ABSTRACT

RADIATIVE PROPERTIES OF IR MATERIALS

by
Manish R. Babladi

The objective of this thesis is to study the radiative properties of materials of interest in the infrared range of wavelengths. In particular, three distinct materials have been considered here - Erbium oxide, alumina and quartz. Erbium oxide has unique selective line emission, which gives a high emittance at a particular wavelength and low emittance in the rest of the infrared spectrum. It has applications in the design and development of thermo-photovoltaic (TPV) generators. Because of its selective emission properties, erbium oxide assists in concentrating the radiant energy into a narrow band near the bandgap energy of the TPV cell, and this results in an efficient energy conversion. Lucalox and sapphire which are IR transparent materials are used as selective absorbers for increasing the efficiency of TPV generators. A novel spectral emissometer has been utilized for measurement of the temperature dependent radiative properties of erbium oxide, sapphire and lucalox. The experimental results presented in this thesis showed that the measurement of high temperature optical properties of these materials can be performed reliably with a novel non-contact, real-time approach using the spectral emissometer. The emissivity of erbium oxide is observed to be low and constant in the wavelength range of 2 to 5 microns and at various temperatures studied. Sapphire and lucalox exhibit almost similar characteristics in 1 to 3.3 micron region. All the materials investigated in this thesis are potential candidates for gate dielectrics in MOS technology.

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by
Manish R Babladi

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APPROVAL PAGE

RADIATIVE PROPERTIES OF IR MATERIALS

Manish R. Babladi

Dr. Nuggehalli M. Ravindra, Thesis Advisor Date
Professor, Department of Physics, NJIT

Dr. Kenneth Sohn, Committe Member Date
Associate Chair, Department of Electrical and Computer Engineering, NJIT

Dr. Edwin Hou, Committee Member Date
Associate Professor, Department of Electrical and Computer Engineering, NJIT

Dr. Oktay. H. Gokce, Committee Member Date
Research Assistant Professor, Department of Physics, NJIT

BIOGRAPHICAL SKETCH

Author: Manish R Babladi

Degree: Master of Science

Date: May 1999

Undergraduate and Graduate Education

- Master of Science in Electrical Engineering,
  New Jersey Institute of Technology, Newark, NJ, 1999.

- Bachelor of Engineering in Electronics and Communication.
  Bangalore University, Karnataka, India, 1996.

Major: Electrical Engineering

This Thesis is dedicated to my Parents

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CHAPTER 1

INTRODUCTION

Optical properties of solids are usually determined by measurements of either the transmittance or the reflectance. Each of these methods has advantages and disadvantages, depending upon the spectral region and the nature of the material being studied. The simultaneous measurement of reflectance, transmittance and hence emittance has obvious advantages. In the design of infrared systems, the transmission, reflection and emittance of the optical materials must be well known to select the best window or prism materials for a particular wavelength region.

All the materials considered in this study - erbium oxide, alumina and quartz are potential candidates for gate dielectrics in MOS Technology. Their high values of dielectric constant make them suitable for such applications.These dielectrics are of interest for use in optical waveguides, antireflection coatings and metal oxide semiconductor (MOS) devices. Thin films of these materials can offer several potential advantages over other dielectric media for optical propagation. They have large bandgap and light of wavelength as short as 300 nm could be propagated and the absorption loss in the visible spectrum can be quite low. The optical losses due to scattering are very small.

One of the materials studied in this thesis, erbium oxide can concentrate the radiant energy into a narrow band near the bandgap of the PV cell. This results in efficient TPV conversion. Selective emitters or radiators comprising of rare-earth oxides such as erbium oxide, ytterium oxide, samarium oxide and neodymium oxide can be used to construct thermophotovoltaic (TPV) cells. For broad-band window and IR filter applications, alumina and quartz are used in the TPV. Sapphire (crystalline alumina) and lucalox (poly-crystalline

alumina) have very common and interesting properties. They have very similar optical characteristics in the IR region.

The objective of this thesis was to develop a reliable multi-wavelength pyrometer for simultaneous measurement of the sample temperature and the radiative properties of these IR materials in the wavelength range of 1 to 20 microns and temperature range of 30 to 1000°C. The spectral emissometer was utilized for the measurement of the radiative properties of rare-earth oxides such as erbium oxide and wide-band materials like sapphire and quartz. A C++ program was used for the deconvolution of the measured radiative properties into an estimation of the fundamental optical constants. It has been demonstrated that the emissometer yields reliable values of optical properties as a function of wavelength and temperature. The samples were heated using a propane torch or an oxy-acetylene flame. Since there is no control over the temperature attained, work aimed at replacing the currently used source of heating is in progress. It may be possible to use CO_2 laser.

The investigation of the temperature dependent optical properties of erbium oxide, sapphire and quartz has been distributed over the next seven chapters. In chapter 2, the background of thermophotovoltaic (TPV) generators and the methods for improving their efficiency is discussed. In chapter 3, the selective emitter, erbium oxide and broadband materials-sapphire and lucalox are discussed and their properties have also been presented. The reason for the choice of erbium oxide being the material used in TPV is also discussed. In chapter 4, the equations employed to deconvolute the measured radiative properties to yield the refractive index (n) and extinction coefficient (k) are presented. The reason for interest in the radiative properties is also discussed. In chapter 5, experimental details and methodology

employed for the measurement of radiative properties of materials has been presented. In chapter 6, the measured high temperature optical properties of erbium oxide, sapphire and quartz are discussed. These measured properties have been compared with those available in the literature. Conclusions and recommendations based on these studies are presented in chapter 7.

CHAPTER 2

THERMO-PHOTOVOLTAIC CELLS

A thermo-photovoltaic power generation system converts thermal radiation directly into electrical energy. The emitter which is excited by a thermal source provides photons for photovoltaic (PV) cells. The PV cell then converts the photon energy into electricity. Several advantages of a TPV system are easy coupling to any thermal source, such as combustion or solar, quite, nonpolluting, and easy n ıance (no moving parts)[2].

Natural gas flames burn clean creating minimum pollution. It would be nice if it were possible to take a clean hot flame and produce electricity directly and the machine doing this has no moving parts. It would become a reliable backup power source at remote sites relying upon solar power and storage batteries.

Solar photovoltaics (solar cells) are limited by inherent problems with the source. First, the sun is approximately 93 million miles away causing the energy reaching the earth to be very small. Also, sun only shines during the day, and expensive battery storage is required for extensive periods of cloud cover. Since the energy source for TPV energy conversion is man-made, no such expensive storage is required.

2.1 Advantages of TPV

TPV has many advantages over conventional power systems [1]. Some of these advantages are modularity, portability, wide choice of fuels, silent operation, reduced air pollution, rapid startup and high energy density. TPV might be used for portable electric

power, standby electric power, stand-alone electric generation, residential cogeneration and clean electric vehicles.

2.2 TPV Generator

Unlike the bandgap of silicon solar cells that is tailored for a heat source of 6000K - the bandgap corresponding to the sun's visible light - the temperature of the flame is on the order of 1500K to 2500K. Cells built from the ternary compounds (with bandgaps that can be tailored to be between 0.25 to 0.5 eV) provide a much more efficient and denser source of electric power from the lower-temperature (compared with the sun) radiation source. InGaAs cells operate on the low end of the temperature range with the long wavelength infrared energy, while GaAs cells use IR energy which has higher temperatures and shorter wavelengths. Scientists are considering very expensive, tandem cells, in which a GaSb cell is located behind an InGaAs cell in order to get both long and short wavelength IR energy. Fig. 1 shows the TPV electric generator which burns natural gas inside a silicon-carbide tube and the emitter that glows red hot. The TPV cells receive IR photons from the emitter.

The generator offers the following advantages over solar-to-electric power sources.

1. The radiation energy source is within 1 in. of the cells, whereas the sun is 93 million miles away from the earth. The proximity of the cells to the IR source provides the cells with radiant energy at 1000 times the power density of the energy they would receive from the sun. The power density, in turn, increases the conversion efficiency of heat to electricity.

2. Unlike solar electric generators, the TPV operates on demand day or night, cloudy or clear, not simply when sun is shining.

3. TPV generators also can supply heat for recreational vehicles, marine vehicles, and any off-the-power-grid dwelling in varieties of climates.

2.3 TPV Efficiency

The overall efficiency of energy conversion for the TPV system is determined by emitter efficiency (n_E), which is defined as the ratio of photon convertible power (P_E) to total photon power (P_T) from the same emitter area,

$$n_E = \frac{P_E}{P_T}$$

and PV cell efficiency, n_{PV}, which is the ratio of photon power to output electric power. The PV cell efficiency has been greatly improved using high quality and new bandgap energy semiconducting materials. The emitter efficiency now becomes a key issue in TPV research.

Using selective emitter to improve the overall efficiency of a TPV system has been reported by many authors (Parent. and Nelson 1986, Chubb 1990, and Whiteand and Schwartz 1967). Selective emitters concentrate the radiant energy into a narrow band near the bandgap energy of the PV cell, and results in efficient TPV conversion. The most promising selective emitters are the rare earth oxides. However, early studies have reported low emitter efficiency even though the solid erbium oxide emitter has high output power from its high erbium volume concentration.

In addition to efficiency, the power emitted from the selective emitters also is an important parameter. The higher power from the emitter means that more photons strike the PV cell and more electric power can be generated. Therefore, understanding these basic parameters is needed for improving the TPV systems. This thesis discusses the optical properties of erbium oxide used for TPV generators. Results for the emittance, transmittance, reflectance, spectral extinction coefficient and refractive index will be reported in the later chapter.

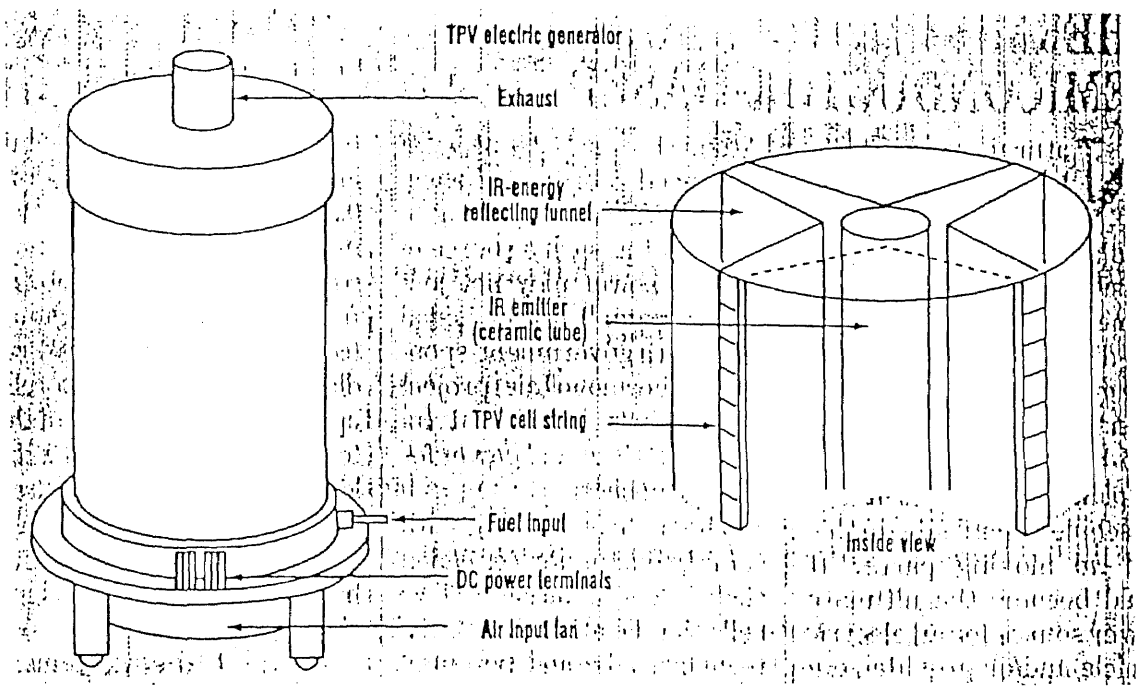


Fig. 1 Schematic of Electric Thermo-Photovoltaic (TPV) Generator

CHAPTER 3

INFRARED MATERIALS

3.1 Erbium Oxide

Erbium Oxide (Er_2O_3) is a rare earth oxide. It is of interest because of its chemical and thermal stability and high melting point of 2430 °C [3]. Some of the properties of erbium oxide are resistance to chemical attacks. The low temperature stable phase for erbium oxide has a body centered cubic (bcc) lattice. Erbium oxide undergoes a polymorphic transformation at 2320 °C $\pm$ 20 °C due to nucleation and growth which leads to a change in its crystal structure to hexagonal close packed (hcp) crystal structure. The erbium oxide bcc structure belongs to the Ia 3 space group with a lattice constant of a=10.55 A°. The unit cell contains 80 atoms, where 32 erbium atoms are located on the 8b and 24d Wyckoff position and the 48 oxygen atoms are on the 48e position. The closest packed planes are in the {110} family.

Few general advantages of rare earth oxides are [4]:

1. their refractive indices are in the range of 1.8 – 1.95;
2. they have good transparency over a wide spectral region;
3. when appropriately evaporated they have a very good stability with time;
4. they are characterized by high mechanical and chemical resistance; and
5. the conventional evaporation parameters when kept at a constant level allows one to produce films with reproducible properties.

3.1.1 Dielectric Behavior of Erbium Oxide

It is found that the values of dielectric constant ε_0 become higher with increasing thickness for films in the thickness range of 100-700 A° [5], and it assumes a constant thickness-independent value for films of thickness about 1300 A° and higher. However, in the intermediate region, i.e. 700-1300 A°, the value of ε decreases and assumes a minimum value and later increases. This is because of the amorphous to crystalline and fcc to bcc crystalline transformation. Both these transformations are thickness dependent [7].

3.1.2 Erbium Oxide Based Metal-Insulator Semiconductors

Recently, there has been a tremendous interest in developing high dielectric constant materials as gate insulators for silicon VLSI technology. These high dielectric constant gate insulators enhance the transconductance of metal-oxide-semiconductor transistors and reduce the size of storage capacitors in dynamic random access memories. Dielectric properties of erbium oxide in capacitor structures show interesting behavior with the dielectric constant increasing with increasing dielectric thickness. A future study focusing on the device properties of erbium oxide is required to establish this novel material as a candidate for VLSI Technology.

3.1.3 Optical Properties of Erbium Oxide

High purity ceramic oxides are among the most promising candidates as materials to be utilized in high temperature environments commonly encountered in industrial and scientific endeavors [6]. At high temperatures, thermal emission accounts for a large part of all heat transfer. In space applications, radiant heat transfer is the only method of heating or cooling. A specific feature of interest with the rare earth oxides such as erbium oxide, is their strong band

emission, which ranges from the visible to near-infrared wavelength region. These bands permit strong thermal excitation at temperatures compatible with high temperature stability of these materials. Therefore, their use as a selective spectral radiation source has become a subject of increasing interest. The emittance of a real body is defined as the ratio of real-body radiation to blackbody radiation at the same true temperature.

Improvement in the experimental emittance of Er_2O_3 emitters will occur if the temperature difference[1], ΔT across the emitters can be reduced. This temperature difference is a function of the emitter material properties and physical dimensions and can be expressed as

$$\Delta T = \frac{qd}{k}$$

where q is the heat transferred across a unit area, k is the thermal conductivity of the emitter materials, and d is the thickness of the emitter. One way to reduce ΔT is to decrease the emitter thickness, d. A reduction in porosity and optimization in thickness of the emitters can significantly increase their emittance.

3.1.4 Infrared to Visible Upconversion in Erbium

There is a growing interest in rare-earth ion doped materials capable of converting infrared to visible radiation by means of sequential excitation-upconversion [20]. Erbium is the most commonly used rare-earth dopant and upconverted visible fluorescence has been observed in a variety of Er^{3+} doped glasses and few oxide glasses. The mechanism of increasing emission with Er^{3+} concentration is attributed to the energy transfer among excited Er^{3+} ions.

3.2 Sapphire and Lucalox

Sapphire is a widely used optical material [14]. It is a direct bandgap material and its main applications include infrared windows, substrate material for infrared detectors, light emitting diodes, lasers [14] and its application as a selective absorber. High temperature solar selective absorbers should be stable above 400°C and should have high solar absorptance (greater than 0.9) and low emittance (less than 0.1) at the operating temperature [15]. In Table 1, some of the properties of sapphire are summarized.

Table 1 Summary of Properties of Sapphire [18, 19]

Melting Temperature (K)	2319	lattice constant (A°)	a = 4.759 c = 12.989
Thermal Expansion (10^{-6}/K)	6.65 (a)7.15 (c)	Density (g cm^{-3})	3.987
Poisson's ratio	0.23	S^{L}_{11} (TPa)	2.38
Hardness (Kg/mm^2)	2250	S^{L}_{12} (TPa)	-0.70
Molecular Weight (amu)	101.96	S^{L}_{44} (TPa)	7.03
Heat Capacity (J/g K)	0.777	Thermal Conductivity (Wcm^{-1} K^{-1})	0.46
Debye Temperature (K)	1030	Crystal System	Hexagonal
Elastic Moduli (GPa)	400	Bulk Moduli (GPa)	250

S^{L} is the elastic compliance (10^{-2} cm^2 $dyne^{-1}$)

3.3 Quartz

When earth was formed, and had begun to cool, the heavier elements such as iron were pulled towards the center, while lighter elements such as silicon and oxygen came to the surface [21]. It happens that silicon and oxygen bound very easily, forming SiO_2 molecules. The SiO_2 molecule naturally occurs in a lattice structure as crystal quartz. Quartz crystal that is suitable for optical use is in very limited resources. In electronics, the demand for higher quality systems and devices will require higher-grade quartz and quartz glass. In many optical applications, natural quartz, and quartz glass made from natural quartz, are useful. It also combines excellent elastic properties and high fatigue strength, with exceptional chemical resistance to most chemicals. Table 2 lists the mechanical properties of Quartz.

Table 2 Mechanical properties of Quartz

Density (g/cm^3)	2.2
Mohs hardness	6
Modolus of elasticity (N/mm^2) (at 20°C)	7×10^4
Poisson's ratio	0.17
Compressive strength (N/mm^2)	1150
Tensile strength (N/mm^2)	50
Bending strength (N/mm^2)	67
Torsional strength (N/mm^2)	30

Fused quartz or silica has many optical advantages such as extremely wide spectral transmission range in middle IR region. It has very high transmittance and very low absorbance. It can withstand high temperature upto 1200°C and rapid changes in temperature.

CHAPTER 4

OPTICAL PROPERTIES

4.1 A Blackbody: The Perfect Emitter

A blackbody emitter is useful for comparison with materials that do not emit perfectly at all wavelengths, which is the case for most of the matter in the universe. Anything that emits energy with a Planck distribution can be called a blackbody. If we used an infrared spectrometer to measure this emitted energy and plotted the result, it would follow a Planck distribution.

A blackbody is a perfect absorber of electromagnetic energy and also a perfect emitter. Actually, it is the mathematical function for the spectral radiance of blackbodies.

$$W_{bb}(\lambda, T) = \frac{c1}{\lambda^5 (\exp(c2 / \lambda T) - 1)} \qquad ....(1)$$

Where, $W_{bb}(\lambda, T)$ is known as spectral radial exitance, and describes the power per unit area and wavelength radiated into the forward hemisphere from a blackbody at the absolute temperature T in K, at the wavelength λ in μm [8]. The equation gives $W_{bb}(\lambda, T)$ in units of $Wm^{-2}\mu m^{-1}$, and c1, c2 are constants, with the values 3.7418×10^8 $W\mu m^4 m^{-2}$ and $1.4388 \times 10^4 \mu mK$ respectively. The total energy emitted by a blackbody at any temperature can be found by summing up the energy emitted at each wavelength. This can be done mathematically by integrating this Planck function with respect to wavelength.

The result is that the total energy radiation of a blackbody is proportional to its

absolute temperature to the fourth power (T^4). This is called the Stefan-Boltzmann radiation law,

$$W_{tot,bb} = \sigma T^4 \qquad ....(2)$$

Where, W_{tot} is the total radiation per unit area, $\sigma = 5.67 \times 10^{-8}\ Wm^{-2}\ K^{-4}$ is the Stefan Boltzmann constant and T is in K.

4.2 Link between Radiative and Optical Properties

4.2.1 Optical Properties

If electromagnetic radiation is incident upon a solid body, some of the radiation is reflected, some is absorbed, and the rest is transmitted. If we define the absorptance A as the fraction reflected, and the transmittance T as the fraction transmitted,

$$A + R + T = 1. \qquad ....(3)$$

The emittance E can be defined as the ratio of the thermal radiation per unit area emitted by an object to that emitted by a blackbody at the same temperature [9].

$$E + R + T = 1. \qquad ....(4)$$

The response of a solid to electromagnetic radiation is generally regarded as a consequence of its microscopic elements with the electric field, and hence it can be summarized by defining the dielectric "constant", $\varepsilon_r(\nu)$, which is a function of the frequency of the wave, ν[22].

$$\varepsilon_r(\nu) = \varepsilon_1(\nu) + j\,\varepsilon_2(\nu) \qquad ....(5)$$

The dielectric constant is not usually measured directly, and a number of other properties

are used to describe the optical response of a material. The complex refractive index, n_c, is defined by the relation,

$$n_c = (\varepsilon_r)^{1/2}, \qquad ....(6)$$

Where, frequency dependence of ε_r has been dropped for simplicity. The complex refractive index can be written as

$$n_c = n + jk\ , \qquad ....(7)$$

Where, n is the refractive index and k is the extinction coefficient. The refractive index is equal to the ratio of phase velocity of the wave in vacuum to that in the material. The relationships between the dielectric function and n and k is summarized by the equations,

$$\varepsilon_1 = n^2 - k^2 \qquad ....(8)$$

$$\varepsilon_2 = 2nk \qquad ....(9)$$

For many practical problems, it is convenient to consider loss in a material as being described by the absorption, α, which is defined by,

$$\alpha = 4\pi k / \lambda \qquad ....(10)$$

Where, λ is the wavelength. α is a useful quantity to know because it is closely related to the penetration depth of radiation in a given medium, since the intensity of the radiation decreases according to exp $(-\alpha z)$, where z is the depth beneath the surface of the medium. α is usually expressed in units of cm^{-1}.

