index, n_o 632.8 nm	Refractive Index, n_o 3.39 μm	t_o (mm)	α
BaF_2	1.473[a]	1.460[a]	13.16	b
CaF_2	1.433[c]	1.416[c]	13.41	b,d,e,f
KBr(RAP)	1.557[g]	1.536[g]	11.83	h
KCl(RAP)	1.488[j]	1.473[j]	11.87	h
KCl:KI	1.488[j]	1.473[j]	6.11	h
LiF	1.392[k]	1.360[k]	5.59	h
NaF	1.325[l]	1.312[l]	12.21	h
SrF_2	1.436[m]	1.425[n]	13.15	b
ZnSe(CVD)	2.590[p]	2.436[p]	17.49	q,r

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[q] J.S. Browder & S.S. Ballard, Appl. Optics 8, 793 (1969).

[r] Reference [1].

Table 3. dn/dT of BaF_2 ($10^{-5}K^{-1}$)

Temperature (°C)	Wavelength (μm)	
	0.6328[a]	3.39[b]
-180	- .86	- .81
-160	- .98	- .95
-140	-1.09	-1.07
-120	-1.19	-1.17
-100	-1.27	-1.26
- 80	-1.35	-1.34
- 60	-1.41	-1.41
- 40	-1.47	-1.47
- 20	-1.52	-1.51
0	-1.56	-1.56
20	-1.60	-1.59
40	-1.63	-1.62
60	-1.66	-1.66
80	-1.70	-1.68
100	-1.73	-1.71
120	-1.76	-1.75
140	-1.79	-1.78
160	-1.83	-1.82
180	-1.87	-1.87
200	-1.92	-1.92

[a]Standard deviation from a third degree polynomial fit is .02

[b]Standard deviation from a third degree polynomial fit is .03

Table 4. dn/dT of CaF_2 ($10^{-5}K^{-1}$)

Temperature (°C)	Wavelength (μm)	
	0.6328[a]	3.39[b]
-180	- .40	- .40
-160	- .54	- .52
-140	- .66	- .63
-120	- .77	- .73
-100	- .85	- .82
- 80	- .93	- .89
- 60	- .99	- .95
- 40	-1.03	-1.00
- 20	-1.07	-1.05
0	-1.10	-1.09
20	-1.13	-1.12
40	-1.15	-1.14
60	-1.17	-1.17
80	-1.19	-1.19
100	-1.21	-1.21
120	-1.23	-1.23
140	-1.26	-1.25
160	-1.30	-1.27
180	-1.34	-1.30
200	-1.40	-1.34

[a]Standard deviation from a third degree polynomial fit is .02

[b]Standard deviation from a third degree polynomial fit is .03

Table 5. dn/dT of KBr ($10^{-5} K^{-1}$)

Temperature (°C)	Wavelength (μm)	
	0.6328[a]	3.39[b]
-180	-2.95	-3.05
-160	-3.17	-3.26
-140	-3.36	-3.44
-120	-3.53	-3.60
-100	-3.67	-3.74
- 80	-3.78	-3.85
- 60	-3.88	-3.95
- 40	-3.96	-4.03
- 20	-4.02	-4.10
0	-4.08	-4.16
20	-4.12	-4.21
40	-4.16	-4.25
60	-4.19	-4.29
80	-4.23	-4.33
100	-4.27	-4.36
120	-4.31	-4.40
140	-4.36	-4.44
160	-4.42	-4.49
180	-4.49	-4.55
200	-4.58	-4.62

[a]Standard deviation from a third degree polynomial fit is .03

[b]Standard deviation from a third degree polynomial fit is .03

Table 6. dn/dT of KCl ($10^{-5}K^{-1}$)

Temperature (°C)	Wavelength (μm)	
	0.6328[a]	3.39[b]
-180	-2.32	-2.39
-160	-2.52	-2.58
-140	-2.70	-2.75
-120	-2.86	-2.91
-100	-3.00	-3.05
- 80	-3.13	-3.17
- 60	-3.24	-3.28
- 40	-3.35	-3.38
- 20	-3.43	-3.47
0	-3.51	-3.55
20	-3.58	-3.62
40	-3.65	-3.69
60	-3.70	-3.75
80	-3.76	-3.80
100	-3.81	-3.85
120	-3.86	-3.90
140	-3.91	-3.94
160	-3.96	-3.99
180	-4.02	-4.04
200	-4.08	-4.09

[a]Standard deviation from a third degree polynomial fit is .02

[b]Standard deviation from a third degree polynomial fit is .02

Table 7. dn/dT of KCl:KI ($10^{-5}K^{-1}$)

Temperature (°C)	Wavelength (μm)	
	0.6328[a]	3.39[b]
-180	-2.33	-2.44
-160	-2.53	-2.61
-140	-2.70	-2.77
-120	-2.86	-2.92
-100	-3.00	-3.05
- 80	-3.13	-3.17
- 60	-3.24	-3.28
- 40	-3.35	-3.38
- 20	-3.44	-3.47
0	-3.52	-3.55
20	-3.59	-3.63
40	-3.66	-3.69
60	-3.72	-3.75
80	-3.77	-3.81
100	-3.82	-3.86
120	-3.87	-3.92
140	-3.92	-3.97
160	-3.96	-4.01
180	-4.01	-4.06
200	-4.07	-4.11

