

Solid State Lasers for Use in Non-Contact Temperature Measurements

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Introduction

The last decade has seen a series of dramatic developments in solid state laser technology. Prominent among these has been the emergence of high power semiconductor laser diode arrays and a deepening understanding of the dynamics of solid state lasers. Taken in tandem these two developments enable the design of laser diode pumped solid state lasers [1]. It is possible now to design solid state lasers to meet quite specific and precise criteria such as output wavelength, linewidth, beam quality, stability and tunability. Pumping solid state lasers with semiconductor diodes relieves the need for cumbersome and inefficient flashlamps and results in an efficient and stable laser with the compactness and reliability we have come to associate with solid state technology. It provides a laser source that can be reliably used in space. In this paper I shall describe how to incorporate these new coherent sources into the non-contact measurement of temperature.

The primary focus of the LaRC Solid State Laser Materials Research group is the development and characterization of new optical materials for use in active remote sensors of the atmosphere. In the course of this effort we have studied several new materials and new concepts which can be used for other sensor applications. We are interested in seeing this technology put to use for other NASA missions. We share this interest in the development of new electro-optic sensors with our colleagues at the Center for Fiber and Electro-optics at the Virginia Polytechnic Institute and have been working together in this effort. Our general approach to the problem of new non-contact temperature measurements has had two components. The first component centers on passive sensors using optical fibers; VPI has designed and tested an optical fiber temperature sensor for the drop tube at the Marshall Space Flight Center. Work on this problem has given us some insight into the use of optical fibers, especially new IR fibers, in thermal metrology. This work will be described separately by the VPI group. The second component of our effort is to utilize the experience gained in the study of passive sensors to examine new active sensor concepts. By active sensor we mean a sensing device or mechanism which is interrogated in some way by radiation, usually from a laser.

In the next section I will summarize the status of solid state lasers as sources for active non-contact temperature sensors. Then I will describe some specific electro-optic techniques applicable to the sensor problems at hand. Work on some of these ideas is in progress while other concepts are still being worked out.

Status of Solid State Laser Technology

We survey two separate laser technologies here- semiconductor laser diodes and solid state lasers. Diode lasers provide high brightness light sources which are reliable and compact. Diode lasers and diode laser arrays have been fabricated mainly from GaAlAs; the Al composition determines the bandgap and hence emission wavelength. These wavelengths can range from 700 to 900 nm with most production diodes having emission around 800 nm. The emission wavelength can be further tuned by controlling the diode temperature. The diodes can be operated in cw mode, in a short pulse mode (by, for example, Q-switching) or in a quasi-cw mode (long pulses and low repetition rates). Table 1 shows the operating characteristics of several different diode lasers and diode laser arrays as reported in a recent review article [2]. The highest power reported there is 800W in a 13 bar array operating at 35% efficiency. Efficiency of diode laser arrays is expected to reach about 50%.

Table 1.

Operating Characteristics of Semiconductor Diode Lasers and Laser Arrays

Device	Operating Mode	Peak Output Power	Efficiency
SQW-SCH 10 stripe	cw	0.75 W	50 %
SQW-SCH (high brightness laser)	cw q-cw	3.8 W 8.0 W	----- 40 %
laser bar (1 cm)	cw q-cw	12 W 100 W	40 % 30 %
3 bar array	q-cw	300 W	40 %
13 bar array	q-cw	800 W	35 %

Notation: SQW- Single Quantum Well;
SCH- Separate Confinement Heterostructure; q-cw- quasi-continuous wave (150 μ s pulse with 100 Hz repetition).

Compiled from reference [2].

Solid state lasers operate on the optical properties of individual ions doped into host material. The dopant ions may be either transition metals (Cr, Ti, Ni, ...) or lanthanide rare earths (Nd, Er, Tm, Ho, ...). Dopant transition metal ions couple strongly to their host lattice and as a result electronic transitions may be vibrationally broadened. This results in broad emission and absorption in the visible and near IR. The rare earths ions couple more weakly to the lattice and so have narrower absorption and emission and it occurs further into the IR (1 to 3 μm).

A large number of ions in various hosts have already been made to lase; we report here only the results of diode pumped lasers in Table 2.

Table 2.