4.2.3 EMISSIVITY: The Temperature Equalizer

One of the ways to describe the infrared energy emitted by molecules is in terms of radiance: watts of energy per unit of area. Changes in temperature lead to changes in

radiance. For example, the radiance from a material at one temperature will be different from that at another temperature. In order to make comparison of emission from materials at various temperatures, we need to remove the temperature effect. This is done mathematically by dividing the radiance spectrum of selective emitters by that of a blackbody (perfect emitter) at the same temperature. This result is called an emissivity spectrum. Emissivity then, is a fractional representation of the amount of energy from some material vs. the energy that would come from a black body at the same temperature. The places in an emissivity spectrum that have a value less than one are the wavelength regions corresponding to molecules absorbing energy.

In general, in order to infer the temperature of the target from the measurement of emitted radiation, the value of the surface emissivity must be known. It is a function of wavelength and temperature. Hence, it is a property which must be known for accurate temperature determination of an object by measurement of its emitted electromagnetic radiation with a radiation thermometer. For normal incidence, the emissivity

$$\varepsilon(\lambda) = \frac{[1 - R(\lambda)]\ \{1 - T(\lambda)]}{[1 - R(\lambda).T(\lambda)]} \qquad ....(11)$$

Where, λ is the wavelength, $R(\lambda)$ is the true reflectivity and $T(\lambda)$ is the true transmissivity. $R(\lambda)$ and $T(\lambda)$ are related to the fundamental optical parameters, $n(\lambda)$, the refractive index and $k(\lambda)$, the extinction coefficient by the following relations:

$$R(\lambda) = \frac{[\{n(\lambda) - 1\}^2 + k(\lambda)^2]}{[\{n(\lambda) + 1\}^2 + k(\lambda)^2]} \qquad ....(12)$$

$$T(\lambda) = \exp[-\alpha(\lambda)t / \lambda] = \exp[-4\pi k(\lambda)t / \lambda] \qquad ....(13)$$

α is the absorption coefficient and t is the thickness of the material. When the radiant heat transfer is in an equilibrium state, the emissivity of a perfect opaque body is given by Kirchoff's law as 1- $R(\lambda)$ from the above equation, since $T(\lambda)= 0$.

Hence

$$\varepsilon(\lambda) = [1 - R(\lambda)] \qquad ....(14)$$

The experimentally measured values of transmittance and reflectance include effects such as light trapping and multiple internal reflections depending on the angle of incidence, surface roughness, presence of grains, grain boundaries, internal roughness, etc. The apparent transmittance $T(\lambda)^*$ and the apparent reflectance $R(\lambda)^*$ are related to real or true transmittance $T(\lambda)$, and true reflectance $R(\lambda)$, respectively by the following equations [10].

$$T(\lambda) = \frac{T(\lambda).\ (1 - R(\lambda))^2}{(1 - R(\lambda)^2 T(\lambda)^2)} \qquad ....(15)$$

$$R(\lambda)^* = \frac{R(\lambda).\ 1 + [T(\lambda)^2(1 - R(\lambda))^2]}{[1 - R(\lambda)^2\ T(\lambda)^2]} \qquad ....(16)$$

The above equations (15) and (16) are the results of considering multiple internal reflections. A simultaneous measurement of reflectance and transmittance can yield true values of reflectance and transmittance and therefore, the refractive index, $n(\lambda)$ and the extinction coefficient, $k(\lambda)$ of single substrate materials. Using equations (15) and (16), we get real R and T from apparent R* and T* and is given by,

$$R = T^{*2} - R^{*2} + 2R^* + 1 \pm SQT\{T^{*2}(T^{*2} + 2(-R^{*2} + 2R + 1)) + (R^* - 1)^4\}$$

$$T = \frac{R^*/R - 1}{T^*}$$

$$n = \frac{R + 1 \pm SQT\{4R - k^2 * (1 - R)^2\}}{(1 - R)}$$

$$\alpha = \frac{4\pi . k}{\lambda}$$

$$k = \frac{\alpha . \lambda}{4\pi}$$

With the choice of appropriate models, $n(\lambda)$ and $k(\lambda)$ of multilayers can also be resolved from experimentally measured spectral properties [11]. Emissivity models can convey to a process engineer information about films and thickness to achieve the desired emissivity. The total contribution to emissivity, $\varepsilon(\lambda, T)$, is given by [11],

$$\varepsilon(\lambda, T)_{total} = \varepsilon(\lambda, T)_{free\ carrier} + \varepsilon(\lambda, T)_{absorption\ edge} + \varepsilon(\lambda, T)_{phonon} \qquad ....(17)$$

For photon energy, $E_{photon} \geq E_g$, E_g is the bandgap, i.e., $\lambda_{photon} \leq \lambda_E$, the wavelength corresponding to the absorption edge, emissivity contributions are due to bandgap or above bandgap absorption. For $E_{photon} < E_g$, the emissivity contributions are due to below bandgap absorption. The free carrier absorption mechanism plays a dominant role in doped semiconductors in the short-wavelength range [12]. In the long-wavelength range(>10 microns), phonons contribute to the emissivity changes. These properties are function of temperature.

CHAPTER 5

EXPERIMENTAL DETAILS

5.1 EMISSOMETER- Description of the Apparatus

A spectral emissometer has been used to measure the optical properties of the materials investigated in this study. This instrument measures the radiative properties of a sample over a wide spectral range, in the near and mid-infrared, from 12,500 cm^{-1} to 500 cm^{-1} (0.8 to 20 μm). The schematic of the spectral emissometer is shown in Fig. 2. It consists of a hemi-ellipsoidal mirror having two foci, both inside the mirror. At one focus, the exciting source which is a near blackbody is placed and the sample under investigation at the other focus. A microprocessor controlled motorized chopper facilitates to measure radiance, reflectance and transmittance of the sample simultaneously. When the chopper closes, the black body source, the detector detects only directional radiance of the sample and when the chopper is open, the measured radiance will include both the emitted radiation of the sample and the blackbody radiation reflected by the sample. The Fourier transform infrared (FTIR) data collection system consisting of Ge (0.8 - 1.6 μm) and HgCdTe (1.6 - 20 μm) detector, is synchronized with the two states of the chopper allowing for the distinction of sample radiation from reflected/transmitted radiation. A carefully adjusted set of five mirrors provide the optical path for measurement of the optical properties. Three intersecting He-Ne laser beams are used to align the sample precisely at the focal point of the mirror. A high resolution Bomem FTIR detector, interfaced with a Pentium processor, permits data acquisition of the measured optical

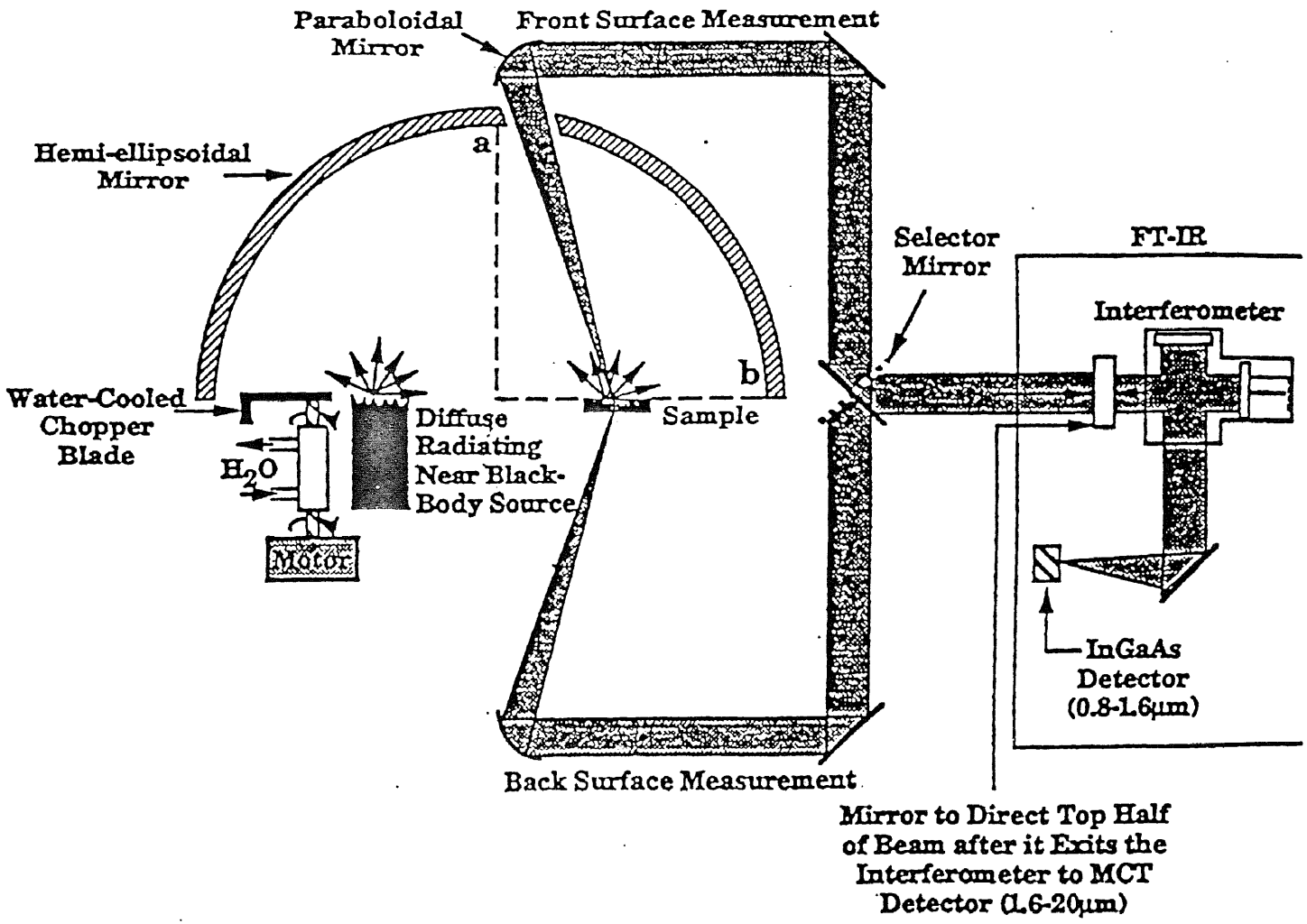


Fig. 2 Schematic of Benchtop Emissometer.

processor, permits data acquisition of the measured optical properties. This on-line computer enables the user to flip the mirror to acquire transmission/reflection via a software called Spectra Calc. This instrument has applications for: 1) industrial quality control of radiative properties of processed materials, 2) research and development of new materials, and 3) temperature measurements by optical techniques in the near and mid IR.

5.2 Methodology

Temperature Measurements:

By using the spectral emissometer, it is possible to measure radiance, reflectance, transmittance and the temperature of the sample simultaneously. A microprocessor controlled motorized chopper facilitates to measure the spectral properties of the sample. When the chopper is closed, the directional spectral radiance of the sample is given as follows[13].

$$R_v(T) = \varepsilon_v(T)\, R^b_v(T) \qquad ....(1)$$

where $\varepsilon_v(T)$ is the emissivity at temperature T, and R^b_v is the theoretical Planck function at temperature T.

When the chopper is open, the measured radiation is given by,

$$M_o = R_v(T) + \rho_v(T)\, R^b_v(T_{bb}) \qquad ....(2)$$

where, T_{bb} is the constant blackbody source temperature which is maintained at 900°C and ρ_v is the spectral directional-hemispherical reflectivity. The difference in the two measurements yields $\rho_v(T)\, R^b_v(T_{bb})$.

$$M_o - R_v(T) = \rho_v(T)\, R^b_v(T_{bb}). \qquad ....(3)$$

The constant source radiation is quantified by replacing the sample with the perfect reflector (a gold mirror, $\rho_v^{gold}(T) \cong 1.0$) and measuring the spectrum in the chopper open condition.

$$M_v^{ref} = \rho_v^{gold}(T)\, R^b_v(T_{bb}) = R^b_v(T_{bb}) \qquad ....(4)$$

The ratio of (3) to (4) results in the measurement of the directional hemispherical reflectance of the sample, ρ_v at the unknown temperature T.

$$M_o - R_v(T) / M_v^{ref} = \rho_v(T)\, R^b_v(T_{bb}) = R^b_v(T_{bb}) \qquad ....(5)$$

For an opaque sample, the spectral emittance, ε_v, can be determined from $\varepsilon_v = 1 - \rho_v$.

Once the spectral emissivity is known, the precise sample temperature can be determined by rearranging (1).

$$R^b_v(T) = R_v(T) / \varepsilon_v(T) \qquad ....(6)$$

Comparing (6) with Planck function leads to temperature evaluation:

$$R^b_\lambda = \frac{c_1 \lambda^{-5}}{\exp\{(c_2/\lambda T) - 1\}} \qquad ....(7)$$

where c_1 and c_2 are constants.

An on-line computer does all the mathematical operations on the raw data using Spectra calc. It transforms the interferograms into spectra, calculates spectral emittance from reflectance and transmittance data and automatically determines the temperature from radiance data.

CHAPTER 6

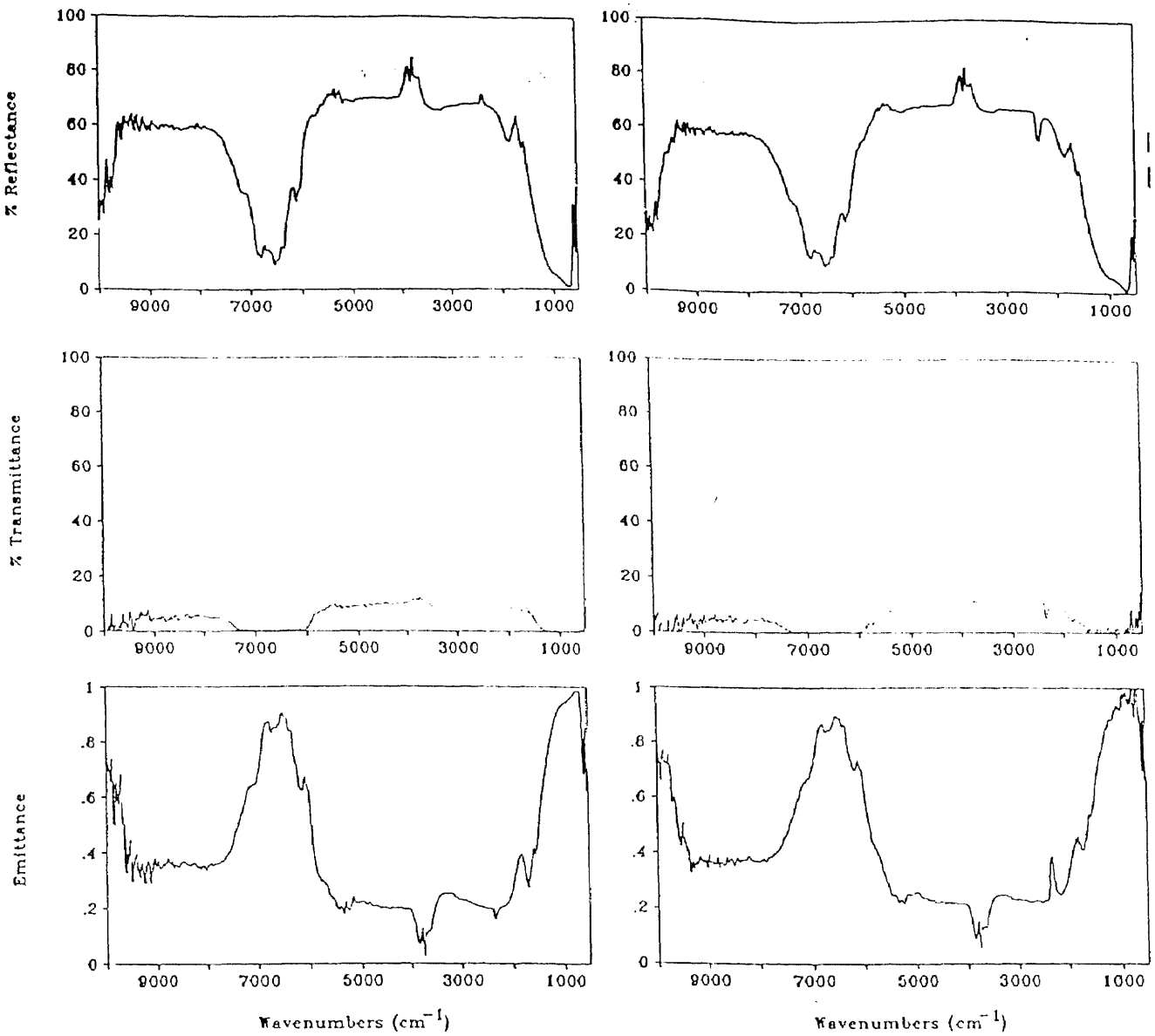
EXPERIMENTAL RESULTS

6.1 Erbium Oxide

6.1.1 Experimental Data of Optical Properties

The optical properties of Er_2O_3 sample, 2.03 mm thick is investigated using spectral emissometer at various wavelengths. The radiative properties at temperatures of 66, 360, 570 and 838°C while heating the sample and at temperatures of 517, 379 and 191°C during cooling down the sample are shown in Figs. (3-6). The experimental data has been deconvoluted to yield an estimate of the fundamental optical constants of this material. For this material, the emissivity is low in the wavelength range of 1 to 5 μm. At 10 μm, there is a sharp peak in the emissivity. The emissivity is fairly constant and low in the wavelength range of 2 to 5 μm.

By studying the optical properties at various temperatures, it can be observed that the emissivity data remains the same. Thus, it is possible to say that erbium oxide is a stable material and optical properties do not change much with temperature. This stability of erbium oxide and its low and high emissivity in the IR region could be exploited for its application as selective emitter in TPV. The rationale for measuring the high temperature optical properties and then subsequently cooling the sample in air and recording the room temperature data was to account for possible changes in the chemical composition of the sample.



(a) (b)

Fig. 3 Temperature dependent optical properties of Erbium Oxide:
(a) 66°C (b) 360°C

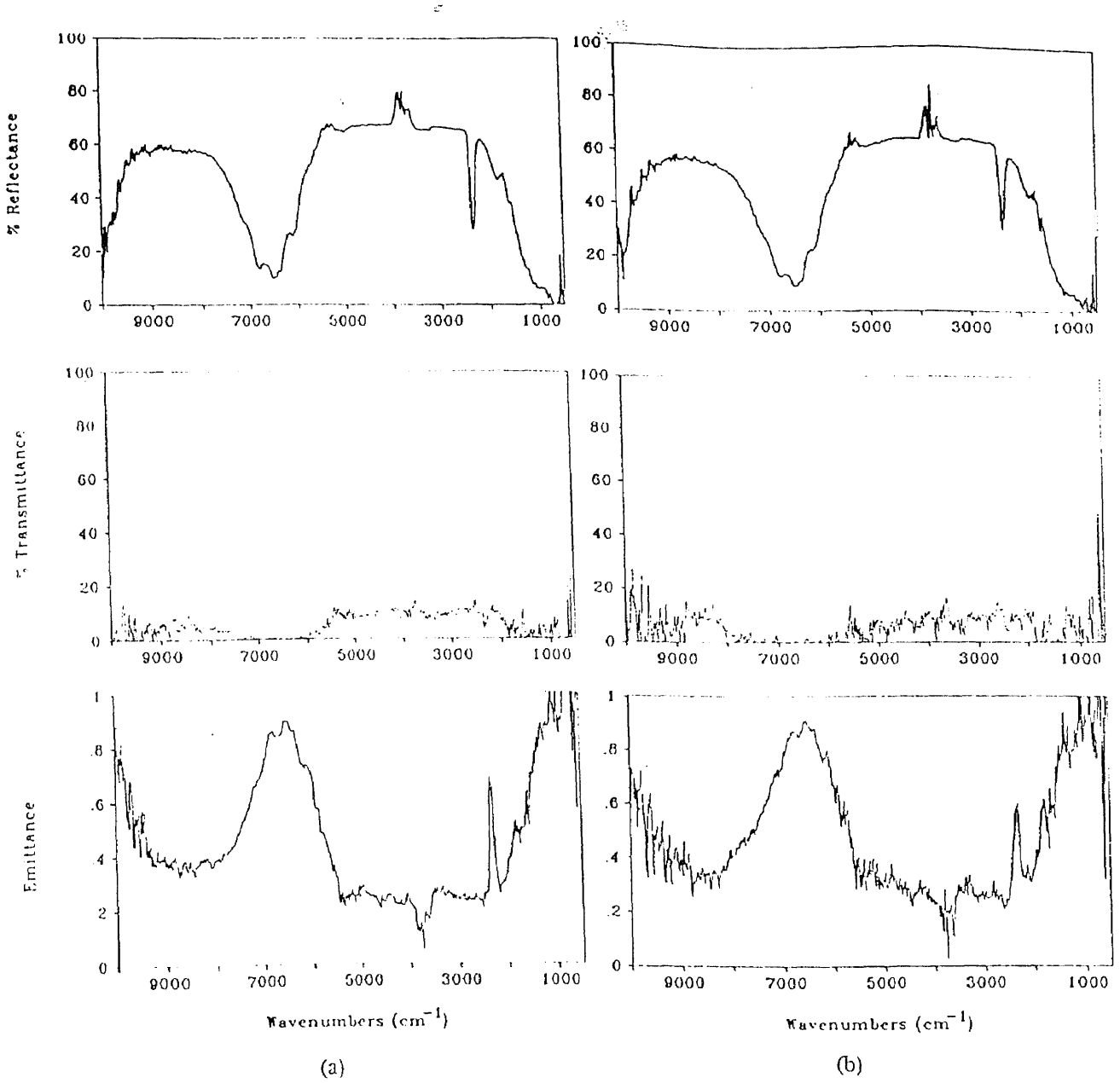
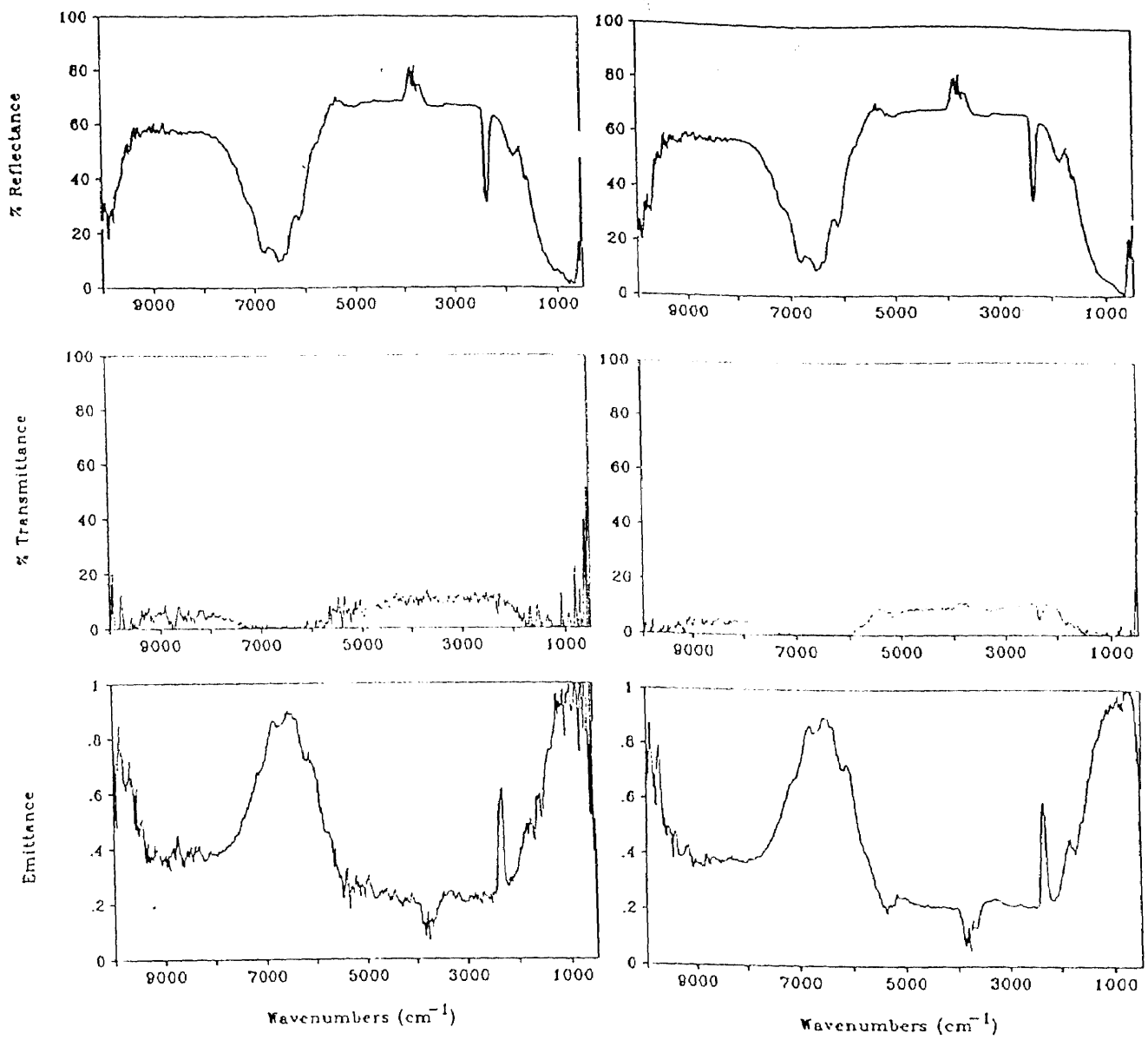