[a]Standard deviation from a third degree polynomial fit is .02

[b]Standard deviation from a third degree polynomial fit is .03

Table 8. dn/dT of LiF ($10^{-5}K^{-1}$)

Temperature (°C)	Wavelength (μm)	
	0.6328[a]	3.39[b]
-180	- .36	- .40
-160	- .63	- .60
-140	- .86	- .78
-120	-1.05	- .93
-100	-1.21	-1.06
- 80	-1.34	-1.16
- 60	-1.44	-1.25
- 40	-1.52	-1.32
- 20	-1.59	-1.37
0	-1.63	-1.42
20	-1.67	-1.45
40	-1.70	-1.48
60	-1.72	-1.51
80	-1.75	-1.53
100	-1.78	-1.56
120	-1.81	-1.59
140	-1.85	-1.63
160	-1.91	-1.67
180	-1.99	-1.73
200	-2.09	-1.80

[a]Standard deviation from a third degree polynomial fit is .02

[b]Standard deviation from a third degree polynomial fit is .04

Table 9. dn/dT of NaF ($10^{-5}K^{-1}$)

Temperature (°C)	Wavelength (μm)	
	0.6328[a]	3.39[b]
-180	- .51	- .55
-160	- .67	- .69
-140	- .81	- .82
-120	- .92	- .92
-100	-1.00	-1.00
- 80	-1.07	-1.06
- 60	-1.12	-1.11
- 40	-1.16	-1.14
- 20	-1.19	-1.17
0	-1.20	-1.18
20	-1.21	-1.19
40	-1.21	-1.19
60	-1.22	-1.19
80	-1.22	-1.20
100	-1.22	-1.20
120	-1.24	-1.21
140	-1.26	-1.23
160	-1.29	-1.26
180	-1.33	-1.30
200	-1.39	-1.35

[a]Standard deviation from a third degree polynomial fit is .05

[b]Standard deviation from a third degree polynomial fit is .05

Table 10. dn/dT of SrF_2 ($10^{-5}K^{-1}$)

Temperature (°C)	Wavelength (μm)	
	0.6328[a]	3.39[b]
-180	- .56	- .56
-160	- .69	- .68
-140	- .81	- .80
-120	- .90	- .89
-100	- .98	- .97
- 80	-1.05	-1.04
- 60	-1.11	-1.10
- 40	-1.15	-1.15
- 20	-1.19	-1.19
0	-1.22	-1.22
20	-1.24	-1.24
40	-1.25	-1.26
60	-1.27	-1.27
80	-1.28	-1.28
100	-1.29	-1.29
120	-1.30	-1.29
140	-1.32	-1.30
160	-1.34	-1.31
180	-1.36	-1.32
200	-1.39	-1.33

[a] Standard deviation from a third degree polynomial fit is .02

[b] Standard deviation from a third degree polynomial fit is .03

Table 11. dn/dT of ZnSe ($10^{-5}K^{-1}$)

Temperature (°C)	Wavelength (μm)	
	0.6328[a]	3.39[b]
-180	7.6	5.0
-160	8.2	5.2
-140	8.7	5.4
-120	9.1	5.6
-100	9.4	5.8
- 80	9.7	5.9
- 60	10.0	6.0
- 40	10.2	6.1
- 20	10.3	6.1
0	10.5	6.2
20	10.6	6.2
40	10.7	6.2
60	10.8	6.3
80	10.9	6.3
100	11.0	6.3
120	11.1	6.4
140	11.3	6.4
160	11.5	6.5
180	11.8	6.6
200	12.1	6.7