Diode Pumped Rare Earth Laser Transitions to Date

Ion	Transition	Wavelength (μm)	Temperature (K)
Nd ³⁺	$4F_{3/2} - 4I_{11/2}$	1.06	300
	$4F_{3/2} - 4I_{13/2}$	1.32	300
	$4F_{3/2} - 4I_{9/2}$	0.95	300
U ³⁺	$4I_{11/2} - 4I_{9/2}$	2.61	4.2
Dy ³⁺	$5I_7 - 5I_8$	2.36	1.9
Yb ³⁺	$2F_{7/2} - 2F_{5/2}$	1.03	77
Ho ³⁺	$5I_7 - 5I_8$	2.10	300
Er ³⁺	$4I_{11/2} - 4I_{13/2}$	2.8	300
	$4I_{13/2} - 4I_{9/2}$	1.6	300
Tm ³⁺	$3F_4 - 3H_5$	2.3	300

from Reference [1].

A diode pumped Nd:YVO4 laser has demonstrated an overall efficiency of 12.5% and cw power output of 750 mW [3]. Extrapolating from this result we can anticipate that improvements in diode operation can lead to overall (electrical to optical) efficiencies exceeding 20%.

Despite the fact that laser emission in the mid-IR region occurs in well separated and narrow bands we can still expect diversity in wavelength by shifting the wavelength in non-linear crystals. Harmonic generation can translate the emission to shorter wavelengths while optical parametric oscillation will allow tunable operation from 1 to 10 μm . The cw single mode emission from a diode pumped Nd-YAG oscillator has had its emission at 1.06 μm doubled to 532 nm with 56% efficiency. This second harmonic generation was in a LiNbO3: MgO crystal external to the laser. The maximum efficiency of second harmonic generation in this system may be as high as 80% [4]. A diode laser pumped Nd:YAG oscillator, injection seeded and q-switched has been used to pump a β -Barium Borate crystal with a tuning range from 0.41 to 2.15 μm [1]. Figure 1. displays the tunable emission region for some of these ions and hosts.

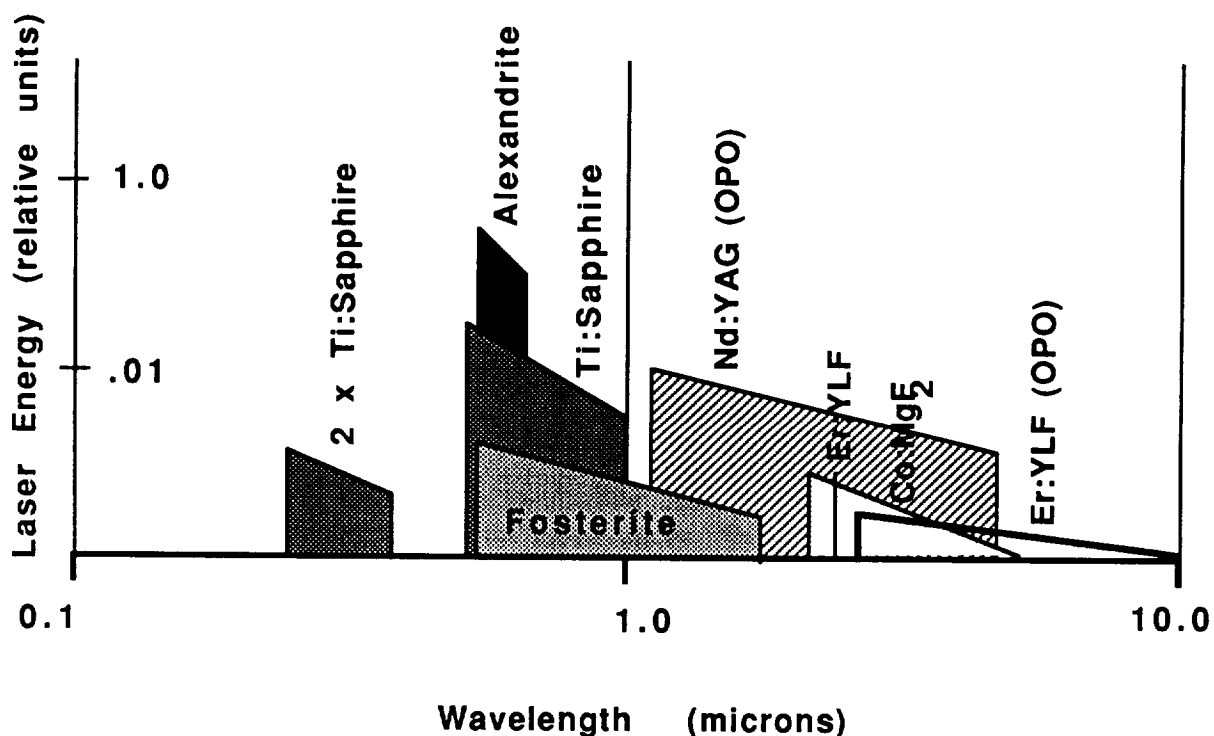


Figure 1. This figure represents the tuning ranges of some solid state laser systems. Most of the recently discovered tunable solid state lasers are represented. In order not to clutter the diagram only one example of second harmonic generation (2 x Ti:Sapphire) and two examples of wavelength shifting by optical parametric oscillation (OPO) are depicted.