Fig. 4 Temperature dependent optical properties of Erbium Oxide:
(a) 570°C (b)838°C



(a) (b)

Fig. 5 Temperature dependent optical properties of Erbium Oxide:
(a) 517°C (on cooling) (b)379°C (on cooling)

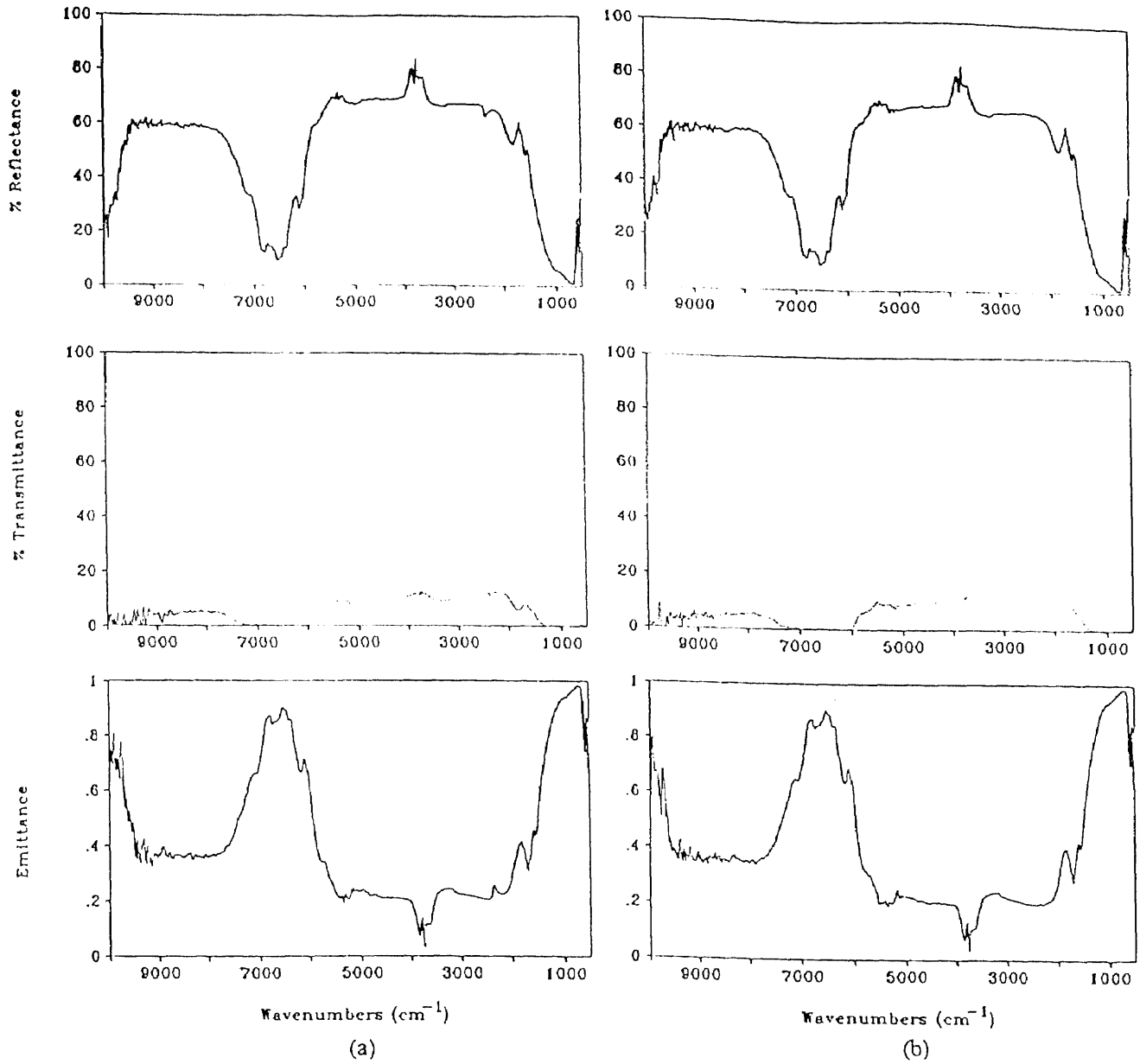


Fig. 6 Temperature dependent optical properties of Erbium Oxide:
(a) 191°C (b)103°C

6.1.2 Comparative Study of Optical Properties

The measured values of emissivity of erbium oxide are in complete accordance with those available in the literature [6]. The emittance of erbium oxide in the wavelength range of 0.5 - 1.9 microns as available in the literature is compared with those obtained from experiments at different temperatures in the same wavelength range and they are found to be similar. The deconvoluted values of refractive index at temperatures of 66, 379, 517 and 838°C, are plotted as function of wavelength in Fig. 7 . In the wavelength range of 0.5 to 3.5 microns, the refractive index n is high.

6.2 Sapphire

6.2.1 Literature Data of Optical Properties

In this section, the data of the refractive index available in the literature [16] are presented. Table 3 shows the refractive index of sapphire in the wavelength range of 1 to 6 microns.

6.2.2 Experimental Data of Optical Properties

The optical properties of a 2.1 mm thick sapphire was measured using the spectral emissometer at different wavelengths and various temperatures. The measured optical properties of sapphire at temperatures of 55, 466, 771, 994°C while heating and 368 and 138°C while cooling are presented. Sapphire is characterized by a very large transmission in the IR with subsequent decrease at 6 μm. Sapphire is highly absorbing in the wavelength range of 7 to 10 μm. Its emissivity approaches 1 at about 8 μm. The influence of high temperature is to broaden the peak in the long wavelength absorption in sapphire.

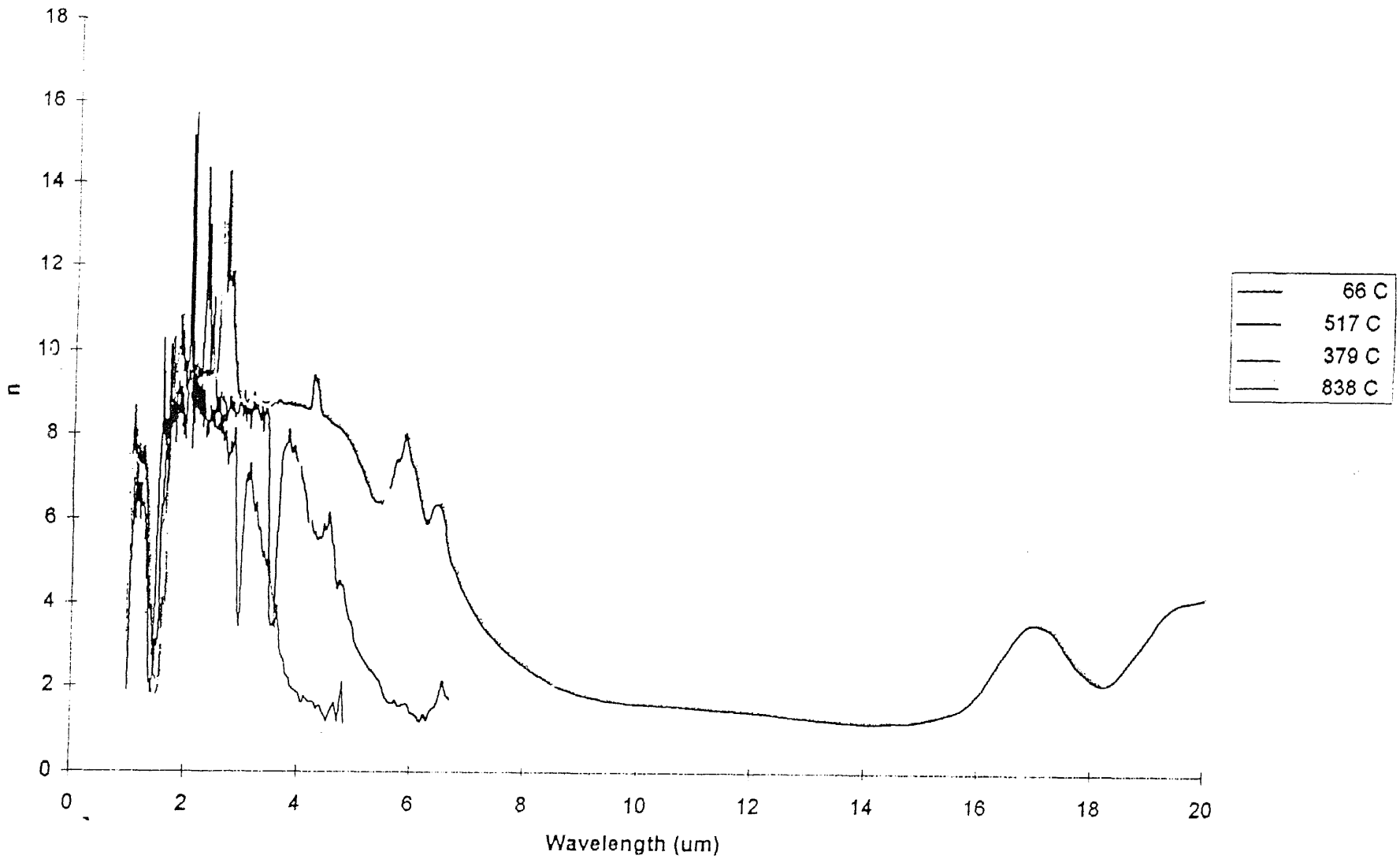


Fig. 7 Refractive index, n of Er_2O_3 as a function of Wavelength (μm) at different temperatures.

Table 3 Refractive index values of Sapphire from literature [18]

λ (microns)	n
1.01398	1.75547
1.52952	1.74660
2.1526	1.73444
2.4374	1.72783
3.2439	1.70437
3.3026	1.70231
3.5070	1.69504
3.7067	1.68746
4.2553	1.66371
4.954	1.62665
5.1456	1.61514
5.419	1.59735
5.577	1.58638

Cooling the sample to 138°C is seen to reproduce the low temperature optical data of sapphire. Thus, heating the sapphire to 994°C and subsequent cooling has not changed the chemical composition of the sample. The experimentally measured data of the optical properties have been deconvoluted to yield the fundamental optical constants. In table 3 some of these optical constants at various wavelengths are presented. In Appendix A2, the full range of data of the optical properties are given. The deconvoluted values of refractive

index, at different temperatures are plotted as a function of wavelength in Fig. 13. In the wavelength range of 12 to 18 microns, the refractive index, n of sapphire approaches high value from its high reflectance.

6.2.3 Comparative Study of Optical Properties

The measured values of emissivity of sapphire are in complete accordance with those available in the literature [13, 17]. The experimental values of refractive index differ by about ± 1 %. This is reasonable because of the approximation used in deconvoluting the experimental data to yield optical constants.

6.3 Comparison of Optical Properties of Sapphire and Lucalox

Lucalox is a very stable material as compared to sapphire and could withstand very high temperature without degradation. Hence, it finds its application in vapor lamps as it can withstand high temperature of ionization. Lucalox is a good candidate for replacing sapphire. Figs. (8 - 11) compare the optical properties of sapphire with lucalox at various temperatures. From the figures, it may be concluded that the two materials resemble each other very closely. The deconvoluted values of refractive index are plotted as a function of wavelength (microns) at different wavelengths in Fig. 11. From Figs. 12 and 13, we could infer that the two materials behave the same in the IR region.

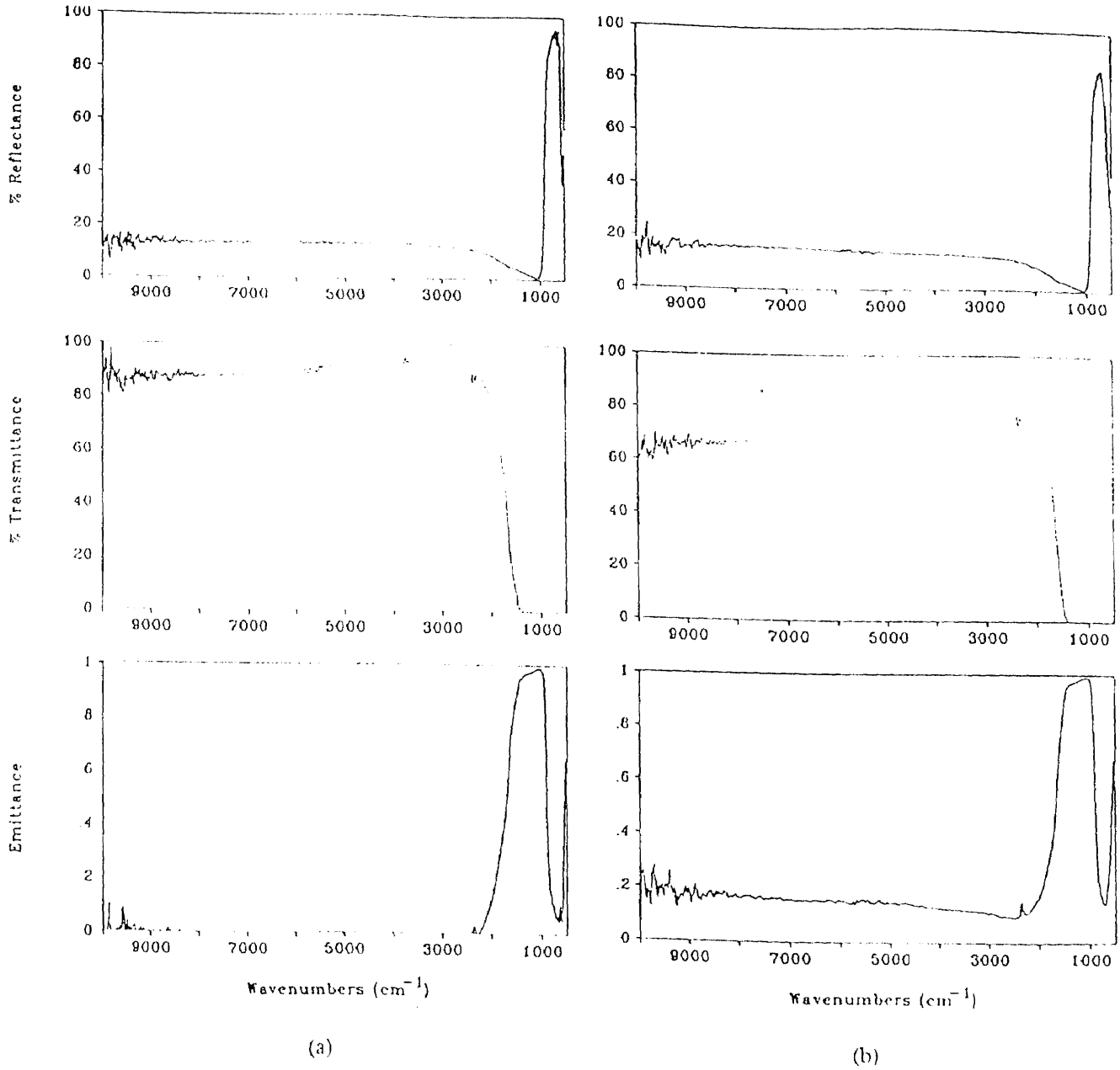


Fig. 8 Comparison of optical properties of (a)Sapphire and (b)Lucalox
(a)55°C (b)86°C