[a]Standard deviation from a third degree polynomial fit is .1

[b]Standard deviation from a third degree polynomial fit is .1

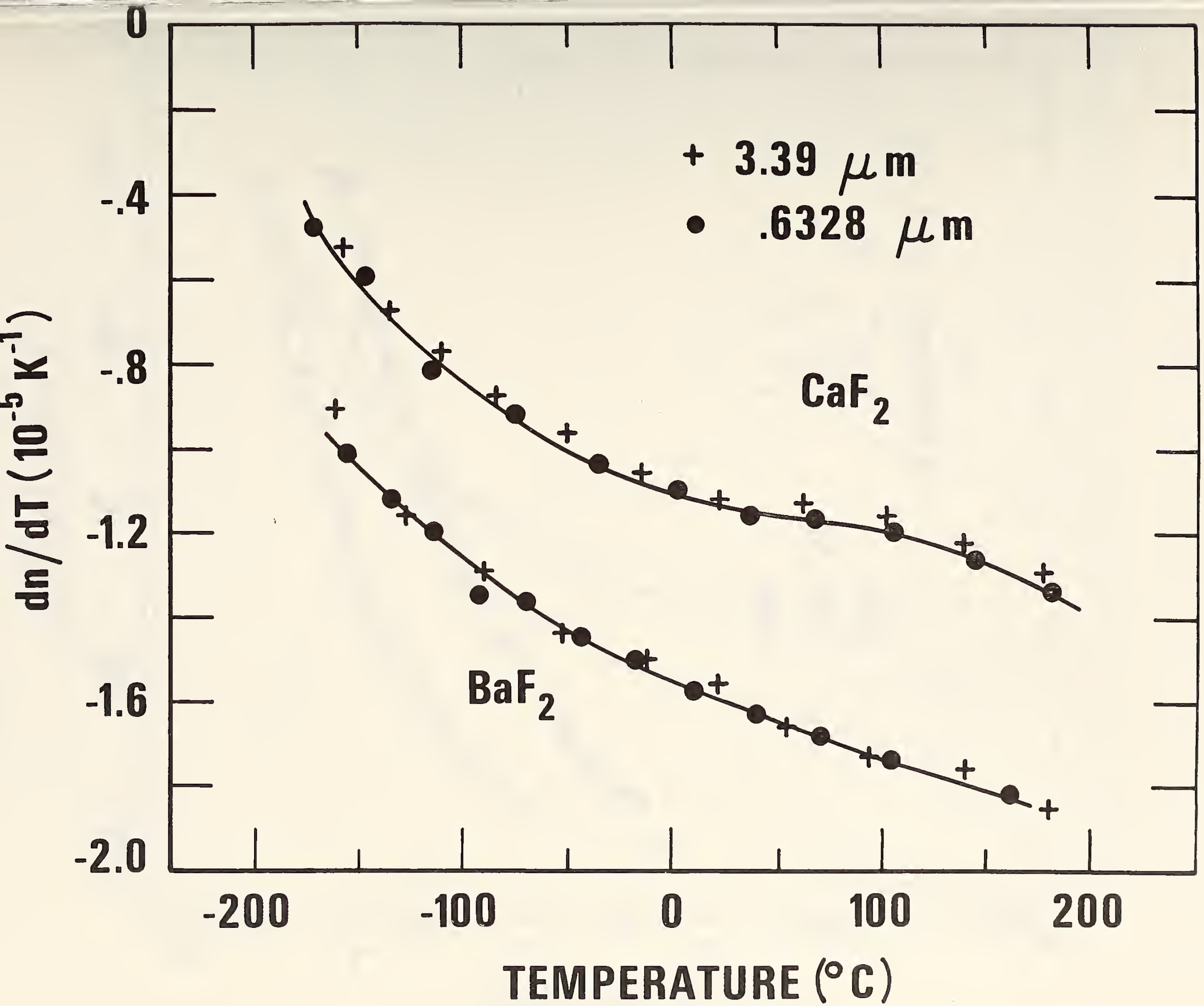

Figure 4. dn/dT of CaF_2 and BaF_2.