This has been a short survey of recent work in diode pumped solid state lasers. It is intended to demonstrate that technology exists to design 'all solid state lasers' with high quality emission from the visible out to 10 μ m. Such lasers provide compact, efficient and reliable sources for active sensing.

Active Sensor Concepts

In this section we describe some ideas about possible non-contact temperature measurements which utilize laser sources. Research has been initiated in some of these techniques while some of the ideas have yet to be tried. An important part of these measurement schemes is their use of optical fibers to transmit and gather the optical signals. Advantages of optical fiber technology will be described more fully in the talk by Professors Claus and May of VPI.

A. Doped Crystal Fibers

Ions doped directly into crystalline or glass fibers can act as sensing elements. This idea has several realizations and I will describe one which was developed from our lab. A few years ago a new technique for the containerless growth of crystals was developed at the Center for Materials Research at Stanford University- the laser heated pedestal to growth of a crystal fiber [5]. We had developed several spectroscopic techniques using these fibers to streamline our optical characterization of new laser materials [6] when it occurred to us that that these techniques could be turned into sensors.

The optical properties of dopant ions are due to the local crystal field seen by the ion. Changes in the environment which alter this crystal field are detectable as changes in the optical properties of the ion. This provides a sensing of the environment on a microscopic scale. To illustrate the possibilities offered by this circumstance I will describe a series of experiments carried out on a Sapphire fiber. In the growth of sapphire (Al_2O_3) unintentional contamination of the crystal with Cr^{3+} ions cannot be avoided so that any sapphire fiber grown has a low concentration of Cr (this concentration was less than 10^{-16} cm^{-3} in the fibers studied). It is these Cr ions that act as sensors. The optical emission from Cr^{3+} ions in Sapphire occurs in two strong and narrow lines in the red (~694.3 nm), the so called R-lines. Temperature shifts in both the lifetime and intensity of this emission have been observed [7] in Sapphire fibers. Tensile stress induces a blue shift in the wavelength of the R-lines [7]. Raman spectra of each active vibrational mode of the Sapphire crystal have been observed and their temperature dependence determined. The Raman spectra are shown in Figure 2. The crystal fiber geometry provides an excellent experimental arrangement for Raman measurements since the exciting light is entrained in the fiber while the Raman shifted light is coupled out of the fiber. These results, which

are for one ion and one host crystal, may not be optimal for specific instrument needs. By varying the dopant ions, their concentration and the host it should be possible to achieve a wide range of temperature sensitivities.

The geometry of a crystal fiber favors certain experiments that would be more difficult with bulk samples. There are two basic modes of excitation and detection as shown in Figure 3. Injection of exciting radiation may be either transverse as described in Ref. [6] or longitudinal as in Ref. [7,8].