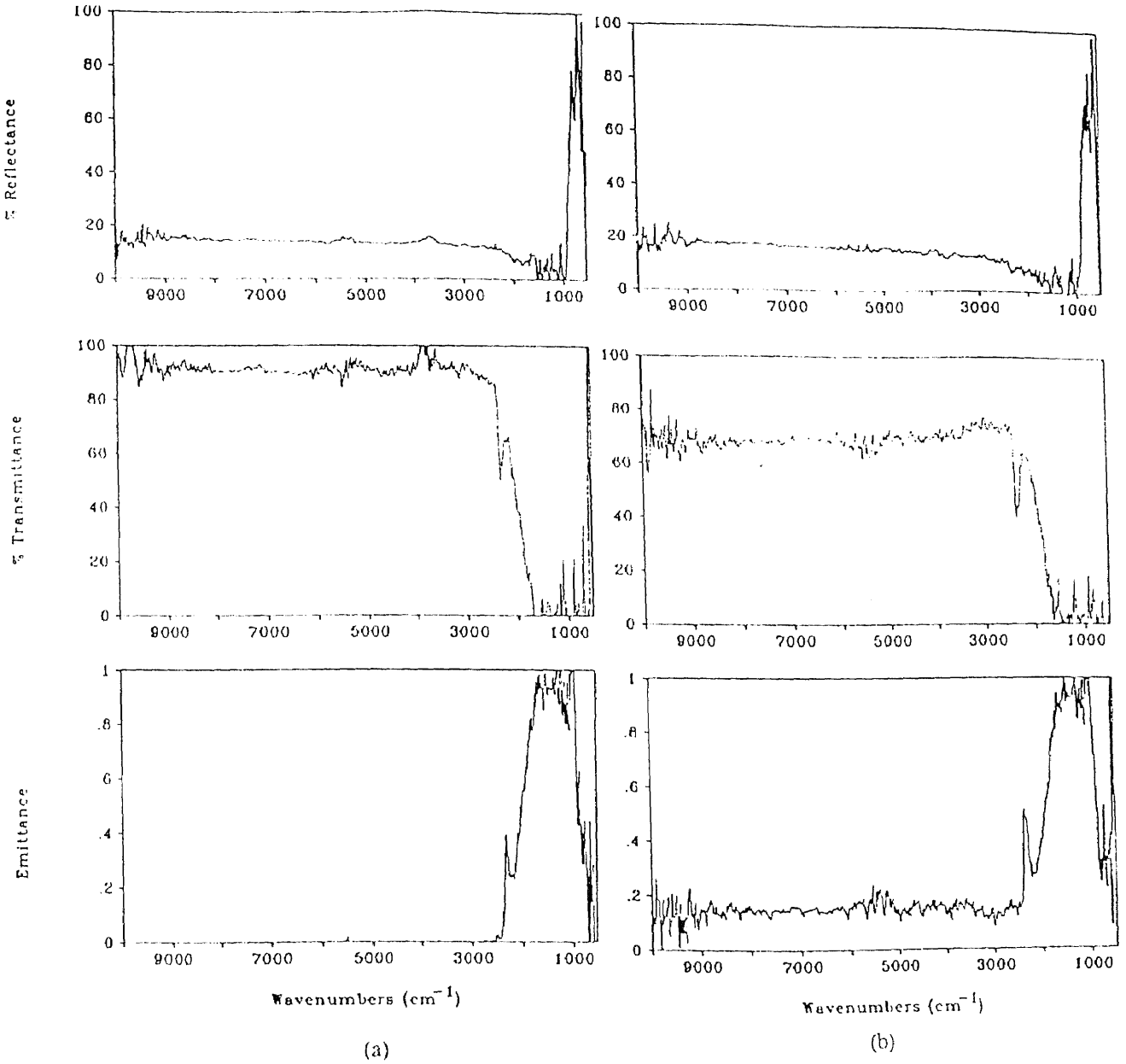
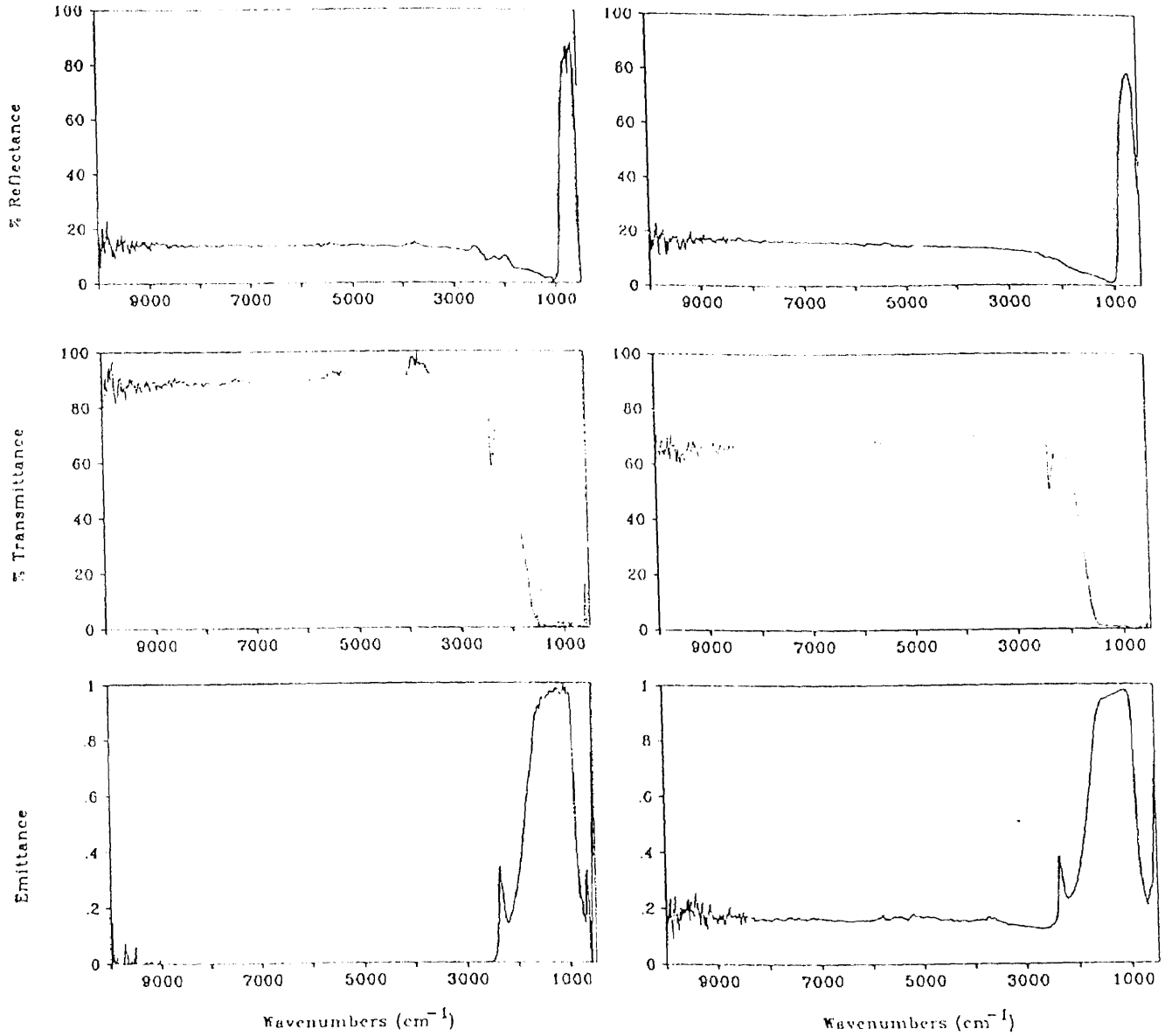


Fig. 9 Comparison of optical properties of (a)Sapphire and (b)Lucalox
(a)994°C (b)945°C



(a) (b)

Fig. 10 Comparison of optical properties of (a)Sapphire and (b)Lucalox
(a)466°C (b)561°C

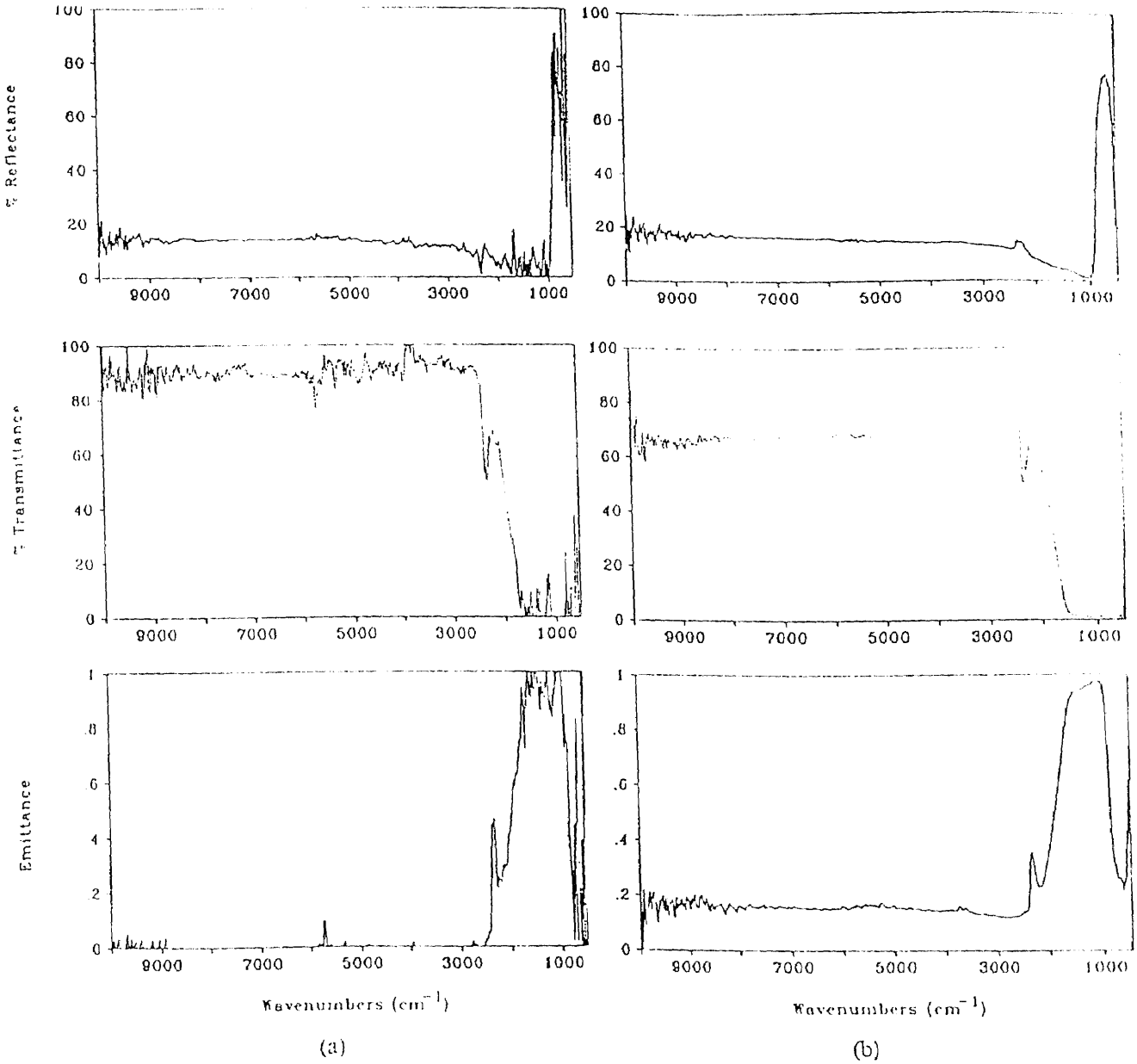


Fig. 11 Comparison of optical properties of (a)Sapphire and (b)Lucalox
(a)771°C (b)720°C

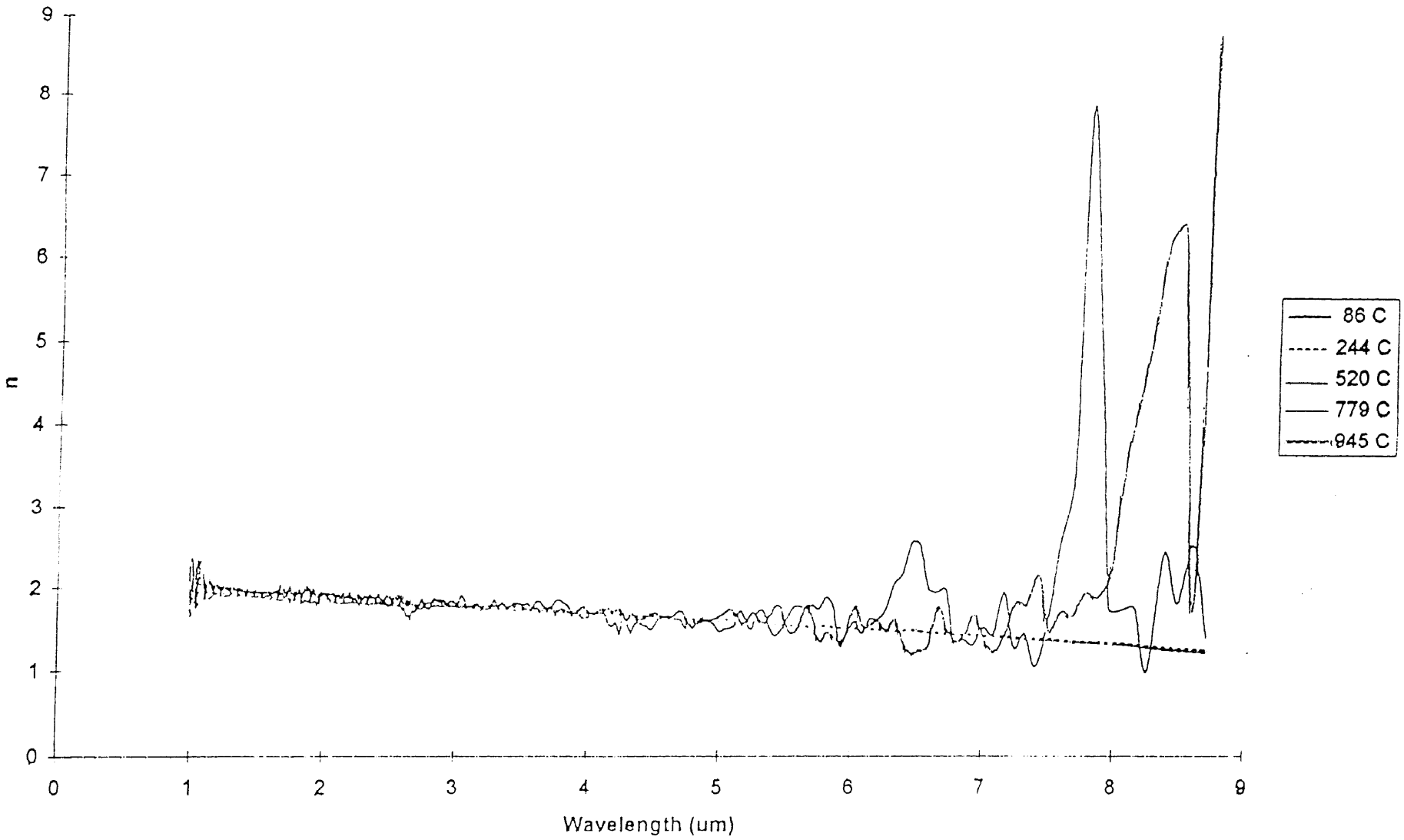


Fig. 12 Refractive index, n of Lucalox as a function of Wavelength (μm) at different temperatures.

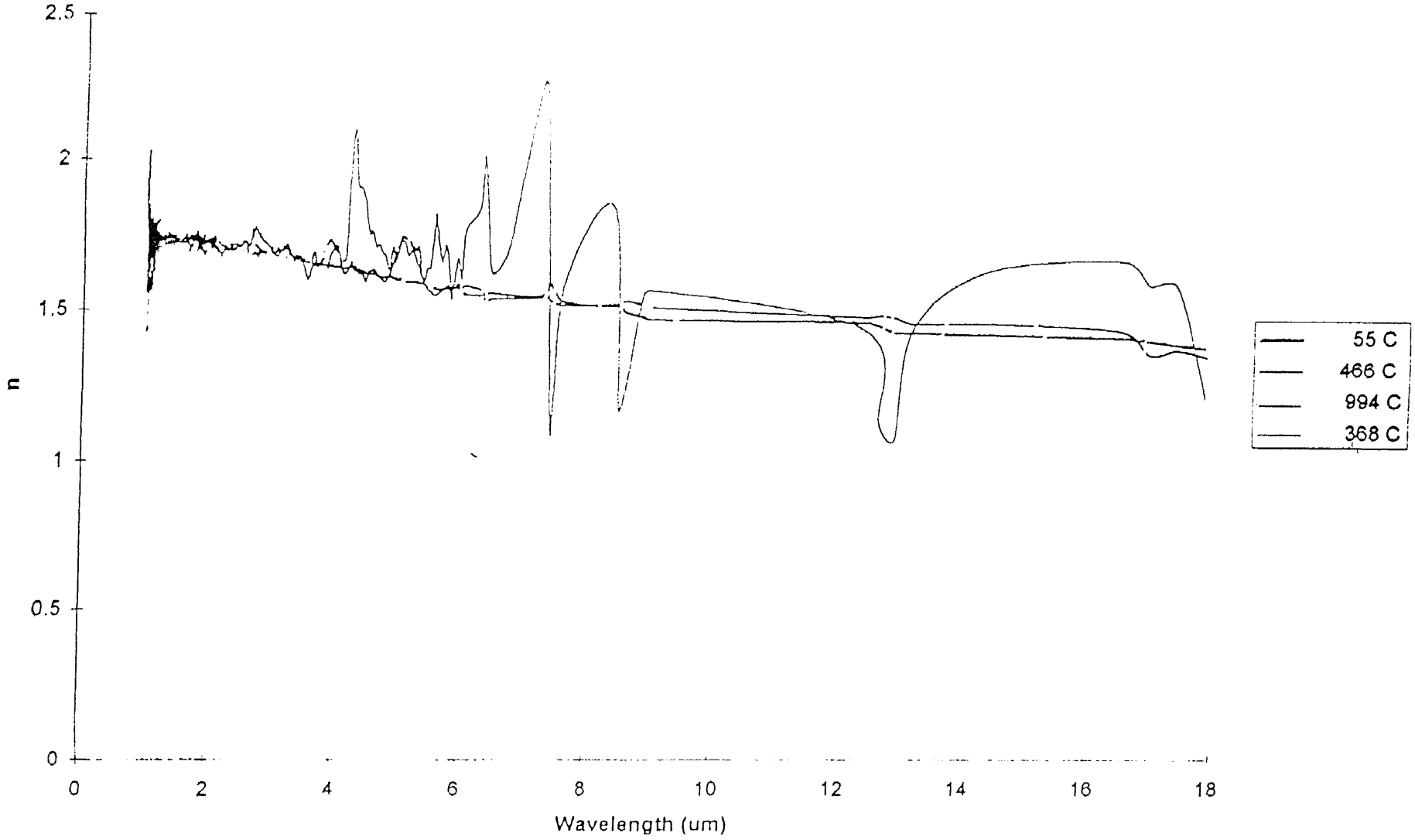


Fig. 13 Refractive index, n of Sapphire as a function of Wavelength (μm) at different temperatures.

6. 4 Quartz

6.4.1 Literature Data of Optical Properties

In this section, the data on refractive index available in the literature [19] are presented. Table 4 shows the refractive index of quartz between 1 to 20 microns wavelength range.

Table 4 Refractive Index of Quartz from the Literature [19].

Wavelength (λ)	n
1.000	1.535
2.053	1.520
3.000	1.499
5.000	1.412
7.000	1.130
9.400	6.336
9.900	2.734
10.250	2.405
14.950	1.795
16.050	1.629
18.800	1.023

6.4.2 Experimental Data of Optical Properties

The optical properties of 3.2 mm thick quartz crystal was measured using spectral emissometer at different wavelengths and temperatures. In Figs. 14 -15, the measured spectra of quartz at temperatures of 182, 521, 677 and 817°C are presented. Fig. 16 compares the spectra of quartz at 182°C after heating and cooling. Thus, heating the quartz crystal to 817°C and subsequent cooling has not changed the chemical composition of quartz. Quartz is characterized by a large transmission in the IR region with subsequent decrease at 9 microns. Quartz has a high emissivity approaching 1 at about 5 microns. The experimentally measured data of the optical properties have been deconvoluted to yield the fundamental optical constants. The measured values of k are strongly influenced by the presence of impurity and defect absorption. For this reason, k values are zero in the lower IR region. In appendix A4, the full range of the optical properties are given.

6.4.3 Comparative Study of Optical Properties

The measured values of emissivity of quartz are in complete accordance with those available in the literature [19]. As seen from Fig. 17, the experimental results of the wavelength dependent refractive index are in good agreement with those in the literature [19]. The experimental values differ by literature values by about $\pm$ 1 % because of approximation used in deconvoluting the experimental data to yield optical constants.