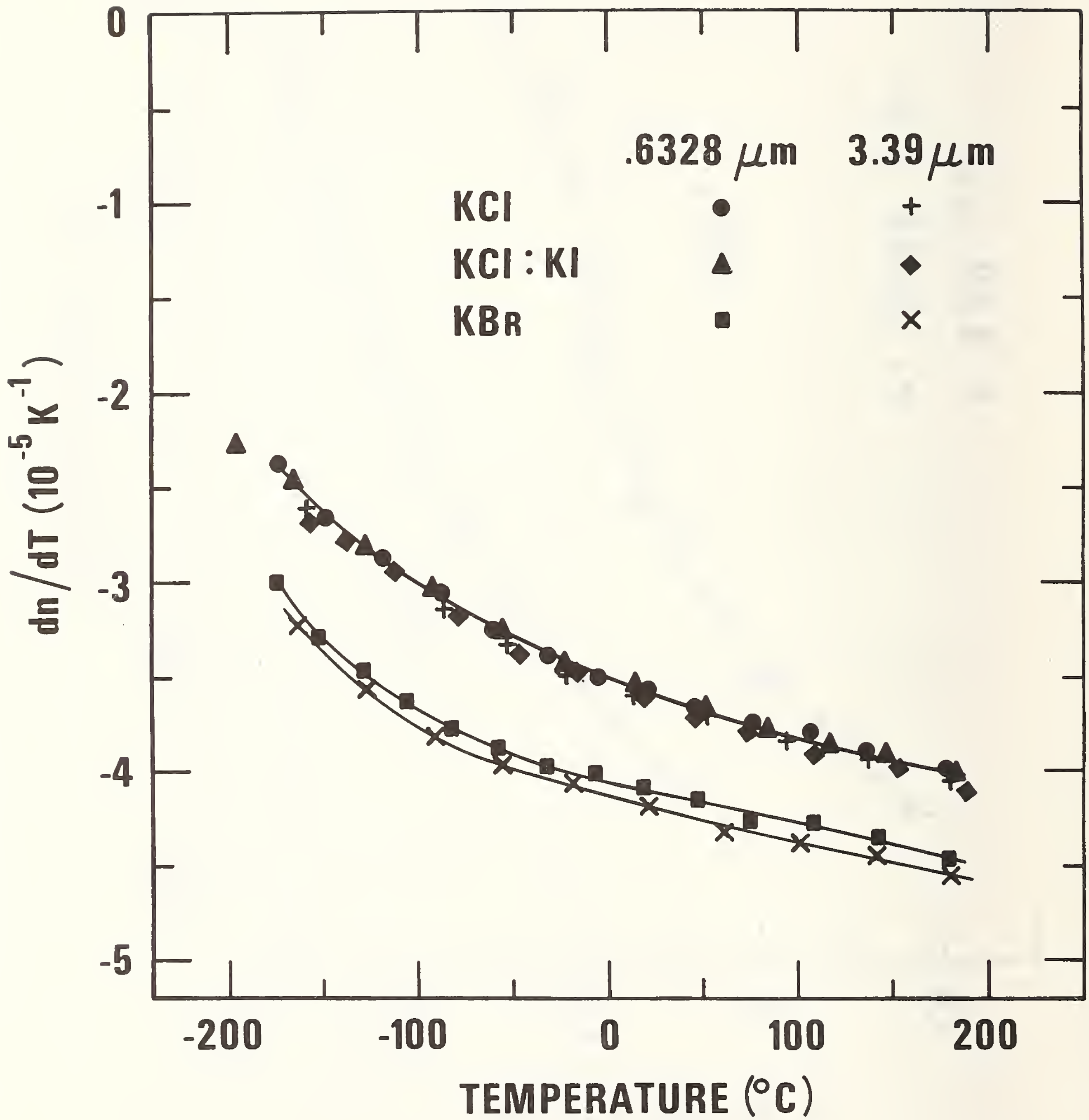

Figure 5. dn/dT of KCl (RAP), KBr (RAP) and KCl doped with KI (KCl:KI).

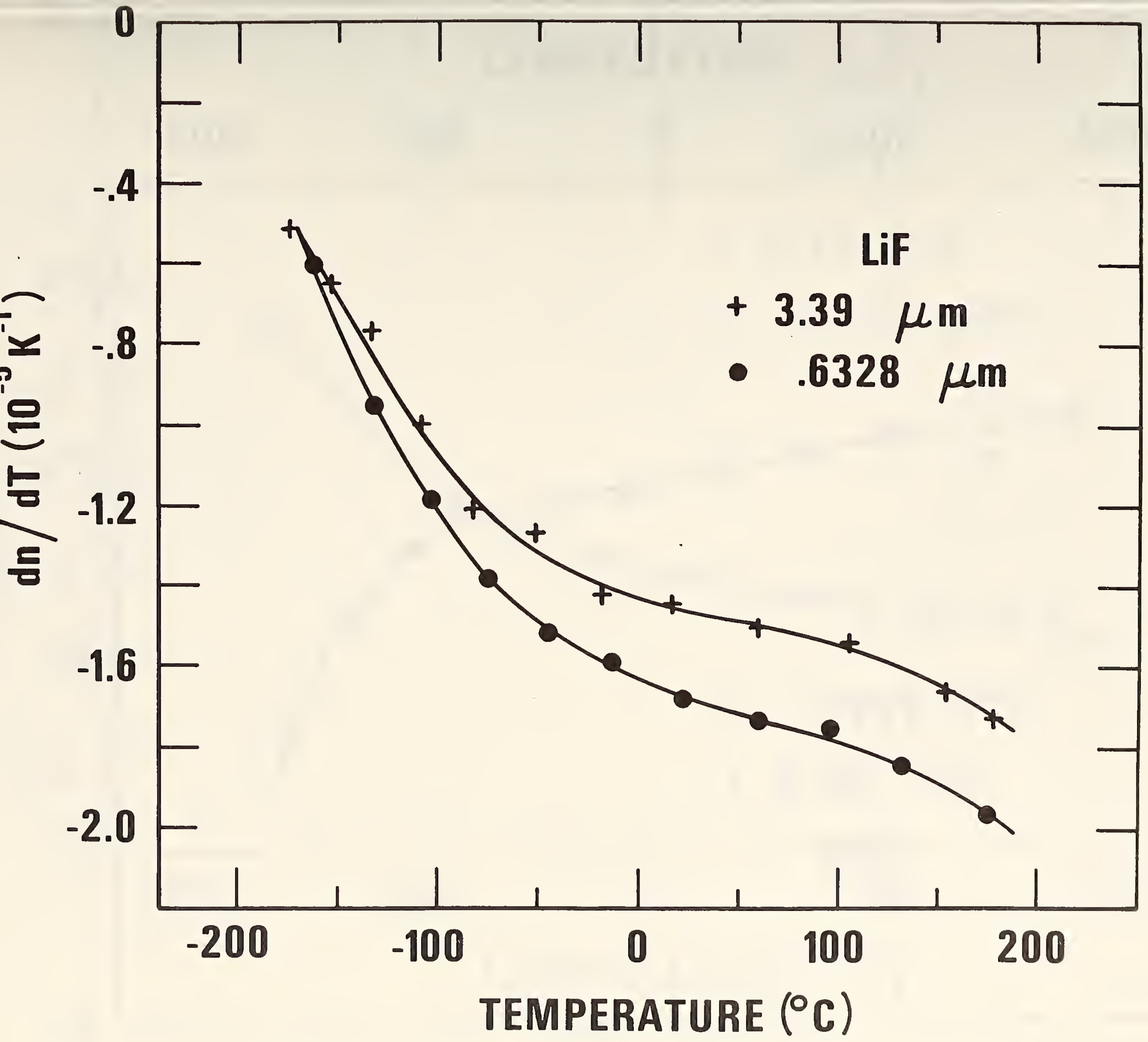

Figure 6. dn/dT of LiF.

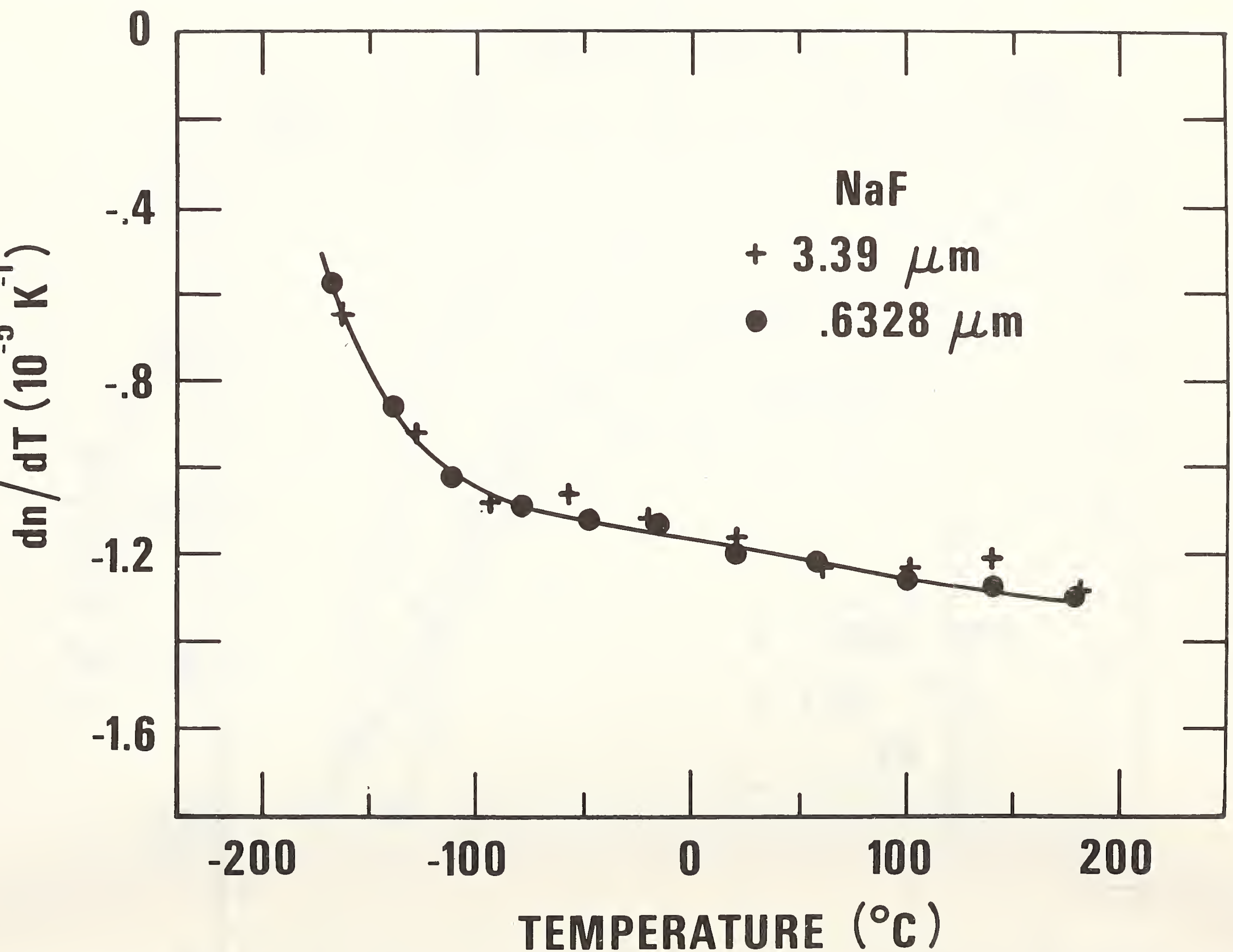

Figure 7. dn/dT of NaF.