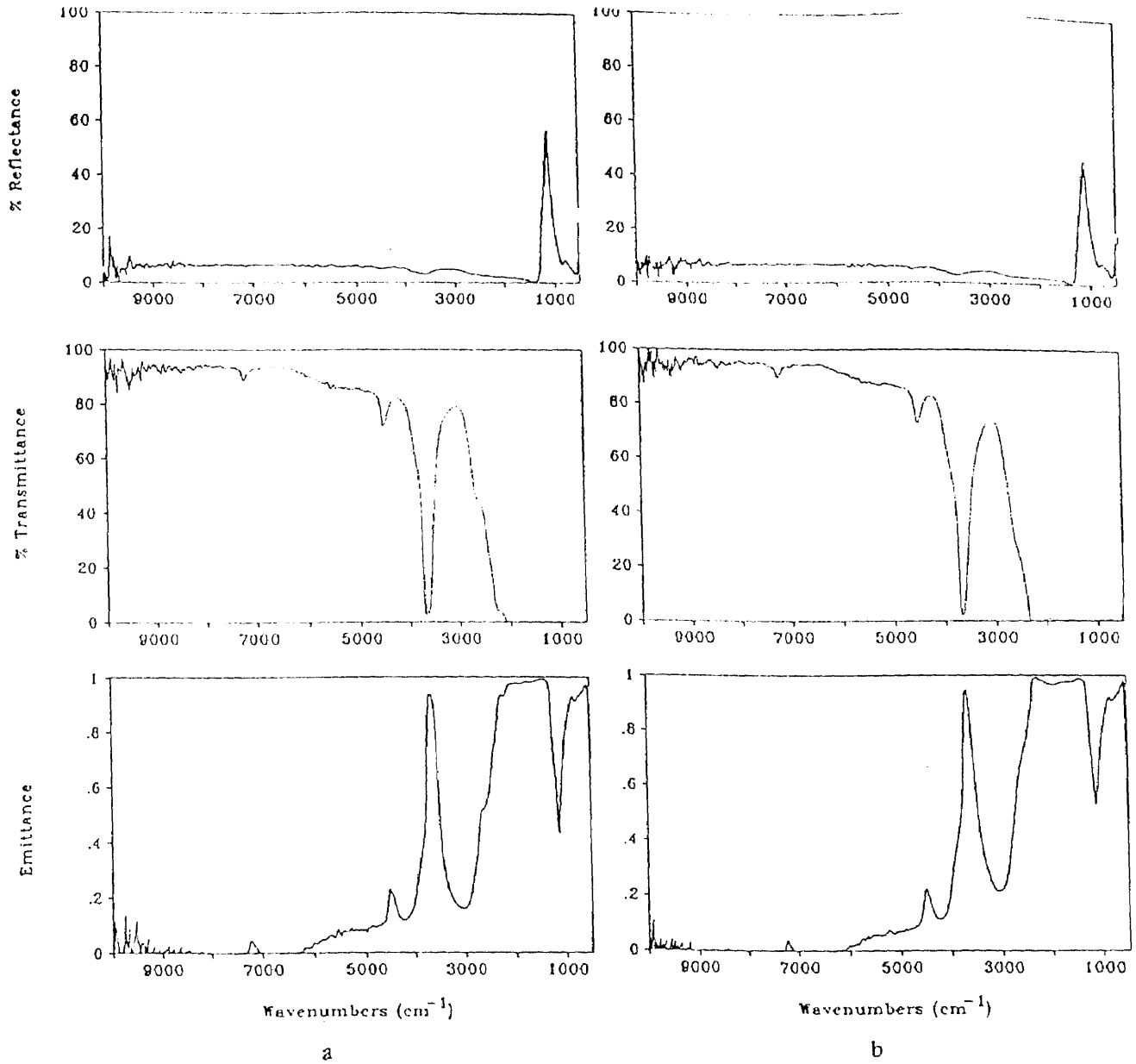


Fig. 14 Temperature Dependent Optical Properties of Quartz
(a)182°C (b)521°C

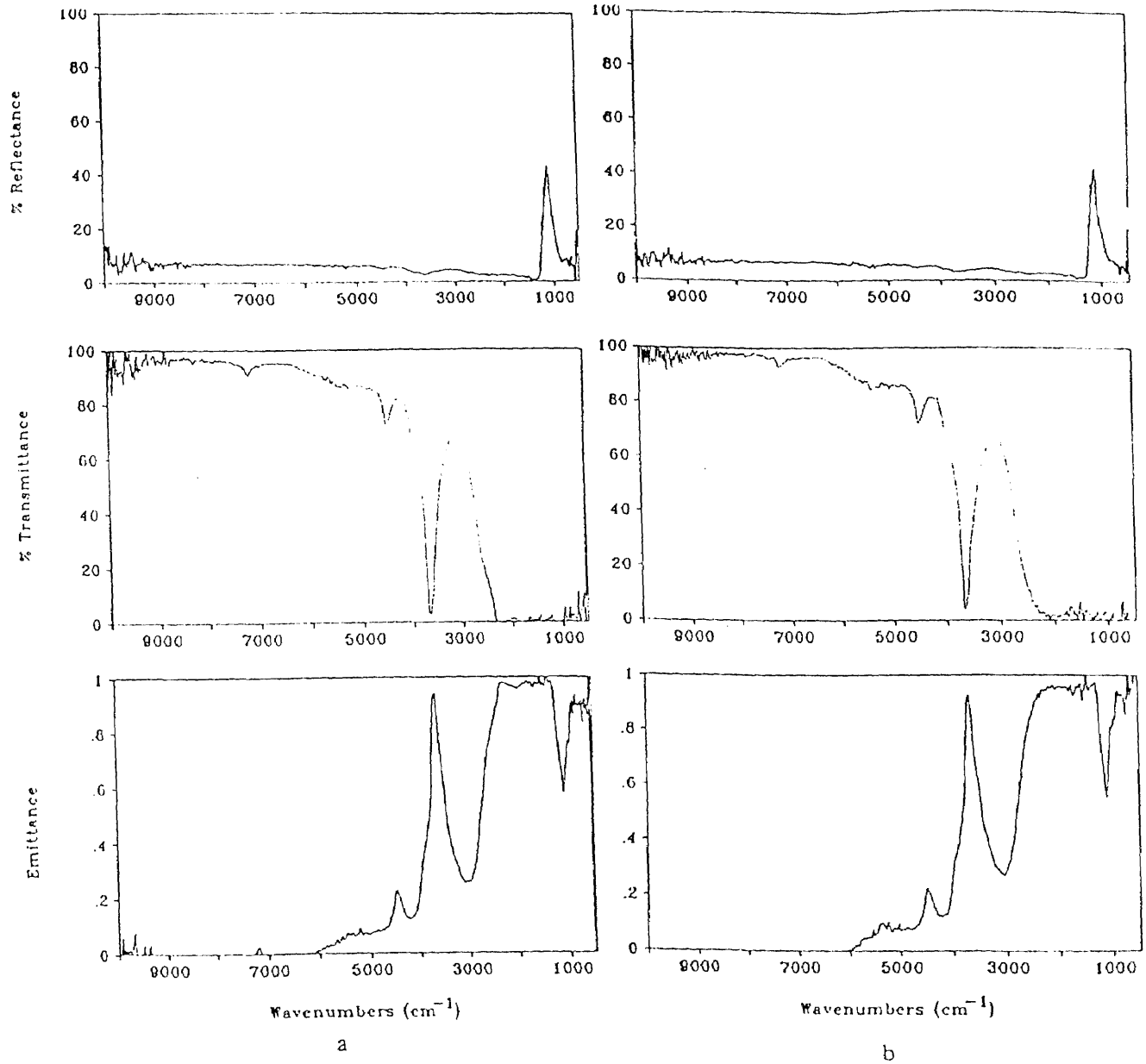
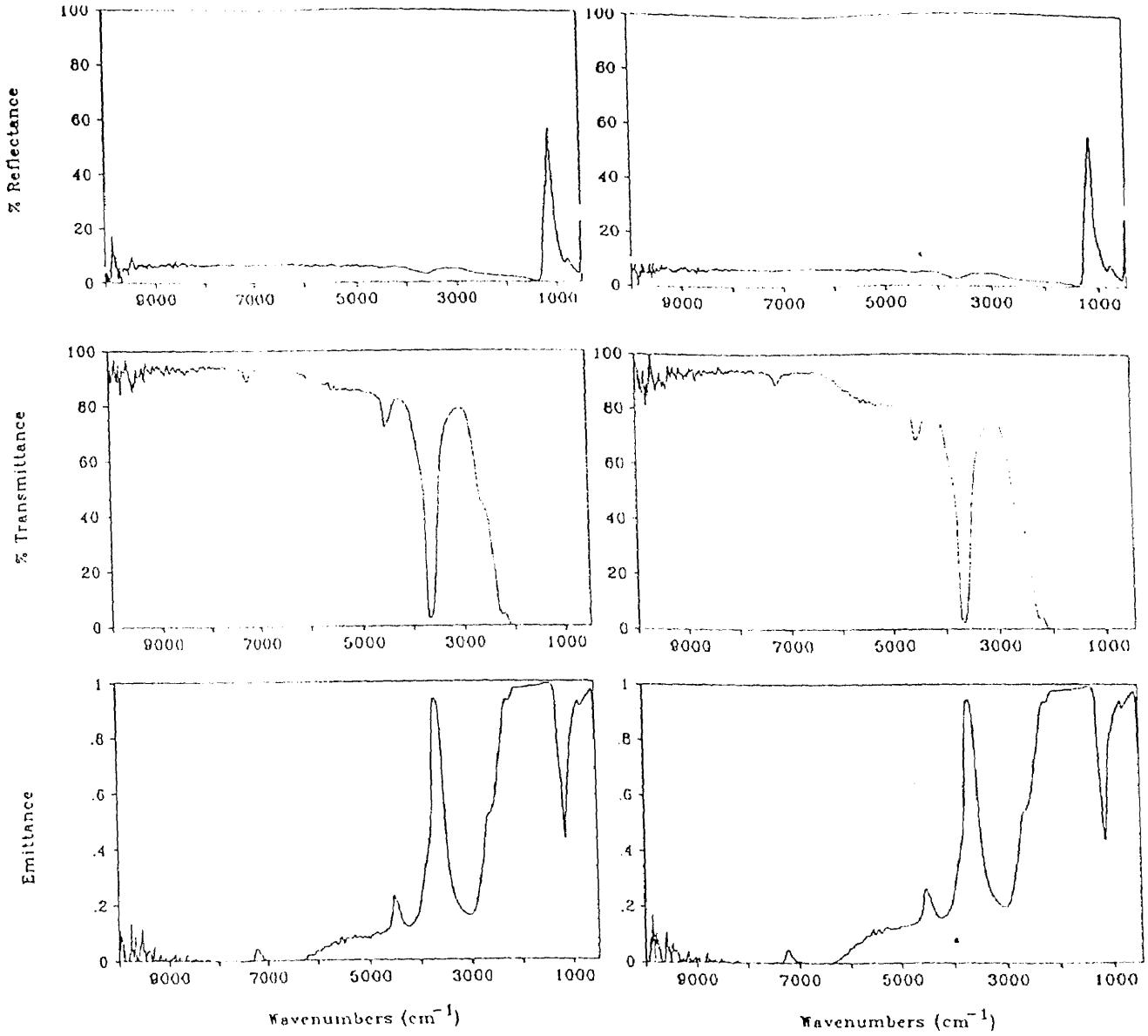


Fig. 15 Temperature Dependent Optical Properties of Quartz
(a)677°C (b)817°C



a b

Fig. 16 Temperature Dependent Optical Properties of Quartz
(a) 182°C (on heating) (b) 182°C (on cooling)

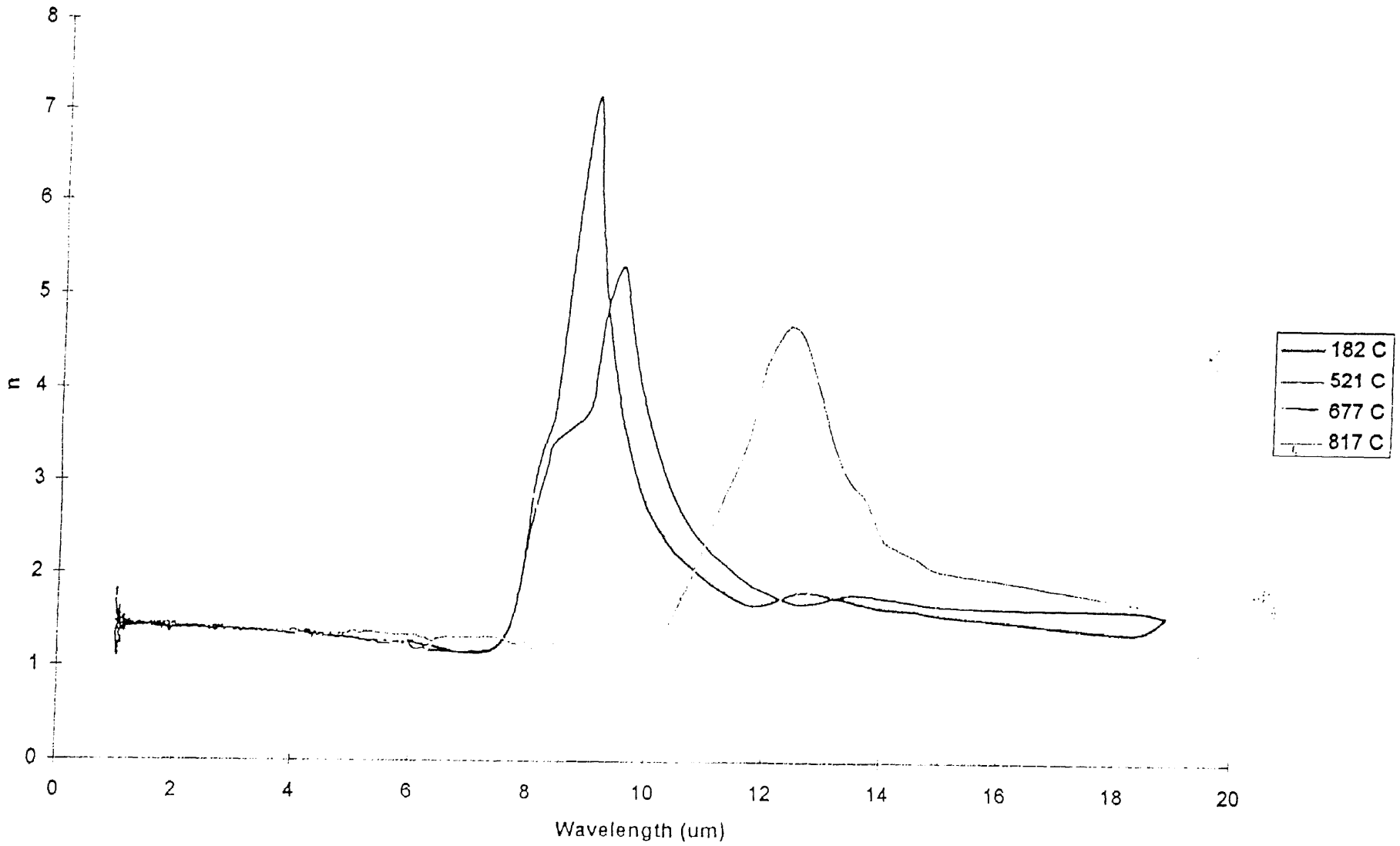


Fig. 17 Refractive index, n of quartz as a function of Wavelength (μm) at various temperatures

CHAPTER 7

CONCLUSIONS

The experimental results presented in this thesis showed that the measurement of high temperature radiative properties over the wavelength range of 1 to 20 microns and temperature range of 30 to 1500°C could be performed reliably with a novel approach based on the use of a spectral emissometer. Methodology of obtaining temperature from simultaneous measurement of reflectance, transmittance and radiance has been shown with application to erbium oxide, sapphire and quartz. In general, results of the temperature and wavelength dependent emissivity of erbium oxide, sapphire and quartz, and comparison with studies in the literature, lead to following observations:

- Erbium oxide emitters have unique selectivity line emission, which gives a high emittance at a particular wavelength and very low emittance in the rest of the infrared spectrum. The highly selective line emission is matched well with some well developed PV cells, e.g., erbium oxide matched with InGaAs cells. Obviously, using these emitters can increase emitter efficiency.
- Erbium oxide is a very stable material, with the emissivity not varying much with temperature. This property finds its application in TPV.
- Lucalox exhibits emissivity approaching 1 at 8 microns. In the wavelength range of 12 to 18 microns, the refractive indices of sapphire approach high values resulting from its high reflectance. The optical properties of lucalox closely match that of sapphire.

- Sapphire is highly absorbing in the wavelength range of 7 to 10 microns and its emissivity reaches 1 at about 8 μm. In the wavelength range of 12 to 18 microns, the refractive index of sapphire approaches high value from its high reflectance.
- Quartz has a high emissivity approaching 1 at about 3 microns. As the measured values of k are strongly influenced by the presence of impurity and defect absorption, k values are zero in the shorter IR region.

APPENDICES

A1: LUCALOX OPTICAL CONSTANTS AT 66°C

A2: ERBIUM OXIDE OPTICAL CONSTANTS AT 54°C

APPENDIX A1: LUCALOX OPTICAL CONSTANTS AT 54°C

Wavelength	Ext coeff	Ref index	Epsilon1	Epsilon2	Alpha
1	0	2.017	4.069	0	0
1.002	0	2.096	4.393	0	0
1.003	0	1.972	3.889	0	0
1.005	0	1.837	3.374	0	0
1.006	0	1.976	3.905	0	0
1.008	0	2.087	4.357	0	0
1.01	0	1.844	3.399	0	0
1.011	0	1.898	3.601	0	0
1.013	0	2.061	4.248	0	0
1.014	0	1.982	3.929	0	0
1.016	0	2.066	4.269	0	0
1.017	0	1.988	3.954	0	0
1.019	0	2.029	4.116	0	0
1.021	0	2.181	4.759	0	0
1.022	0	2.081	4.33	0	0
1.024	0	2.053	4.216	0	0
1.026	0	2.091	4.374	0	0
1.027	0	1.952	3.811	0	0
1.029	0	1.985	3.941	0	0
1.03	0	2.167	4.696	0	0
1.032	0	2.082	4.333	0	0
1.034	0	1.944	3.78	0	0
1.035	0	1.979	3.916	0	0
1.037	0	1.934	3.74	0	0
1.039	0	2.012	4.049	0	0
1.04	0	2.054	4.221	0	0
1.042	0	1.999	3.997	0	0
1.044	0	1.963	3.855	0	0
1.045	0	1.928	3.718	0	0
1.047	0	1.97	3.882	0	0
1.049	0	2.012	4.048	0	0
1.05	0	2.026	4.105	0	0
1.052	0	1.964	3.855	0	0
1.054	0	1.818	3.304	0	0
1.056	0	1.885	3.553	0	0
1.057	0	1.866	3.481	0	0
1.059	0	1.97	3.881	0	0
1.061	0	2.07	4.285	0	0
1.063	0	2.042	4.171	0	0
1.064	0	2.007	4.03	0	0
1.066	0	2.018	4.072	0	0
1.068	0	1.951	3.805	0	0
1.07	0	1.881	3.539	0	0
1.071	0	1.865	3.478	0	0
1.073	0	1.821	3.316	0	0
1.075	0	1.986	3.945	0	0
1.077	0	2.028	4.112	0	0
1.078	0	1.936	3.749	0	0
1.08	0	1.875	3.517	0	0
1.082	0	1.898	3.602	0	0

LUCA154

1.084	0	2.022	4.089	0	0
1.086	0	2.071	4.287	0	0
1.088	0	2.022	4.089	0	0
1.089	0	1.941	3.769	0	0
1.091	0	2.012	4.049	0	0
1.093	0	2.047	4.192	0	0
1.095	0	1.992	3.968	0	0
1.097	0	2.002	4.009	0	0
1.099	0	1.973	3.892	0	0
1.1	0	1.956	3.827	0	0
1.102	0	2.005	4.02	0	0
1.104	0	2.033	4.134	0	0
1.106	0	2.023	4.094	0	0
1.108	0	1.979	3.915	0	0
1.11	0	2.004	4.015	0	0
1.112	0	1.983	3.934	0	0
1.114	0	1.956	3.827	0	0
1.116	0	1.974	3.896	0	0
1.118	0	1.992	3.969	0	0
1.12	0	2.009	4.038	0	0
1.121	0	2.033	4.132	0	0
1.123	0	1.986	3.944	0	0
1.125	0	1.945	3.781	0	0
1.127	0	1.962	3.85	0	0
1.129	0	1.932	3.733	0	0
1.131	0	1.956	3.825	0	0
1.133	0	1.985	3.941	0	0
1.135	0	1.954	3.82	0	0
1.137	0	1.989	3.955	0	0
1.139	0	2.005	4.021	0	0
1.141	0	1.964	3.857	0	0
1.143	0	1.981	3.925	0	0
1.145	0	2.002	4.006	0	0
1.147	0	1.983	3.934	0	0
1.149	0	1.971	3.886	0	0
1.151	0	1.97	3.882	0	0
1.153	0	1.974	3.897	0	0
1.155	0	1.953	3.813	0	0
1.158	0	1.971	3.883	0	0
1.16	0	2.003	4.01	0	0
1.162	0	2	4.001	0	0
1.164	0	1.949	3.798	0	0
1.166	0	1.977	3.908	0	0
1.168	0	1.987	3.948	0	0
1.17	0	1.968	3.873	0	0
1.172	0	1.958	3.833	0	0
1.174	0	1.947	3.791	0	0
1.176	0	1.979	3.915	0	0
1.179	0	1.974	3.896	0	0
1.181	0	1.946	3.789	0	0
1.183	0	1.957	3.83	0	0

LUCA154

1.185	0	1.962	3.85	0	0
1.187	0	1.944	3.779	0	0
1.189	0	1.955	3.823	0	0
1.192	0	1.957	3.829	0	0
1.194	0	1.954	3.819	0	0
1.196	0	1.953	3.814	0	0
1.198	0	1.936	3.746	0	0
1.2	0	1.952	3.812	0	0
1.203	0	1.953	3.815	0	0
1.205	0	1.949	3.8	0	0
1.207	0	1.959	3.837	0	0
1.209	0	1.945	3.785	0	0
1.212	0	1.967	3.869	0	0
1.214	0	1.986	3.946	0	0
1.216	0	1.979	3.918	0	0
1.219	0	1.976	3.903	0	0
1.221	0	1.977	3.907	0	0
1.223	0	1.953	3.816	0	0
1.225	0	1.931	3.727	0	0
1.228	0	1.95	3.803	0	0
1.23	0	1.967	3.867	0	0
1.232	0	1.955	3.821	0	0
1.235	0	1.957	3.829	0	0
1.237	0	1.951	3.808	0	0
1.24	0	1.93	3.723	0	0
1.242	0	1.946	3.789	0	0
1.244	0	1.967	3.868	0	0
1.247	0	1.967	3.868	0	0
1.249	0	1.974	3.898	0	0
1.252	0	1.984	3.935	0	0
1.254	0	1.976	3.903	0	0
1.256	0	1.971	3.886	0	0
1.259	0	1.963	3.854	0	0
1.261	0	1.949	3.797	0	0
1.264	0	1.944	3.78	0	0
1.266	0	1.94	3.763	0	0
1.269	0	1.938	3.755	0	0
1.271	0	1.956	3.825	0	0
1.274	0	1.964	3.859	0	0
1.276	0	1.951	3.806	0	0
1.279	0	1.943	3.777	0	0
1.281	0	1.931	3.73	0	0
1.284	0	1.925	3.706	0	0
1.286	0	1.952	3.811	0	0
1.289	0	1.959	3.836	0	0
1.291	0	1.944	3.781	0	0
1.294	0	1.942	3.772	0	0
1.297	0	1.936	3.749	0	0
1.299	0	1.93	3.723	0	0
1.302	0	1.943	3.773	0	0
1.304	0	1.96	3.842	0	0

LUCA154

1.307	0	1.956	3.825	0	0
1.31	0	1.947	3.791	0	0
1.312	0	1.944	3.777	0	0
1.315	0	1.939	3.76	0	0
1.318	0	1.949	3.798	0	0
1.32	0	1.949	3.797	0	0
1.323	0	1.945	3.785	0	0
1.326	0	1.963	3.855	0	0
1.329	0	1.958	3.834	0	0
1.331	0	1.94	3.763	0	0
1.334	0	1.941	3.766	0	0
1.337	0	1.953	3.813	0	0
1.34	0	1.961	3.846	0	0
1.342	0	1.956	3.827	0	0
1.345	0	1.949	3.797	0	0
1.348	0	1.948	3.793	0	0
1.351	0	1.942	3.77	0	0
1.354	0	1.933	3.736	0	0
1.356	0	1.932	3.731	0	0
1.359	0	1.932	3.734	0	0
1.362	0	1.936	3.748	0	0
1.365	0	1.938	3.755	0	0
1.368	0	1.948	3.793	0	0
1.371	0	1.938	3.757	0	0
1.374	0	1.919	3.682	0	0
1.377	0	1.921	3.69	0	0
1.38	0	1.925	3.707	0	0
1.382	0	1.929	3.722	0	0
1.385	0	1.936	3.75	0	0
1.388	0	1.951	3.807	0	0
1.391	0	1.957	3.832	0	0
1.394	0	1.942	3.771	0	0
1.397	0	1.93	3.725	0	0
1.4	0	1.932	3.732	0	0
1.403	0	1.938	3.754	0	0
1.406	0	1.937	3.751	0	0
1.41	0	1.937	3.754	0	0
1.413	0	1.95	3.802	0	0
1.416	0	1.953	3.814	0	0
1.419	0	1.936	3.749	0	0
1.422	0	1.932	3.733	0	0
1.425	0	1.944	3.779	0	0
1.428	0	1.946	3.788	0	0
1.431	0	1.939	3.76	0	0
1.435	0	1.932	3.732	0	0
1.438	0	1.928	3.719	0	0
1.441	0	1.93	3.726	0	0
1.444	0	1.93	3.724	0	0
1.447	0	1.929	3.72	0	0
1.451	0	1.926	3.708	0	0
1.454	0	1.924	3.701	0	0