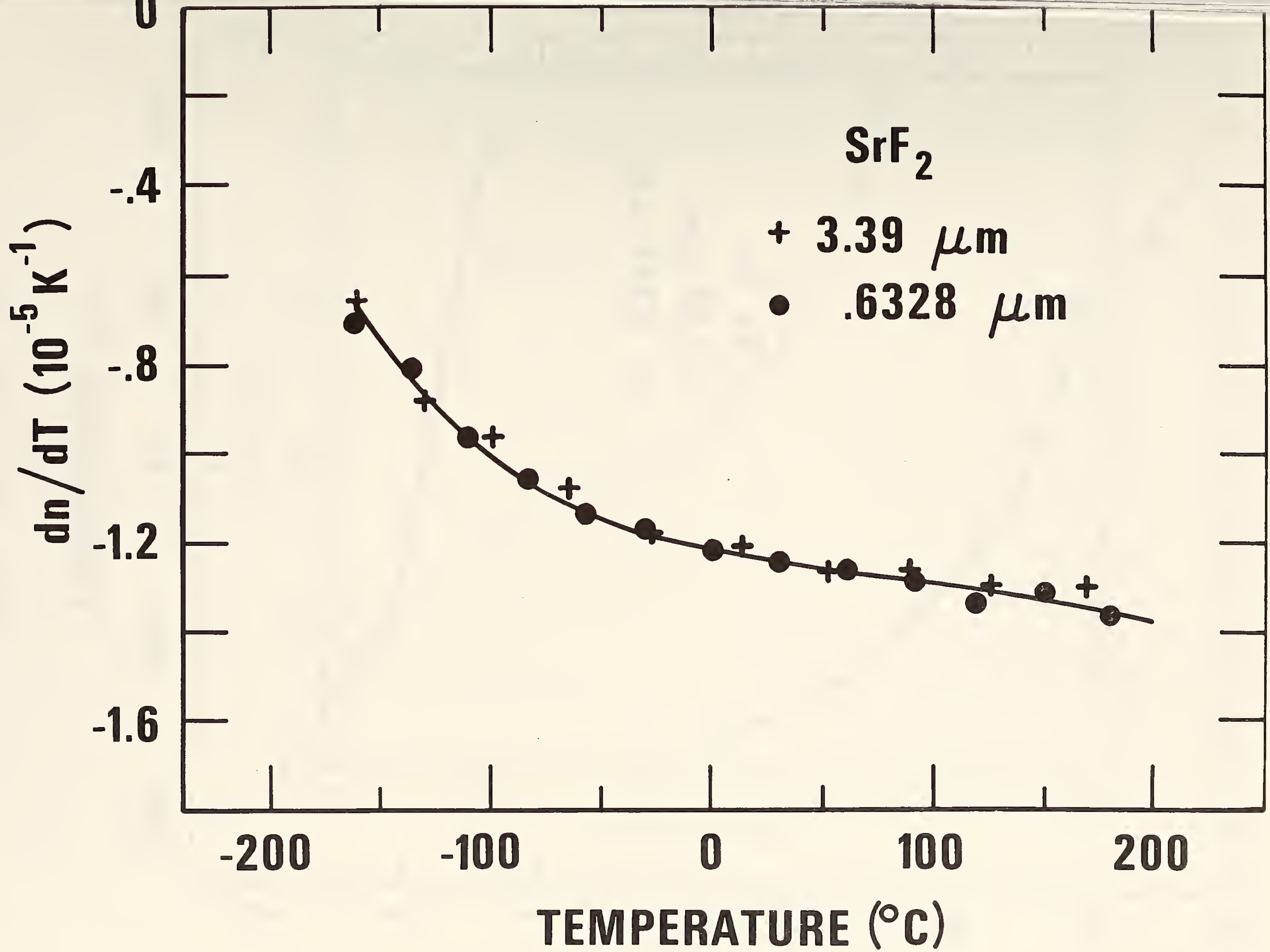

Figure 8. dn/dT of SrF_2.

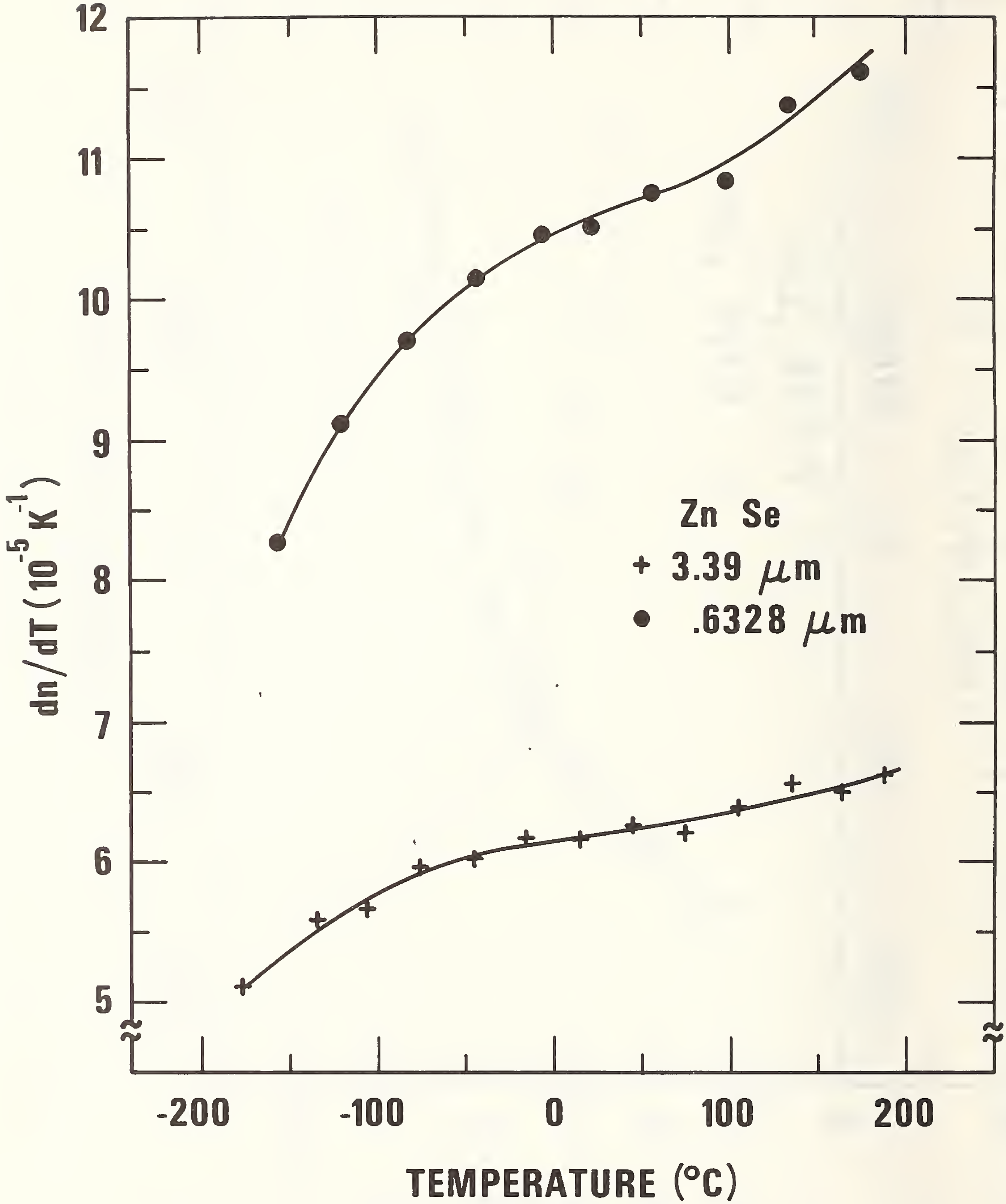

Figure 9. dn/dT of ZnSe (CVD).

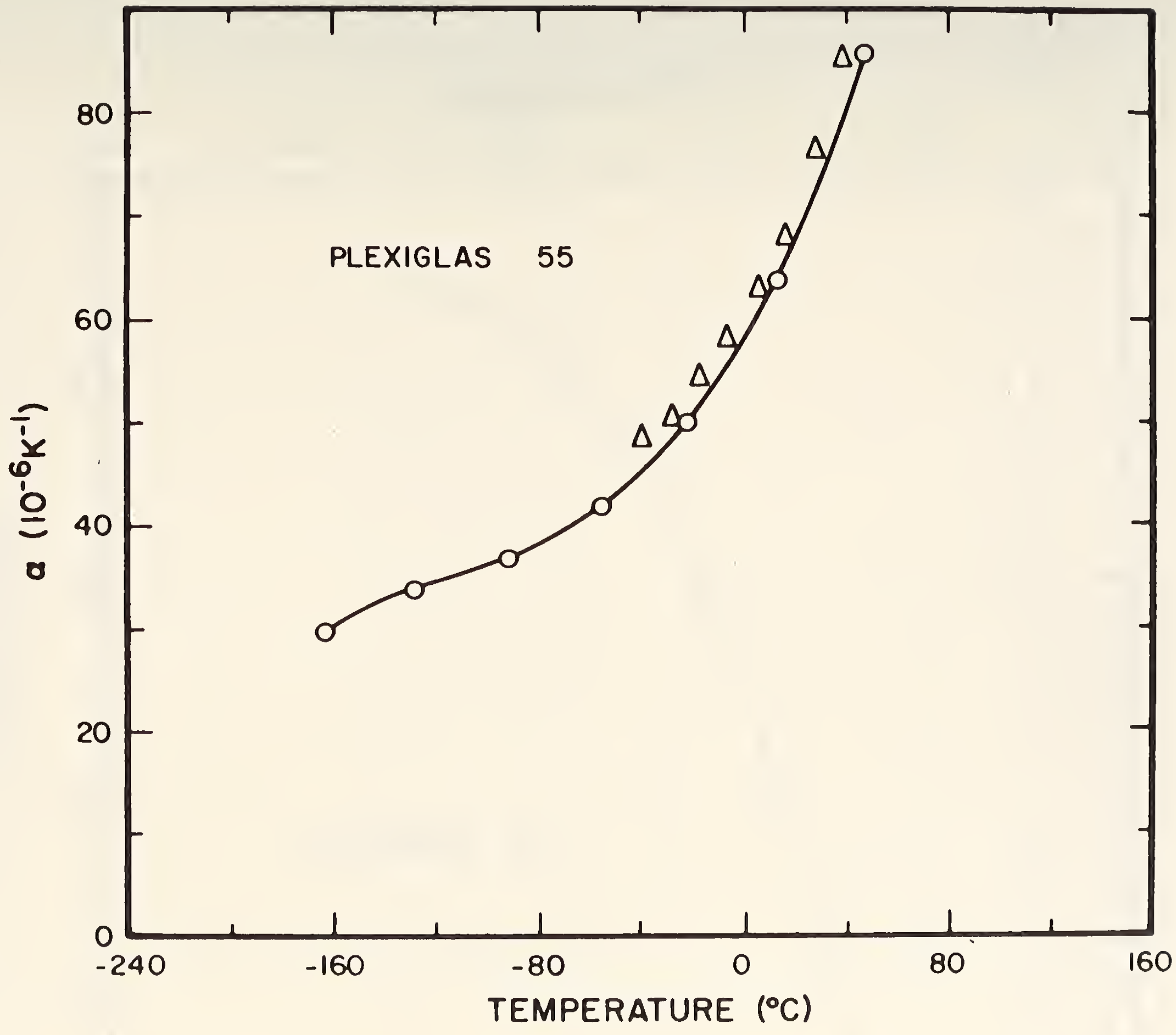

Figure 10. Linear thermal expansion coefficient of Plexiglas 55. Triangles are from the manufacturer's literature.