LUCA154

1.457	0	1.923	3.697	0	0
1.46	0	1.923	3.696	0	0
1.464	0	1.928	3.716	0	0
1.467	0	1.927	3.714	0	0
1.47	0	1.922	3.694	0	0
1.474	0	1.927	3.712	0	0
1.477	0	1.93	3.724	0	0
1.48	0	1.926	3.709	0	0
1.484	0	1.928	3.716	0	0
1.487	0	1.923	3.699	0	0
1.491	0	1.916	3.673	0	0
1.494	0	1.92	3.685	0	0
1.498	0	1.919	3.684	0	0
1.501	0	1.911	3.653	0	0
1.505	0	1.913	3.658	0	0
1.508	0	1.915	3.666	0	0
1.512	0	1.915	3.668	0	0
1.515	0	1.916	3.672	0	0
1.519	0	1.919	3.684	0	0
1.522	0	1.922	3.693	0	0
1.526	0	1.92	3.686	0	0
1.529	0	1.922	3.693	0	0
1.533	0	1.92	3.685	0	0
1.537	0	1.918	3.68	0	0
1.54	0	1.918	3.679	0	0
1.544	0	1.915	3.669	0	0
1.548	0	1.919	3.684	0	0
1.551	0	1.918	3.679	0	0
1.555	0	1.912	3.654	0	0
1.559	0	1.913	3.659	0	0
1.563	0	1.915	3.666	0	0
1.566	0	1.914	3.663	0	0
1.57	0	1.912	3.655	0	0
1.574	0	1.915	3.668	0	0
1.578	0	1.917	3.675	0	0
1.582	0	1.912	3.657	0	0
1.586	0	1.915	3.666	0	0
1.589	0	1.91	3.649	0	0
1.593	0	1.905	3.629	0	0
1.597	0	1.907	3.638	0	0
1.601	0	1.912	3.657	0	0
1.605	0	1.908	3.641	0	0
1.609	0	1.897	3.6	0	0
1.613	0	1.909	3.646	0	0
1.617	0	1.915	3.667	0	0
1.621	0	1.91	3.648	0	0
1.625	0	1.912	3.656	0	0
1.629	0	1.909	3.645	0	0
1.634	0	1.916	3.67	0	0
1.638	0	1.917	3.676	0	0
1.642	0	1.914	3.662	0	0

LUCA154

1.646	0	1.91	3.647	0	0
1.65	0	1.897	3.598	0	0
1.654	0	1.881	3.54	0	0
1.659	0	1.878	3.528	0	0
1.663	0	1.879	3.532	0	0
1.667	0	1.887	3.56	0	0
1.672	0	1.909	3.645	0	0
1.676	0	1.921	3.692	0	0
1.68	0	1.928	3.717	0	0
1.685	0	1.918	3.678	0	0
1.689	0	1.901	3.613	0	0
1.693	0	1.905	3.631	0	0
1.698	0	1.892	3.58	0	0
1.702	0	1.89	3.573	0	0
1.707	0	1.905	3.629	0	0
1.711	0	1.901	3.614	0	0
1.716	0	1.884	3.548	0	0
1.72	0	1.875	3.517	0	0
1.725	0	1.884	3.551	0	0
1.73	0	1.895	3.591	0	0
1.734	0	1.914	3.664	0	0
1.739	0	1.906	3.632	0	0
1.744	0	1.888	3.566	0	0
1.748	0	1.894	3.586	0	0
1.753	0	1.886	3.557	0	0
1.758	0	1.89	3.573	0	0
1.763	0	1.903	3.62	0	0
1.767	0	1.893	3.584	0	0
1.772	0	1.921	3.689	0	0
1.777	0	1.923	3.699	0	0
1.782	0	1.906	3.634	0	0
1.787	0	1.881	3.538	0	0
1.792	0	1.872	3.505	0	0
1.797	0	1.902	3.619	0	0
1.802	0	1.919	3.682	0	0
1.807	0	1.907	3.636	0	0
1.812	0	1.889	3.567	0	0
1.817	0	1.89	3.572	0	0
1.822	0	1.885	3.554	0	0
1.827	0	1.878	3.527	0	0
1.832	0	1.862	3.469	0	0
1.838	0	1.864	3.475	0	0
1.843	0	1.877	3.522	0	0
1.848	0	1.89	3.573	0	0
1.853	0	1.892	3.581	0	0
1.859	0	1.885	3.553	0	0
1.864	0	1.898	3.602	0	0
1.869	0	1.913	3.661	0	0
1.875	0	1.9	3.611	0	0
1.88	0	1.896	3.595	0	0
1.886	0	1.878	3.528	0	0

LUCA154

1.891	0	1.867	3.485	0	0
1.897	0	1.878	3.525	0	0
1.902	0	1.885	3.553	0	0
1.908	0	1.886	3.557	0	0
1.914	0	1.876	3.519	0	0
1.919	0	1.88	3.534	0	0
1.925	0	1.887	3.563	0	0
1.931	0	1.895	3.59	0	0
1.936	0	1.887	3.559	0	0
1.942	0	1.877	3.522	0	0
1.948	0	1.883	3.545	0	0
1.954	0	1.884	3.55	0	0
1.96	0	1.877	3.524	0	0
1.966	0	1.872	3.504	0	0
1.972	0	1.873	3.507	0	0
1.978	0	0	3.479	0	0
1.984	0	1.858	3.453	0	0
1.99	0	1.849	3.418	0	0
1.996	0	1.848	3.416	0	0
2.002	0	1.865	3.477	0	0
2.009	0	1.867	3.484	0	0
2.015	0	1.871	3.5	0	0
2.021	0	1.866	3.481	0	0
2.027	0	1.85	3.421	0	0
2.034	0	1.851	3.427	0	0
2.04	0	1.867	3.487	0	0
2.047	0	1.865	3.477	0	0
2.053	0	1.853	3.434	0	0
2.06	0	1.87	3.496	0	0
2.066	0	1.873	3.507	0	0
2.073	0	1.855	3.44	0	0
2.08	0	1.853	3.434	0	0
2.086	0	1.862	3.467	0	0
2.093	0	1.866	3.48	0	0
2.1	0	1.862	3.468	0	0
2.107	0	1.861	3.464	0	0
2.113	0	1.861	3.465	0	0
2.12	0	1.857	3.449	0	0
2.127	0	1.856	3.443	0	0
2.134	0	1.854	3.439	0	0
2.141	0	1.849	3.42	0	0
2.149	0	1.845	3.403	0	0
2.156	0	1.846	3.407	0	0
2.163	0	1.844	3.401	0	0
2.17	0	1.845	3.406	0	0
2.177	0	1.848	3.415	0	0
2.185	0	1.846	3.409	0	0
2.192	0	1.844	3.4	0	0
2.2	0	1.845	3.404	0	0
2.207	0	1.848	3.417	0	0
2.215	0	1.845	3.402	0	0

LUCA154

2.222	0	1.838	3.379	0	0
2.23	0	1.831	3.354	0	0
2.238	0	1.833	3.36	0	0
2.245	0	1.842	3.395	0	0
2.253	0	1.845	3.406	0	0
2.261	0	1.847	3.41	0	0
2.269	0	1.847	3.41	0	0
2.277	0	1.84	3.386	0	0
2.285	0	1.835	3.367	0	0
2.293	0	1.838	3.38	0	0
2.301	0	1.838	3.379	0	0
2.309	0	1.833	3.358	0	0
2.318	0	1.827	3.337	0	0
2.326	0	1.828	3.343	0	0
2.334	0	1.827	3.337	0	0
2.343	0	1.828	3.343	0	0
2.351	0	1.834	3.362	0	0
2.36	0	1.828	3.34	0	0
2.369	0	1.83	3.349	0	0
2.377	0	1.836	3.369	0	0
2.386	0	1.834	3.363	0	0
2.395	0	1.83	3.351	0	0
2.404	0	1.83	3.349	0	0
2.413	0	1.827	3.34	0	0
2.422	0	1.828	3.34	0	0
2.431	0	1.826	3.334	0	0
2.44	0	1.825	3.33	0	0
2.449	0	1.829	3.344	0	0
2.459	0	1.831	3.352	0	0
2.468	0	1.827	3.338	0	0
2.477	0	1.824	3.325	0	0
2.487	0	1.824	3.327	0	0
2.496	0	1.824	3.327	0	0
2.506	0	1.823	3.322	0	0
2.516	0	1.821	3.317	0	0
2.526	0	1.825	3.33	0	0
2.535	0	1.824	3.325	0	0
2.546	0	1.818	3.306	0	0
2.556	0	1.819	3.307	0	0
2.566	0	1.819	3.308	0	0
2.576	0	1.817	3.302	0	0
2.586	0	1.817	3.301	0	0
2.597	0	1.816	3.296	0	0
2.607	0	1.81	3.278	0	0
2.618	0	1.815	3.293	0	0
2.628	0	1.814	3.292	0	0
2.639	0	1.812	3.285	0	0
2.65	0	1.818	3.307	0	0
2.661	0	1.822	3.318	0	0
2.672	0	1.817	3.303	0	0
2.683	0	1.816	3.299	0	0

LUCA154

2.694	0	1.818	3.307	0	0
2.705	0	1.828	3.342	0	0
2.716	0	1.828	3.342	0	0
2.728	0	1.819	3.308	0	0
2.739	0	1.817	3.3	0	0
2.751	0	1.823	3.325	0	0
2.763	0	1.827	3.338	0	0
2.775	0	1.818	3.306	0	0
2.786	0	1.816	3.296	0	0
2.799	0	1.818	3.306	0	0
2.811	0	1.817	3.3	0	0
2.823	0	1.812	3.283	0	0
2.835	0	1.809	3.273	0	0
2.848	0	1.807	3.266	0	0
2.86	0	1.805	3.26	0	0
2.873	0	1.803	3.25	0	0
2.886	0	1.803	3.25	0	0
2.899	0	1.802	3.247	0	0
2.912	0	1.8	3.241	0	0
2.925	0	1.801	3.245	0	0
2.938	0	1.8	3.241	0	0
2.952	0	1.799	3.237	0	0
2.965	0	1.798	3.234	0	0
2.979	0	1.797	3.228	0	0
2.992	0	1.798	3.233	0	0
3.006	0	1.796	3.225	0	0
3.02	0	1.79	3.206	0	0
3.035	0	1.79	3.203	0	0
3.049	0	1.789	3.202	0	0
3.063	0	1.787	3.195	0	0
3.078	0	1.786	3.191	0	0
3.093	0	1.785	3.187	0	0
3.107	0	1.784	3.181	0	0
3.122	0	1.783	3.18	0	0
3.138	0	1.782	3.176	0	0
3.153	0	1.78	3.17	0	0
3.168	0	1.779	3.163	0	0
3.184	0	1.776	3.156	0	0
3.2	0	1.775	3.15	0	0
3.215	0	1.776	3.155	0	0
3.232	0	1.778	3.16	0	0
3.248	0	1.774	3.148	0	0
3.264	0	1.77	3.132	0	0
3.281	0	1.767	3.121	0	0
3.297	0	1.765	3.117	0	0
3.314	0	1.764	3.111	0	0
3.331	0	1.762	3.105	0	0
3.349	0	1.763	3.108	0	0
3.366	0	1.763	3.108	0	0
3.383	0	1.761	3.1	0	0
3.401	0	1.761	3.102	0	0

LUCA154

3.419	0	1.761	3.103	0	0
3.437	0	1.758	3.092	0	0
3.456	0	1.756	3.082	0	0
3.474	0	1.758	3.089	0	0
3.493	0	1.759	3.094	0	0
3.512	0	1.757	3.087	0	0
3.531	0	1.754	3.077	0	0
3.55	0	1.752	3.069	0	0
3.57	0	1.748	3.057	0	0
3.59	0	1.747	3.053	0	0
3.61	0	1.749	3.061	0	0
3.63	0	1.75	3.063	0	0
3.651	0	1.752	3.068	0	0
3.671	0	1.751	3.066	0	0
3.692	0	1.748	3.056	0	0
3.713	0	1.745	3.045	0	0
3.735	0	1.743	3.038	0	0
3.756	0	1.742	3.035	0	0
3.778	0	1.74	3.029	0	0
3.801	0	1.739	3.023	0	0
3.823	0	1.738	3.021	0	0
3.846	0	1.737	3.019	0	0
3.869	0	1.734	3.006	0	0
3.892	0	1.73	2.994	0	0
3.915	0	1.732	3.001	0	0
3.939	0	1.73	2.993	0	0
3.963	0	1.726	2.98	0	0
3.988	0	1.724	2.974	0	0
4.013	0	1.722	2.967	0	0
4.037	0	1.722	2.966	0	0
4.063	0	1.722	2.966	0	0
4.088	0	1.722	2.964	0	0
4.114	0	1.726	2.98	0	0
4.141	0	1.732	3	0	0
4.167	0	1.735	3.009	0	0
4.194	0	1.777	3.156	0	0
4.222	0	1.888	3.565	0	0
4.25	0	1.91	3.648	0	0
4.278	0	1.933	3.736	0	0
4.306	0	1.875	3.516	0	0
4.335	0	1.815	3.295	0	0
4.364	0	1.791	3.209	0	0
4.394	0	1.783	3.177	0	0
4.424	0	1.767	3.121	0	0
4.454	0	1.748	3.057	0	0
4.485	0	1.732	3.001	0	0
4.516	0	1.717	2.949	0	0
4.548	0	1.703	2.899	0	0
4.58	0	1.689	2.853	0	0
4.613	0	1.679	2.82	0	0
4.646	0	1.674	2.802	0	0

LUCA154

4.679	0	1.669	2.786	0	0
4.713	0	1.664	2.769	0	0
4.748	0	1.661	2.758	0	0
4.783	0	1.658	2.749	0	0
4.819	0	1.653	2.734	0	0
4.855	0	1.649	2.72	0	0
4.891	0	1.646	2.71	0	0
4.929	0	1.645	2.705	0	0
4.966	0	1.644	2.702	0	0
5.005	0	1.638	2.684	0	0
5.044	0	1.637	2.678	0	0
5.084	0	1.635	2.673	0	0
5.124	0	1.631	2.659	0	0
5.165	0	1.627	2.648	0	0
5.206	0	1.625	2.641	0	0
5.248	0	1.621	2.626	0	0
5.291	0	1.614	2.605	0	0
5.335	0	1.614	2.606	0	0
5.379	0	1.615	2.607	0	0
5.424	0	1.61	2.591	0	0
5.47	0	1.604	2.571	0	0
5.517	0	1.603	2.569	0	0.000001
5.564	0	1.599	2.558	0	0.000001
5.612	0	1.593	2.537	0	0.000001
5.661	0	1.591	2.533	0	0.000001
5.711	0	1.587	2.519	0	0.000001
5.762	0	1.575	2.48	0	0.000001
5.814	0	1.569	2.463	0	0.000001
5.866	0	1.574	2.477	0	0.000001
5.92	0	1.581	2.499	0	0.000001
5.975	0	1.573	2.475	0	0.000001
6.03	0.000001	1.559	2.43	0	0.000001
6.087	0.000001	1.547	2.395	0	0.000001
6.145	0.000001	1.535	2.357	0	0.000001
6.204	0.000001	1.526	2.328	0	0.000002
6.264	0.000001	1.519	2.306	0	0.000002
6.325	0.000001	1.502	2.257	0	0.000002
6.387	0.000001	1.491	2.224	0	0.000002
6.451	0.000001	1.49	2.22	0	0.000002
6.516	0.000001	1.481	2.194	0	0.000003
6.582	0.000002	1.486	2.208	0	0.000003
6.65	0.000002	1.474	2.173	0.00001	0.000003
6.719	0.000002	1.462	2.136	0.00001	0.000004
6.789	0.000002	1.465	2.146	0.00001	0.000004
6.861	0.000002	1.456	2.121	0.00001	0.000004
6.935	0.000003	1.443	2.082	0.00001	0.000005
7.01	0.000003	1.437	2.064	0.00001	0.000005
7.087	0.000003	1.436	2.062	0.00001	0.000006
7.165	0.000004	1.424	2.027	0.00001	0.000007
7.245	0.000004	1.406	1.977	0.00001	0.000007
7.327	0.000004	1.404	1.971	0.00001	0.000007

LUCA154

7.86	0.000005	1.349	1.82	0.00001	0.000008
7.957	0.000005	1.345	1.81	0.00001	0.000007
8.478	0.000005	1.278	1.634	0.00001	0.000007

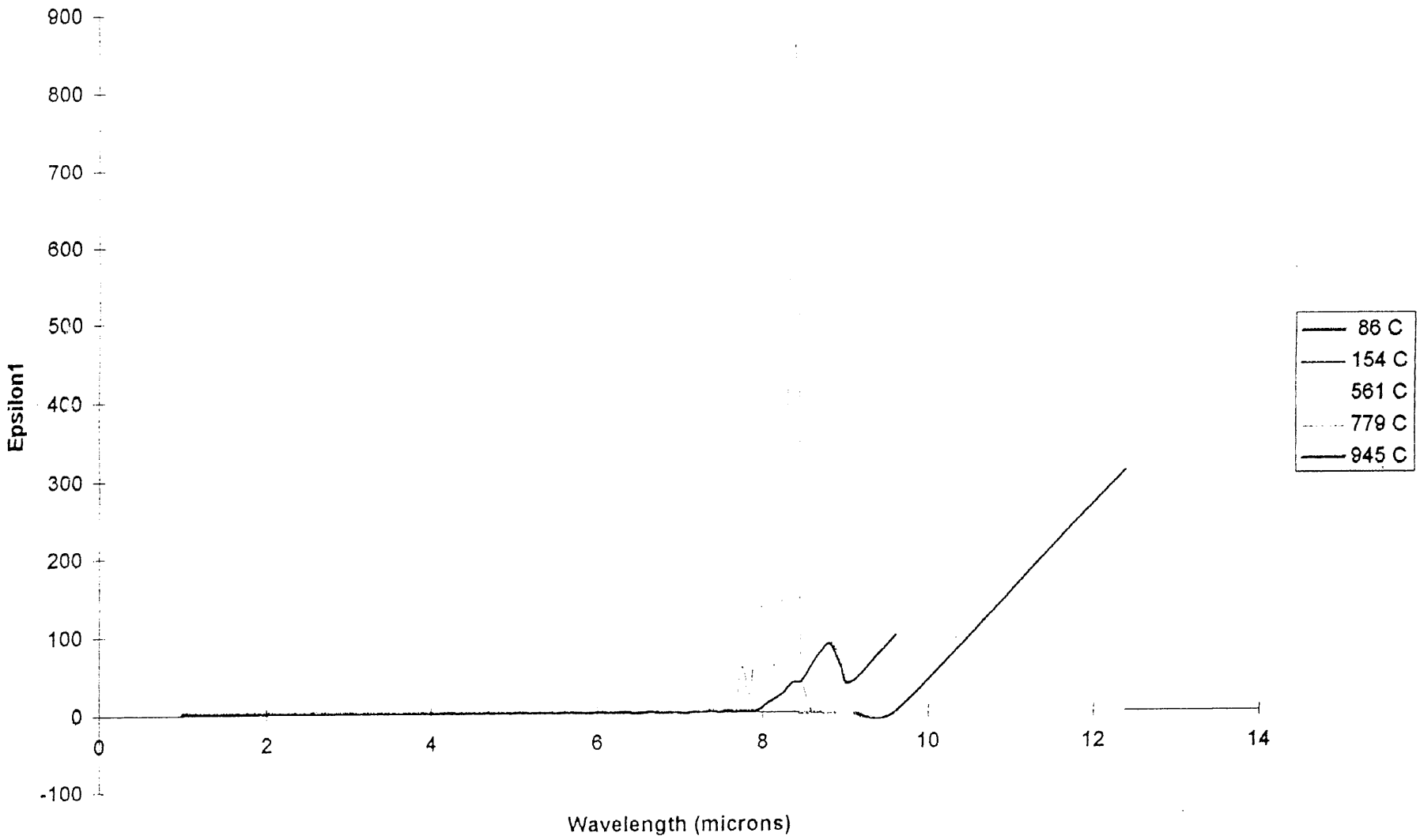


Fig. A2.2 Plot of wavelength (microns) v/s epsilon1 at different temperatures

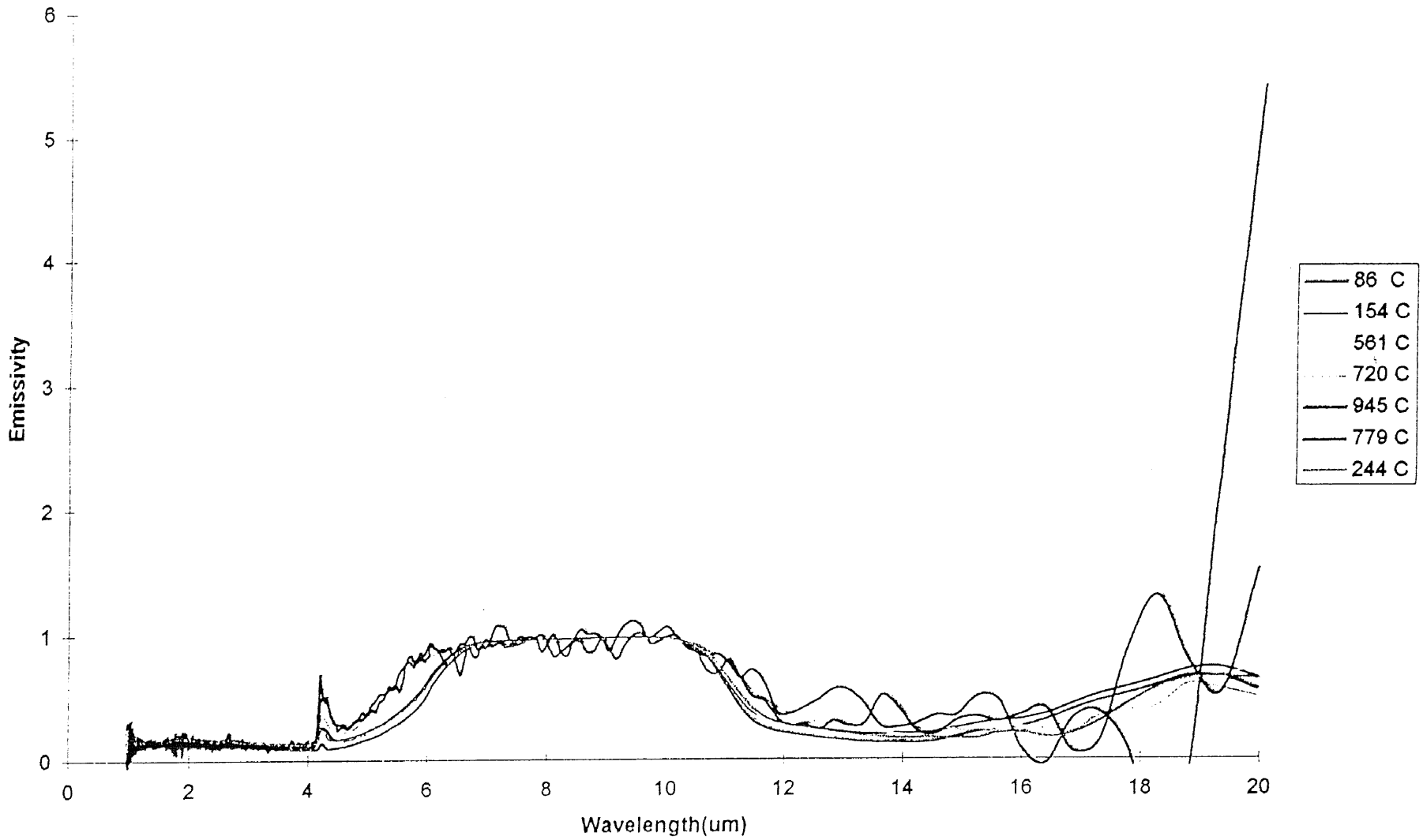


Fig. A2.1 Plot of wavelength (microns) v/s refractive index, n at different temperatures

APPENDIX A2 : ERBIUM OXIDE OPTICAL CONSTANTS AT 66°C

Lambda	EXTCOEF	REFINDEX	Epsilon1	Epsilon2	Alpha
1	0	1.424	2.027	0	0
1.003	0	1.246	1.554	0	0
1.005	0	1.297	1.682	0	0
1.006	0	1.154	1.333	0	0
1.011	0	1.296	1.68	0	0
1.013	0	1.607	2.582	0	0
1.014	0	1.831	3.354	0	0
1.016	0	1.745	3.044	0	0
1.017	0	1.666	2.776	0	0
1.019	0	1.535	2.356	0	0
1.021	0	1.42	2.016	0	0
1.022	0	1.592	2.533	0	0
1.024	0	1.559	2.432	0	0
1.026	0	1.261	1.59	0	0
1.027	0	1.181	1.394	0	0
1.029	0	1.329	1.766	0	0
1.03	0	1.449	2.1	0	0
1.032	0	1.321	1.746	0	0
1.035	0	1.126	1.268	0	0
1.037	0	1.335	1.782	0	0
1.039	0	1.416	2.004	0	0
1.04	0	1.362	1.855	0	0
1.042	0	1.41	1.989	0	0
1.044	0	1.403	1.969	0	0
1.045	0	1.352	1.828	0	0
1.047	0	1.429	2.043	0	0
1.049	0	1.295	1.678	0	0
1.05	0	1.316	1.733	0	0
1.052	0	1.496	2.237	0	0
1.054	0	1.514	2.294	0	0
1.056	0	1.556	2.421	0	0
1.057	0	1.597	2.551	0	0
1.059	0	1.529	2.338	0	0
1.061	0	1.487	2.21	0	0
1.063	0	1.435	2.06	0	0
1.064	0	1.379	1.902	0	0
1.066	0	1.417	2.008	0	0
1.068	0	1.404	1.97	0	0
1.07	0	1.409	1.984	0	0
1.071	0	1.462	2.136	0	0
1.073	0	1.471	2.163	0	0
1.075	0	1.463	2.14	0	0
1.077	0	1.446	2.092	0	0
1.078	0	1.462	2.138	0	0
1.08	0	1.469	2.159	0	0
1.082	0	1.406	1.976	0	0
1.084	0	1.422	2.021	0	0
1.086	0	1.435	2.058	0	0
1.088	0	1.461	2.133	0	0

ERBI66

Wavelength	Ext Coeff	Ref index	Epsilon 1	Epsilon2	Alpha
1.01	0	3.625	13.138	0	0.000001
1.014	0	4.27	18.236	0	0.000002
1.016	0	4.799	23.028	0	0.000001
1.017	0	5.365	28.784	0	0.000001
1.022	0	3.888	15.114	0	0.000001
1.024	0	4.162	17.324	0	0.000002
1.026	0	4.581	20.983	0	0.000001
1.032	0	5.036	25.356	0	0.000001
1.034	0	5.266	27.727	0	0.000001
1.037	0	5.775	33.351	0	0.000002
1.039	0	6.912	47.772	0	0.000001
1.04	0	7.637	58.323	0	0
1.042	0	7.503	56.288	0	0.000001
1.044	0	7.339	53.865	0	0.000001
1.045	0	7.796	60.783	0	0.000001
1.047	0	7.25	52.557	0	0.000001
1.049	0	6.605	43.625	0	0.000002
1.05	0	6.698	44.866	0	0.000001
1.052	0	7.487	56.049	0	0.000001
1.054	0	8.122	65.974	0	0
1.056	0	7.817	61.102	0	0
1.057	0	7.806	60.93	0	0.000001
1.059	0	7.867	61.889	0	0.000001
1.061	0	8.15	66.42	0	0.000002
1.064	0	7.579	57.436	0	0.000001
1.066	0	8.044	64.704	0	0.000001
1.068	0	8.285	68.637	0	0.000001
1.07	0	8.285	68.64	0	0.000001
1.071	0	8.684	75.415	0	0.000001
1.073	0	8.245	67.976	0	0.000001
1.075	0	7.45	55.506	0	0.000001
1.077	0	6.998	48.969	0	0
1.078	0	7.514	56.454	0	0.000001
1.08	0	8.338	69.525	0	0.000001
1.082	0	8.284	68.632	0	0
1.084	0	8.054	64.872	0	0
1.086	0	7.489	56.088	0	0.000001
1.088	0	7.261	52.721	0	0.000001
1.089	0	7.04	49.568	0	0.000001
1.091	0	7.14	50.978	0	0.000001
1.093	0	7.326	53.671	0	0.000001
1.095	0	7.733	59.802	0	0
1.097	0	8.027	64.43	0	0
1.099	0	8.126	66.027	0	0.000001
1.1	0	7.893	62.302	0	0.000001
1.102	0	7.84	61.462	0	0.000001
1.104	0	7.419	55.049	0	0.000001
1.106	0	7.217	52.082	0	0.000001
1.108	0	7.646	58.459	0	0.000001
1.11	0	7.632	58.249	0	0.000001

ERBI66

1.112	0	7.554	57.064	0	0.000001
1.114	0	7.212	52.012	0	0.000001
1.116	0	7.362	54.198	0	0.000001
1.118	0	8.094	65.515	0	0.000001
1.12	0	7.988	63.8	0	0.000001
1.121	0	7.727	59.71	0	0.000001
1.123	0	7.719	59.586	0	0.000001
1.125	0	7.734	59.811	0	0.000001
1.127	0	7.707	59.393	0	0.000001
1.129	0	7.415	54.976	0	0.000001
1.131	0	7.561	57.166	0	0.000001
1.133	0	7.367	54.266	0	0.000001
1.135	0	7.239	52.398	0	0.000001
1.137	0	7.417	55.016	0	0.000001
1.139	0	7.358	54.147	0	0.000001
1.141	0	7.673	58.871	0	0.000001
1.143	0	7.738	59.877	0	0.000001
1.145	0	7.603	57.811	0	0.000001
1.147	0	7.729	59.734	0	0.000001
1.149	0	7.701	59.31	0	0.000001
1.151	0	7.458	55.621	0	0.000001
1.153	0	7.604	57.826	0	0.000001
1.155	0	7.659	58.664	0	0.000001
1.158	0	7.774	60.433	0	0.000001
1.16	0	7.723	59.65	0	0.000001
1.162	0	7.585	57.528	0	0.000001
1.164	0	7.61	57.914	0	0.000001
1.166	0	7.362	54.193	0	0.000001
1.168	0	7.378	54.442	0	0.000001
1.17	0	7.528	56.664	0	0.000001
1.172	0	7.649	58.509	0	0.000001
1.174	0	7.752	60.093	0	0.000001
1.176	0	7.531	56.722	0	0.000001
1.179	0	7.279	52.979	0	0.000001
1.181	0	7.335	53.807	0	0.000001
1.183	0	7.408	54.884	0	0.000001
1.185	0	7.489	56.086	0	0.000001
1.187	0	7.489	56.079	0	0.000001
1.189	0	7.409	54.901	0	0.000001
1.192	0	7.343	53.925	0	0.000001
1.194	0	7.255	52.637	0	0.000001
1.196	0	7.211	51.995	0	0.000001
1.198	0	7.147	51.078	0	0.000001
1.2	0	7.183	51.598	0	0.000001
1.203	0	7.245	52.494	0	0.000001
1.205	0	7.25	52.56	0	0.000001
1.207	0	7.364	54.228	0	0.000001
1.209	0	7.417	55.008	0	0.000001
1.212	0	7.321	53.596	0	0.000001
1.214	0	7.346	53.957	0	0.000001
1.216	0	7.377	54.421	0	0.000001

ERBI66

1.219	0	7.42	55.053	0	0.000001
1.221	0	7.343	53.922	0	0.000001
1.223	0	7.49	56.094	0	0.000001
1.225	0	7.553	57.044	0	0.000001
1.228	0	7.45	55.504	0	0.000001
1.23	0	7.492	56.134	0	0.000001
1.232	0	7.451	55.513	0	0.000001
1.235	0	7.43	55.201	0	0.000001
1.237	0	7.509	56.392	0	0.000001
1.24	0	7.359	54.158	0	0.000001
1.242	0	7.395	54.687	0	0.000001
1.244	0	7.722	59.625	0	0.000001
1.247	0	7.733	59.806	0	0.000001
1.249	0	7.664	58.735	0	0.000001
1.252	0	7.503	56.297	0	0.000001
1.254	0	7.44	55.347	0	0.000001
1.256	0	7.349	54.006	0	0.000001
1.259	0	7.315	53.514	0	0.000001
1.261	0	7.387	54.567	0	0.000001
1.264	0	7.422	55.087	0	0.000001
1.266	0	7.55	57.004	0	0.000001
1.269	0	7.591	57.627	0	0.000001
1.271	0	7.493	56.143	0	0.000001
1.274	0	7.454	55.562	0	0.000001
1.276	0	7.354	54.075	0	0.000001
1.279	0	7.343	53.915	0	0.000001
1.281	0	7.406	54.846	0	0.000001
1.284	0	7.35	54.025	0	0.000001
1.286	0	7.299	53.273	0	0.000001
1.289	0	7.388	54.585	0	0.000001
1.291	0	7.261	52.722	0	0.000001
1.294	0	7.183	51.601	0	0.000001
1.297	0	7.284	53.063	0	0.000001
1.299	0	7.23	52.275	0	0.000001
1.302	0	7.151	51.131	0	0.000001
1.304	0	7.107	50.504	0	0.000001
1.307	0	7.096	50.352	0	0.000001
1.31	0	6.963	48.478	0	0.000001
1.312	0	6.884	47.394	0	0.000001
1.315	0	6.915	47.818	0	0.000001
1.318	0	6.844	46.84	0	0.000001
1.32	0	6.793	46.151	0	0.000001
1.323	0	6.758	45.671	0	0.000001
1.326	0	6.737	45.381	0	0.000001
1.329	0	6.64	44.096	0	0.000001
1.331	0	6.512	42.401	0	0.000001
1.334	0	6.41	41.09	0	0.000001
1.337	0	6.248	39.032	0	0.000001
1.34	0	6.045	36.539	0	0.000001
1.342	0	5.845	34.162	0	0.000001
1.345	0	5.77	33.295	0	0.000001

ERBI66

1.348	0	5.745	33.001	0	0.000001
1.351	0	5.676	32.222	0	0.000001
1.354	0	5.594	31.289	0	0.000001
1.356	0	5.491	30.149	0	0.000001
1.359	0	5.398	29.143	0	0.000002
1.362	0	5.255	27.613	0	0.000002
1.365	0	5.147	26.49	0	0.000002
1.368	0	5.068	25.687	0	0.000002
1.371	0	4.89	23.908	0	0.000002
1.374	0	4.732	22.39	0	0.000002
1.377	0	4.625	21.386	0	0.000002
1.38	0	4.532	20.538	0	0.000002
1.382	0	4.401	19.371	0	0.000002
1.385	0	4.234	17.928	0	0.000002
1.388	0	4.084	16.675	0	0.000002
1.391	0	4.009	16.07	0	0.000002
1.394	0	3.977	15.819	0	0.000002
1.397	0	3.958	15.669	0	0.000002
1.4	0	3.974	15.796	0	0.000002
1.403	0	3.945	15.561	0	0.000002
1.406	0	3.893	15.155	0	0.000002
1.41	0	3.887	15.111	0	0.000002
1.413	0	3.904	15.243	0	0.000002
1.416	0	3.919	15.361	0	0.000002
1.419	0	3.884	15.088	0	0.000002
1.422	0	3.797	14.415	0	0.000002
1.425	0	3.661	13.405	0	0.000002
1.428	0	3.525	12.423	0	0.000002
1.431	0	3.405	11.592	0	0.000002
1.435	0	3.285	10.794	0	0.000003
1.438	0	3.15	9.92	0	0.000002
1.441	0	2.999	8.996	0	0.000002
1.444	0	2.824	7.975	0	0.000002
1.447	0	2.634	6.938	0	0.000003
1.451	0	2.409	5.805	0	0.000003
1.454	0	2.24	5.017	0	0.000002
1.457	0	2.165	4.687	0	0.000003
1.46	0	2.106	4.437	0	0.000003
1.464	0	2.122	4.503	0	0.000003
1.467	0	2.099	4.404	0	0.000003
1.47	0	2.046	4.185	0	0.000002
1.474	0	2.045	4.184	0	0.000002
1.477	0	2.074	4.301	0	0.000003
1.48	0	2.204	4.859	0	0.000003
1.484	0	2.338	5.465	0	0.000002
1.487	0	2.349	5.52	0	0.000002
1.491	0	2.256	5.091	0	0.000002
1.494	0	2.207	4.87	0	0.000003
1.498	0	2.222	4.939	0	0.000003
1.501	0	2.215	4.908	0	0.000003
1.505	0	2.249	5.057	0	0.000002

ERBI66

1.508	0	2.238	5.009	0	0.000003
1.512	0	2.152	4.632	0	0.000003
1.515	0	2.138	4.572	0	0.000003
1.519	0	2.166	4.691	0	0.000003
1.522	0	2.062	4.25	0	0.000003
1.526	0	1.931	3.727	0	0.000003
1.529	0	1.881	3.537	0	0.000003
1.533	0	1.857	3.45	0	0.000003
1.537	0	1.929	3.722	0	0.000003
1.54	0	1.98	3.919	0	0.000003
1.544	0	1.966	3.866	0	0.000003
1.548	0	1.986	3.946	0	0.000003
1.551	0	1.988	3.951	0	0.000003
1.555	0	2.084	4.344	0	0.000003
1.559	0	2.26	5.108	0	0.000003
1.563	0	2.314	5.354	0	0.000003
1.566	0	2.301	5.296	0	0.000002
1.57	0	2.268	5.144	0	0.000002
1.574	0	2.254	5.08	0	0.000002
1.578	0	2.361	5.573	0	0.000002
1.582	0	2.631	6.923	0	0.000002
1.586	0	2.907	8.449	0	0.000002
1.589	0	3.042	9.252	0	0.000002
1.593	0	3.145	9.891	0	0.000003
1.597	0	3.234	10.459	0	0.000002
1.601	0	3.434	11.795	0	0.000002
1.605	0	3.739	13.98	0	0.000002
1.609	0	3.946	15.568	0	0.000002
1.613	0	4.07	16.561	0	0.000003
1.621	0	4.142	17.154	0	0.000002
1.625	0	4.105	16.847	0	0.000002
1.629	0	4.037	16.296	0	0.000002
1.634	0	3.824	14.62	0	0.000002
1.638	0	3.612	13.045	0	0.000002
1.642	0	3.685	13.576	0	0.000002
1.646	0	3.901	15.221	0	0.000002
1.654	0	4.046	16.374	0	0.000002
1.659	0	4.118	16.959	0	0.000002
1.663	0	4.299	18.482	0	0.000002
1.667	0	4.804	23.074	0	0.000002
1.672	0	5.403	29.195	0	0.000001
1.676	0	5.928	35.147	0	0.000001
1.68	0	6.375	40.642	0	0.000001
1.685	0	6.76	45.699	0	0.000001
1.689	0	7.025	49.358	0	0.000001
1.693	0	7.244	52.481	0	0.000001
1.698	0	7.396	54.7	0	0.000001
1.702	0	7.625	58.144	0	0.000001
1.707	0	7.812	61.02	0	0
1.711	0	7.881	62.103	0	0
1.716	0	8.078	65.248	0	0

ERBI66

1.72	0	8.175	66.835	0	0
1.725	0	8.186	67.012	0	0
1.73	0	8.269	68.372	0	0
1.734	0	8.261	68.239	0	0
1.739	0	8.191	67.096	0	0
1.744	0	8.205	67.323	0	0
1.748	0	8.147	66.376	0	0
1.753	0	8.203	67.29	0	0
1.758	0	8.359	69.879	0	0
1.763	0	8.534	72.821	0	0
1.767	0	8.695	75.596	0	0
1.772	0	8.754	76.628	0	0
1.777	0	8.866	78.606	0	0
1.782	0	9.04	81.725	0	0
1.787	0	9.104	82.884	0	0
1.792	0	8.934	79.807	0	0
1.797	0	8.801	77.463	0	0
1.802	0	9.061	82.108	0	0
1.807	0	9.25	85.557	0	0
1.812	0	9.311	86.704	0	0
1.817	0	9.505	90.347	0	0
1.822	0	9.518	90.592	0	0
1.827	0	9.625	92.638	0	0
1.832	0	9.981	99.611	0	0
1.838	0	10.118	102.377	0	0
1.843	0	10.012	100.25	0	0
1.848	0	10.018	100.369	0	0
1.853	0	9.947	98.938	0	0
1.859	0	9.914	98.294	0	0
1.864	0	10.462	109.446	0	0
1.869	0	10.838	117.453	0	0
1.875	0	10.235	104.762	0	0
1.88	0	9.839	96.812	0	0
1.886	0	9.983	99.651	0	0
1.891	0	9.985	99.692	0	0
1.897	0	10.189	103.814	0	0
1.902	0	10.48	109.828	0	0
1.908	0	10.487	109.978	0	0
1.914	0	10.214	104.325	0	0
1.919	0	9.818	96.387	0	0
1.925	0	9.569	91.56	0	0
1.931	0	9.193	84.513	0	0
1.936	0	9.275	86.018	0	0
1.942	0	9.465	89.589	0	0
1.948	0	9.452	89.331	0	0
1.954	0	9.525	90.718	0	0
1.96	0	9.581	91.801	0	0
1.966	0	9.473	89.729	0	0
1.972	0	9.413	88.6	0	0
1.978	0	9.365	87.696	0	0
1.984	0	9.318	86.83	0	0

ERBI66

1.99	0	9.365	87.706	0	0
1.996	0	9.382	88.027	0	0
2.002	0	9.306	86.604	0	0
2.009	0	9.225	85.103	0	0
2.015	0	9.247	85.513	0	0
2.021	0	9.259	85.738	0	0
2.027	0	9.266	85.856	0	0
2.034	0	9.431	88.935	0	0
2.04	0	9.488	90.03	0	0
2.047	0	9.387	88.112	0	0
2.053	0	9.507	90.38	0	0
2.06	0	9.714	94.358	0	0
2.066	0	9.706	94.211	0	0
2.073	0	9.645	93.035	0	0
2.08	0	9.547	91.155	0	0
2.086	0	9.402	88.402	0	0
2.093	0	9.477	89.813	0	0
2.1	0	9.503	90.306	0	0
2.107	0	9.567	91.536	0	0
2.113	0	9.648	93.081	0	0
2.12	0	9.674	93.588	0	0
2.127	0	9.614	92.423	0	0
2.134	0	9.553	91.256	0	0
2.141	0	9.56	91.39	0	0
2.149	0	9.504	90.319	0	0
2.156	0	9.524	90.705	0	0
2.163	0	9.501	90.268	0	0
2.17	0	9.491	90.087	0	0
2.177	0	9.588	91.937	0	0
2.185	0	9.599	92.138	0	0
2.192	0	9.599	92.132	0	0
2.2	0	9.594	92.044	0	0
2.207	0	9.606	92.282	0	0
2.215	0	9.596	92.079	0	0
2.222	0	9.567	91.532	0	0
2.23	0	9.489	90.043	0	0
2.238	0	9.422	88.781	0	0
2.245	0	9.407	88.489	0	0
2.253	0	9.441	89.14	0	0
2.261	0	9.515	90.533	0	0
2.269	0	9.498	90.213	0	0
2.277	0	9.494	90.133	0	0
2.285	0	9.535	90.917	0	0
2.293	0	9.526	90.736	0	0
2.301	0	9.52	90.637	0	0
2.309	0	9.569	91.573	0	0
2.318	0	9.51	90.446	0	0
2.326	0	9.456	89.424	0	0
2.334	0	9.461	89.514	0	0
2.343	0	9.454	89.37	0	0
2.351	0	9.443	89.166	0	0

ERBI66

2.36	0	9.533	90.873	0	0
2.369	0	9.555	91.293	0	0
2.377	0	9.48	89.864	0	0
2.386	0	9.437	89.058	0	0
2.395	0	9.46	89.498	0	0
2.404	0	9.512	90.474	0	0
2.413	0	9.49	90.067	0	0
2.422	0	9.495	90.148	0	0
2.431	0	9.528	90.79	0	0
2.44	0	9.568	91.552	0	0
2.449	0	9.575	91.69	0	0
2.459	0	9.6	92.152	0	0
2.468	0	9.613	92.405	0	0
2.477	0	9.567	91.536	0	0
2.487	0	9.499	90.225	0	0
2.496	0	9.623	92.606	0	0
2.506	0	9.847	96.969	0	0
2.516	0	9.974	99.485	0	0
2.526	0	10.222	104.496	0	0
2.535	0	10.516	110.58	0	0
2.546	0	10.696	114.396	0	0
2.556	0	11.166	124.682	0	0
2.566	0	11.772	138.571	0	0
2.576	0	12.45	154.991	0	0
2.586	0	13.047	170.223	0	0
2.597	0	13.127	172.313	0	0
2.607	0	12.91	166.656	0	0
2.618	0	12.182	148.391	0	0
2.628	0	11.35	128.821	0	0
2.639	0	11.081	122.794	0	0
2.65	0	11.972	143.324	0	0
2.661	0	14.277	203.839	0	0
2.672	0	14.308	204.716	0	0
2.683	0	12.603	158.846	0	0
2.694	0	11.692	136.706	0	0
2.705	0	11.781	138.781	0	0
2.716	0	11.747	137.998	0	0
2.728	0	11.546	133.308	0	0
2.739	0	11.636	135.392	0	0
2.751	0	11.878	141.088	0	0
2.763	0	11.813	139.541	0	0
2.775	0	11.126	123.796	0	0
2.786	0	10.685	114.171	0	0
2.799	0	10.409	108.348	0	0
2.811	0	10.067	101.342	0	0
2.823	0	9.841	96.852	0	0
2.835	0	9.707	94.23	0	0
2.848	0	9.55	91.194	0	0
2.86	0	9.31	86.669	0	0
2.873	0	9.11	82.997	0	0
2.886	0	9.023	81.41	0	0