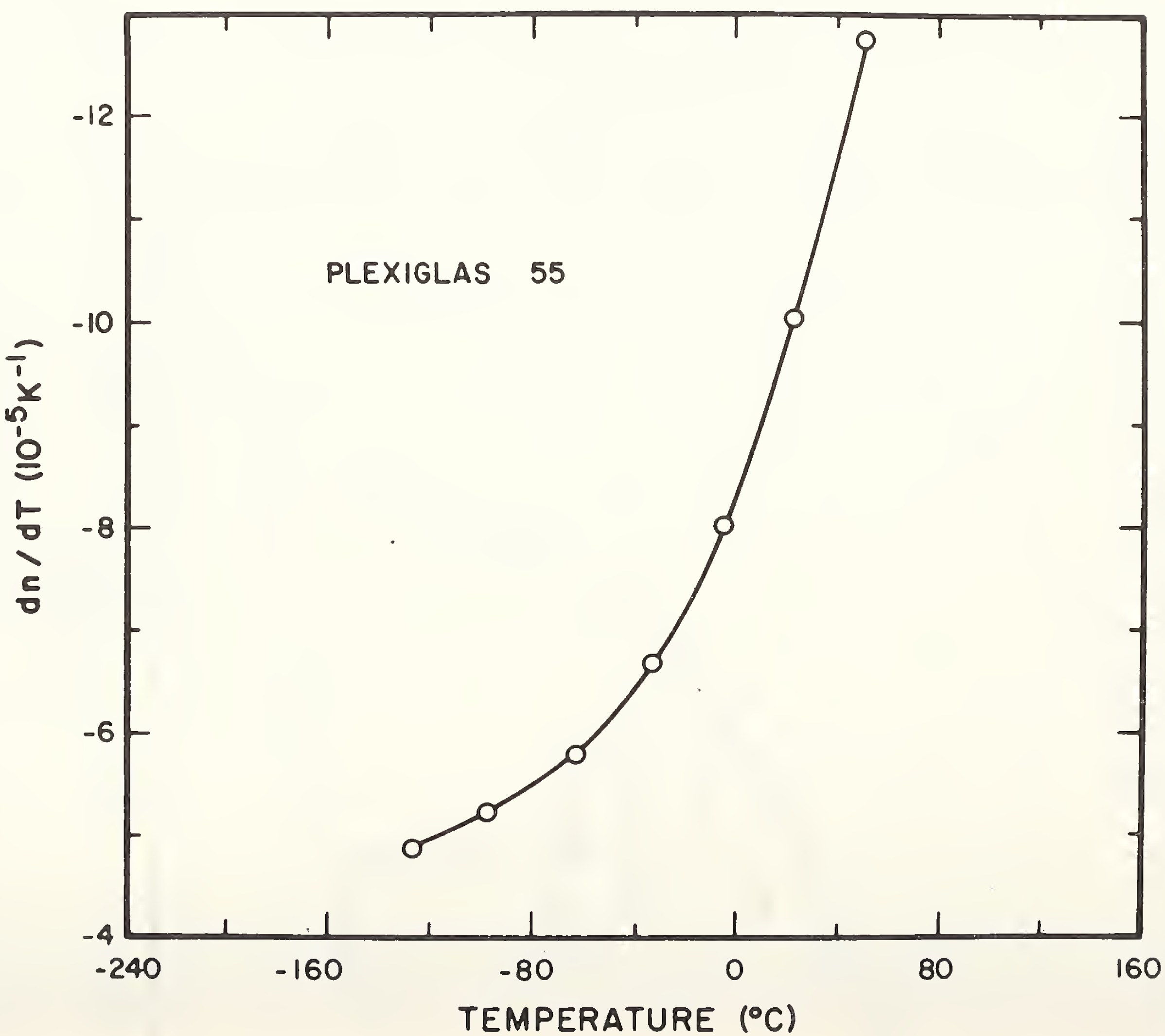

Figure 11. dn/dT of Plexiglas 55.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The refractive indices of three prisms of chemical vapor deposited ZnS were measured at room temperature over the wavelength range 540 nm to 1.083 μm. The refractive indices of eight specimens of CaF_2 doped with Er were measured from 404.7 nm to 1.083 μm. The doping range was 0.001% to 3% Er. Interferometric measurements of dn/dT were made over the temperature range -180 °C to 200 °C at the wavelengths 632.8 nm and 3.39 μm on single crystal specimens of BaF_2, CaF_2, reactive atmosphere processed (RAP) KBr, RAP KCl, KCl doped with KI, LiF, NaF and SrF_2, and on chemical vapor deposited (CVD) ZnSe and hot forged CaF_2.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

BaF_2; CaF_2; KBr; KCl; LiF; NaF; refractive index; SrF_2; thermal coefficient of refractive index; ZnSe.

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