ERBI66

2.899	0	8.997	80.952	0	0
2.912	0	8.938	79.89	0	0
2.925	0	8.886	78.964	0	0
2.938	0	8.854	78.398	0	0
2.952	0	8.788	77.228	0	0
2.965	0	8.768	76.871	0	0
2.979	0	8.713	75.91	0	0
2.992	0	8.719	76.028	0	0
3.006	0	8.686	75.441	0	0
3.02	0	8.629	74.458	0	0
3.035	0	8.674	75.234	0	0
3.049	0	8.667	75.125	0	0
3.063	0	8.64	74.647	0	0
3.078	0	8.646	74.746	0	0
3.093	0	8.661	75.014	0	0
3.107	0	8.61	74.137	0	0
3.122	0	8.568	73.409	0	0
3.138	0	8.589	73.771	0	0
3.153	0	8.603	74.012	0	0
3.168	0	8.624	74.369	0	0
3.184	0	8.702	75.725	0	0
3.2	0	8.793	77.321	0	0
3.215	0	8.796	77.375	0	0
3.232	0	8.789	77.241	0	0
3.248	0	8.804	77.512	0	0
3.264	0	8.777	77.033	0	0
3.281	0	8.78	77.087	0	0
3.297	0	8.825	77.88	0	0
3.314	0	8.832	77.995	0	0
3.331	0	8.801	77.462	0	0
3.349	0	8.797	77.381	0	0
3.366	0	8.806	77.542	0	0
3.383	0	8.805	77.524	0	0
3.401	0	8.807	77.568	0	0
3.419	0	8.782	77.129	0	0
3.437	0	8.746	76.486	0	0
3.456	0	8.739	76.367	0	0
3.474	0	8.758	76.701	0	0
3.493	0	8.785	77.184	0	0
3.512	0	8.778	77.047	0	0
3.531	0	8.776	77.02	0	0
3.55	0	8.786	77.188	0	0
3.57	0	8.8	77.432	0	0
3.59	0	8.846	78.255	0	0
3.61	0	8.853	78.378	0	0
3.63	0	8.822	77.835	0	0
3.651	0	8.82	77.787	0	0
3.671	0	8.789	77.249	0	0
3.692	0	8.775	77.006	0	0
3.713	0	8.791	77.283	0	0
3.735	0	8.779	77.072	0	0

ERBI66

3.756	0	8.791	77.281	0	0
3.778	0	8.808	77.587	0	0
3.801	0	8.816	77.715	0	0
3.823	0	8.762	76.778	0	0
3.846	0	8.738	76.354	0	0
3.869	0	8.775	76.993	0	0
3.892	0	8.754	76.633	0	0
3.915	0	8.737	76.337	0	0
3.939	0	8.743	76.445	0	0
3.963	0	8.739	76.363	0	0
3.988	0	8.739	76.369	0	0
4.013	0	8.732	76.249	0	0
4.037	0	8.711	75.889	0	0
4.063	0	8.691	75.542	0	0
4.088	0	8.678	75.308	0	0
4.114	0	8.67	75.173	0	0
4.141	0	8.654	74.893	0	0
4.167	0	8.711	75.89	0	0
4.194	0	8.982	80.669	0	0
4.222	0	9.455	89.396	0	0
4.25	0	9.394	88.244	0	0
4.278	0	9.316	86.79	0	0
4.306	0	9.078	82.405	0	0
4.335	0	8.761	76.761	0	0
4.364	0	8.574	73.517	0	0
4.394	0	8.495	72.166	0	0
4.424	0	8.466	71.677	0	0
4.454	0	8.453	71.458	0	0
4.485	0	8.411	70.741	0	0
4.516	0	8.353	69.769	0	0
4.548	0	8.311	69.08	0	0
4.58	0	8.282	68.588	0	0
4.613	0	8.255	68.145	0	0
4.646	0	8.239	67.884	0	0
4.679	0	8.212	67.431	0	0
4.713	0	8.167	66.707	0	0
4.748	0	8.129	66.081	0	0
4.783	0	8.074	65.187	0	0
4.819	0	8.014	64.224	0	0
4.855	0	7.938	63.011	0	0
4.891	0	7.859	61.765	0	0
4.929	0	7.77	60.378	0	0
4.966	0	7.65	58.515	0	0
5.005	0	7.536	56.79	0	0
5.044	0	7.386	54.556	0	0
5.084	0	7.265	52.775	0	0
5.124	0	7.157	51.22	0	0
5.165	0	7.024	49.334	0	0
5.206	0	6.897	47.567	0	0
5.248	0	6.714	45.077	0	0.000001
5.291	0	6.594	43.479	0	0.000001

ERBI66

5.335	0	6.508	42.36	0	0.000001
5.379	0	6.449	41.587	0	0.000001
5.424	0	6.471	41.874	0	0.000001
5.47	0	6.401	40.968	0	0.000001
5.517	0	6.501	42.26	0	0.000001
5.564	0	6.742	45.448	0	0.000001
5.612	0	6.822	46.54	0	0.000001
5.661	0	7.098	50.388	0	0
5.711	0	7.465	55.726	0	0
5.762	0	7.419	55.044	0	0
5.814	0	7.672	58.861	0	0
5.866	0	8.074	65.191	0	0
5.92	0	7.758	60.184	0	0
5.975	0	7.415	54.976	0	0
6.03	0	7.249	52.542	0	0
6.087	0	6.962	48.472	0	0
6.145	0	6.609	43.68	0	0
6.204	0	6.182	38.214	0	0.000001
6.264	0	5.959	35.51	0	0.000001
6.325	0	6.088	37.069	0	0.000001
6.387	0	6.35	40.328	0	0.000001
6.451	0	6.41	41.09	0	0.000001
6.516	0	6.349	40.304	0	0.000001
6.582	0	6.013	36.153	0	0.000001
6.65	0	5.392	29.076	0.00001	0.000001
6.719	0.000001	5.015	25.15	0.00001	0.000001
6.789	0.000001	4.837	23.4	0.00001	0.000001
6.861	0.000001	4.545	20.653	0.00001	0.000001
6.935	0.000001	4.333	18.775	0.00001	0.000001
7.01	0.000001	4.138	17.12	0.00001	0.000001
7.087	0.000001	3.942	15.542	0.00001	0.000001
7.165	0.000001	3.762	14.156	0.00001	0.000002
7.245	0.000001	3.581	12.827	0.00001	0.000002
7.327	0.000001	3.423	11.714	0.00001	0.000002
7.411	0.000001	3.296	10.864	0.00001	0.000002
7.497	0.000001	3.179	10.105	0.00001	0.000002
7.584	0.000001	3.052	9.312	0.00001	0.000002
7.675	0.000001	2.926	8.56	0.00001	0.000002
7.766	0.000001	2.815	7.926	0.00001	0.000002
7.86	0.000002	2.707	7.327	0.00001	0.000002
7.957	0.000002	2.611	6.819	0.00001	0.000003
8.056	0.000002	2.513	6.316	0.00001	0.000003
8.158	0.000002	2.409	5.801	0.00001	0.000003
8.262	0.000002	2.311	5.343	0.00001	0.000003
8.369	0.000002	2.226	4.957	0.00001	0.000003
8.478	0.000002	2.144	4.595	0.00001	0.000003
8.591	0.000003	2.062	4.251	0.00001	0.000004
8.706	0.000002	1.994	3.978	0.00001	0.000003
8.825	0.000002	1.943	3.774	0.00001	0.000003
8.947	0.000002	1.891	3.577	0.00001	0.000003
9.072	0.000002	1.84	3.385	0.00001	0.000003

ERBI66

9.201	0.000002	1.796	3.226	0.00001	0.000003
9.471	0.000003	1.727	2.982	0.00001	0.000003
9.611	0.000002	1.708	2.919	0.00001	0.000003
9.756	0.000002	1.676	2.809	0.00001	0.000003
9.905	0.000002	1.649	2.718	0.00001	0.000003
10.058	0.000003	1.637	2.678	0.00001	0.000004
10.217	0.000003	1.633	2.667	0.00001	0.000004
10.381	0.000003	1.615	2.608	0.00001	0.000003
10.55	0.000003	1.603	2.569	0.00001	0.000003
10.725	0.000003	1.599	2.556	0.00001	0.000003
10.905	0.000003	1.584	2.508	0.00001	0.000003
11.092	0.000003	1.561	2.438	0.00001	0.000003
11.285	0.000003	1.534	2.353	0.00001	0.000003
11.486	0.000003	1.508	2.275	0.00001	0.000003
11.693	0.000003	1.493	2.229	0.00001	0.000003
11.908	0.000003	1.468	2.154	0.00001	0.000003
12.131	0.000003	1.442	2.078	0.00001	0.000003
12.363	0.000003	1.417	2.007	0.00001	0.000003
12.604	0.000003	1.377	1.895	0.00001	0.000003
12.854	0.000003	1.343	1.805	0.00001	0.000003
13.385	0.000003	1.276	1.628	0.00001	0.000002
13.668	0.000003	1.245	1.551	0.00001	0.000003
13.962	0.000003	1.223	1.496	0.00001	0.000003
14.27	0.000003	1.213	1.47	0.00001	0.000003
14.592	0.000004	1.243	1.544	0.00001	0.000003
14.928	0.000002	1.268	1.607	0	0.000001
15.65	0.000004	1.489	2.217	0.00001	0.000003
16.037	0.000003	1.936	3.748	0.00001	0.000002
16.445	0.000003	2.798	7.829	0.00002	0.000002
16.873	0.000004	3.558	12.661	0.00003	0.000003
17.324	0.000004	3.434	11.789	0.00002	0.000003
17.801	0.000004	2.546	6.481	0.00002	0.000003
18.304	0.000003	2.168	4.701	0.00001	0.000002
18.837	0.000003	2.98	8.88	0.00002	0.000002
19.401	0.000003	4.019	16.156	0.00002	0.000002
20	0.000004	4.275	18.274	0.00003	0.000002

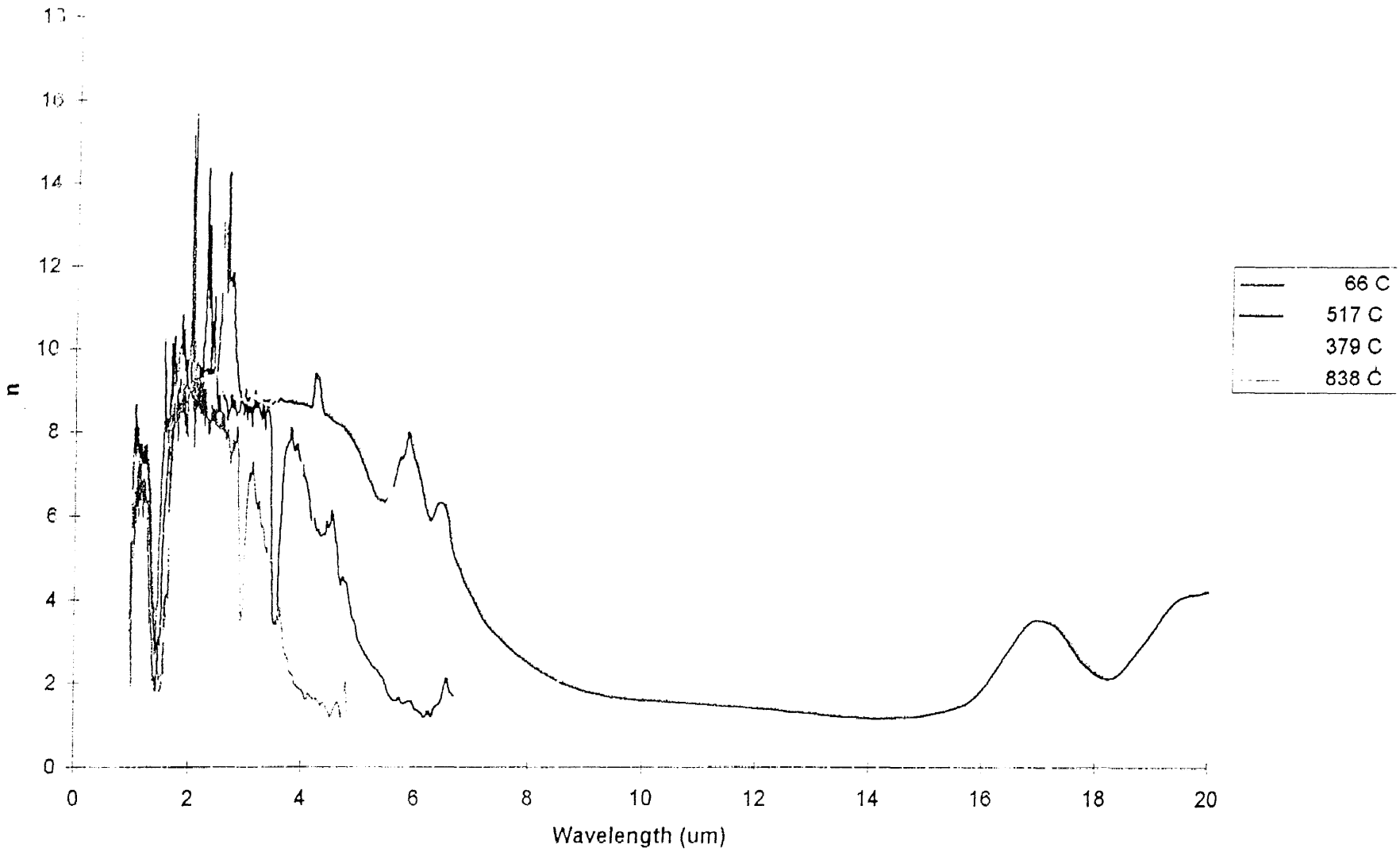


Fig. A1.1 Plot of wavelength (microns) v/s refractive index, n at different temperatures

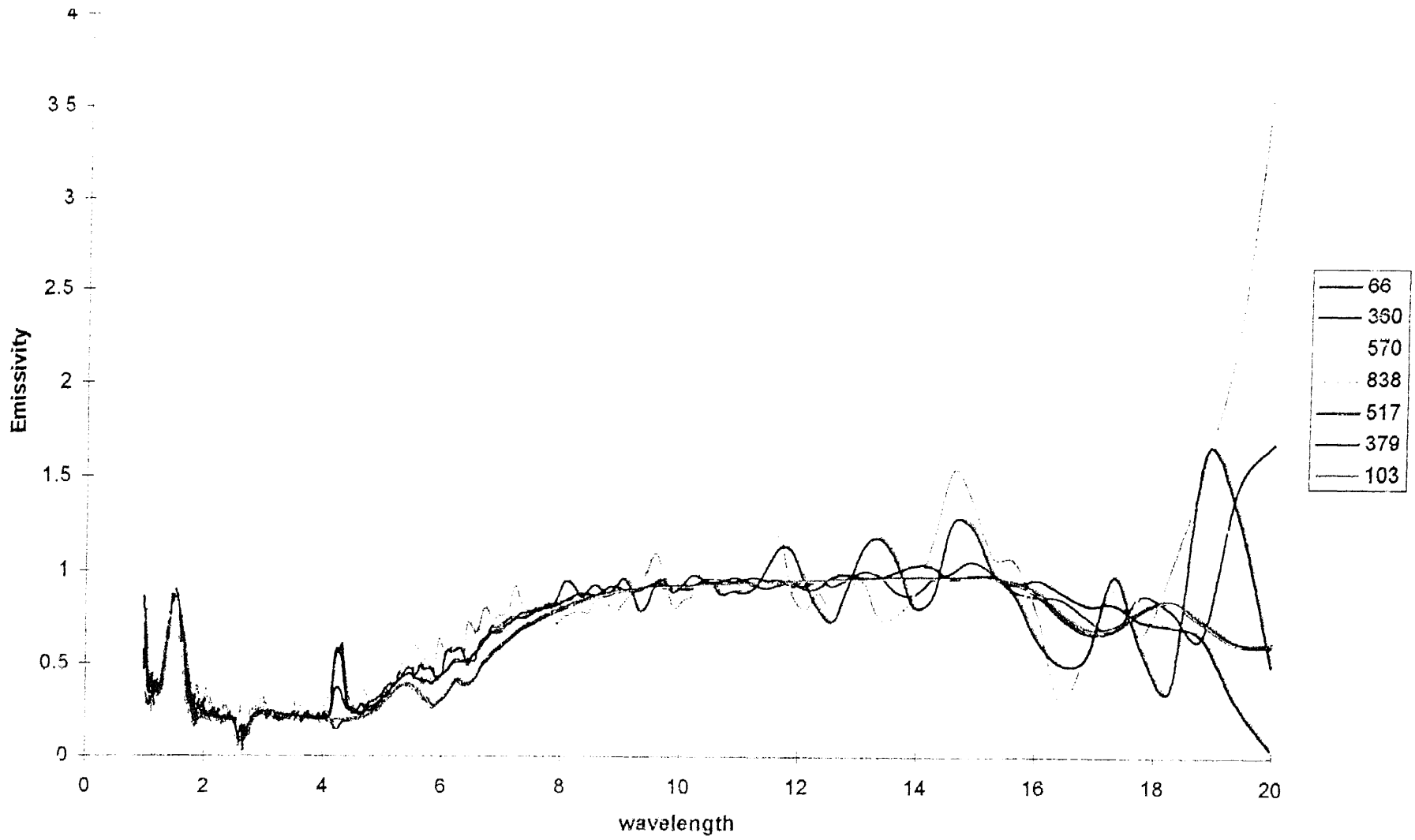


Fig. A1. 3 Plot of wavelength (microns) v/s emissivity at different temperatures

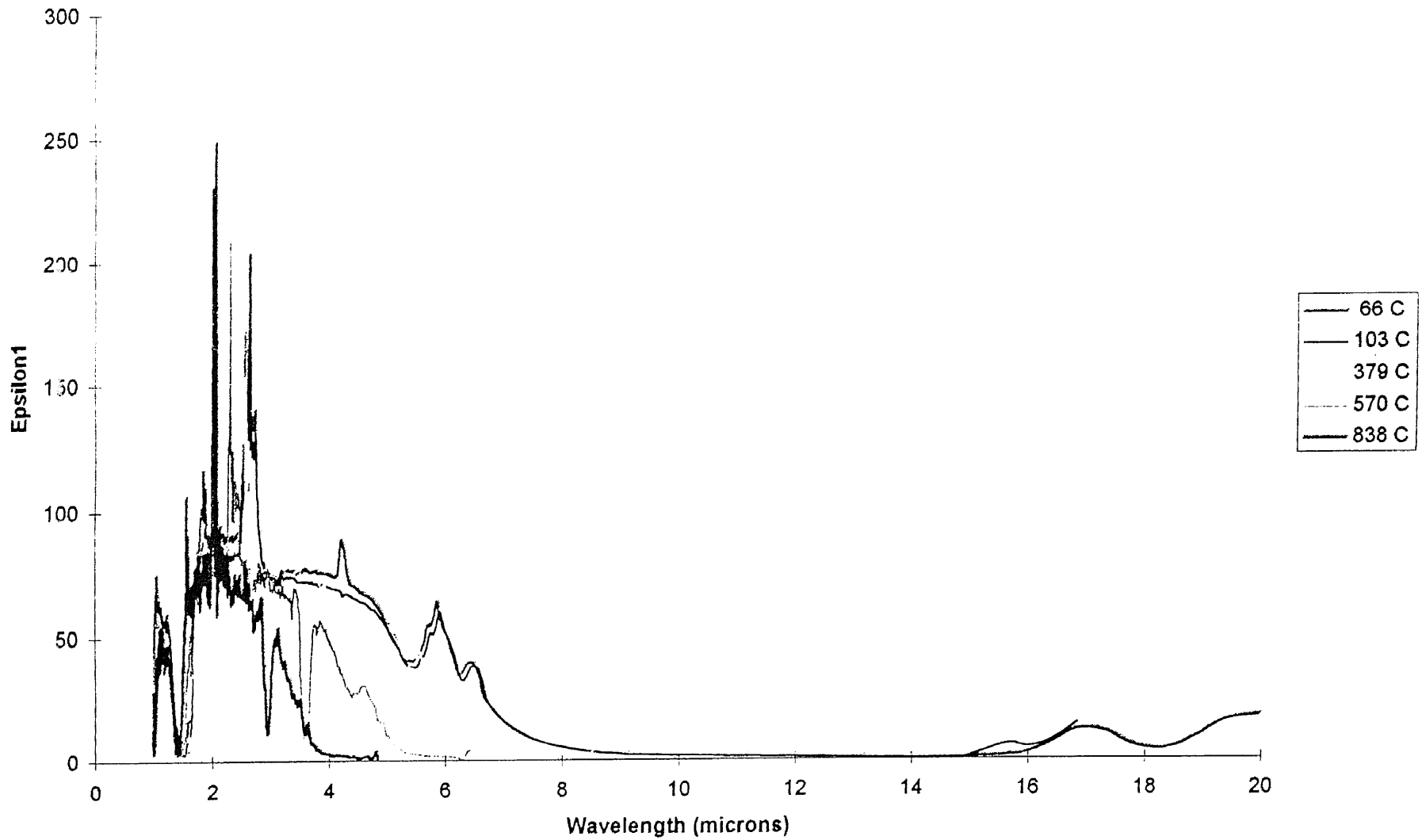


Fig. A1.2 Plot of wavelength (microns) v/s epsilon1 at different temperatures

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