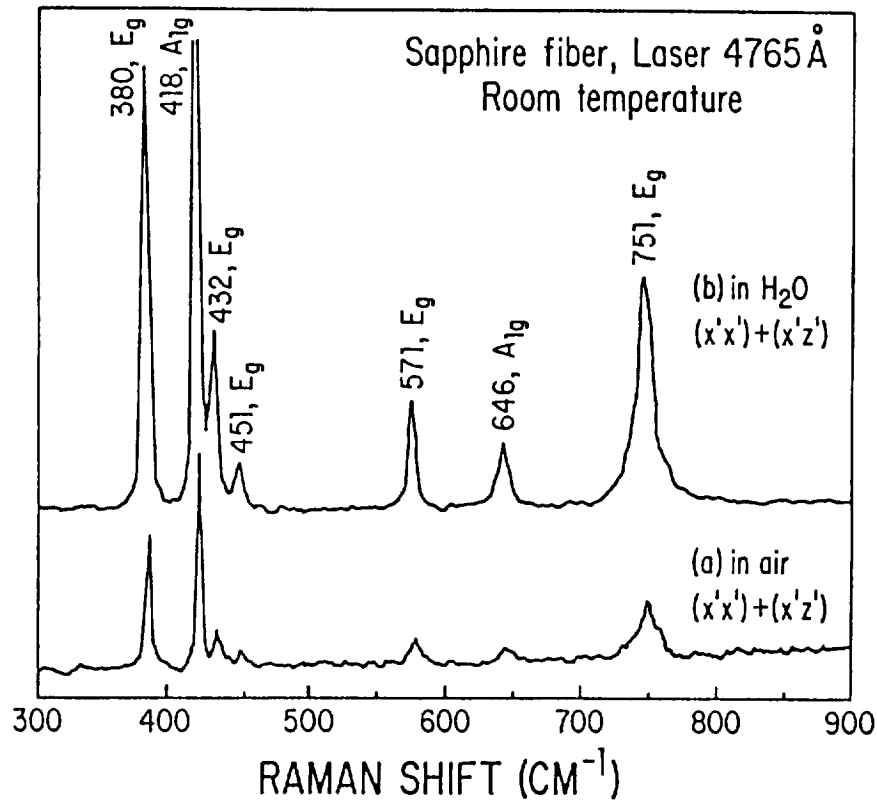


Figure 2. Raman spectra of a single crystal fiber of sapphire at room temperature observed in air and in water. The index matching fluid allows isotropically emitted light to escape the fiber while the excitation laser light, injected longitudinally, remains entrained.

A final remark about this technology. There is a rich variety to the optical properties of ions in solids; all are available for incorporation into optical sensing systems. Optical devices can provide logical operations as well as sensing elements. Furthermore, some of these devices can be optically altered. It has been demonstrated that erasable changes in the refractive index of some glasses doped with Eu can be written with laser light of one frequency and read by light of another frequency [9]. It may be possible to write holographic gratings into optical fibers and to use these gratings as filters for active multiplexing of sensor

signals. This idea is currently under investigation.

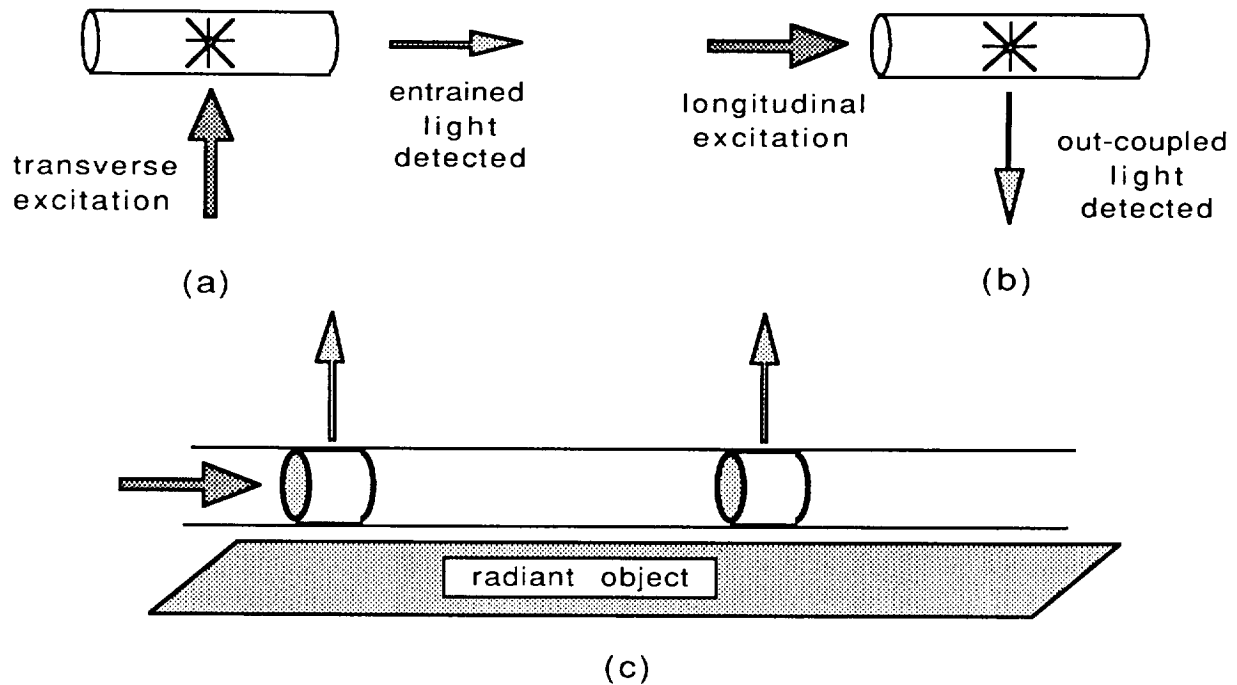


Figure 3. This figure depicts the basic excitation and detection modes for an active element of a fiber system: (a) transverse excitation with entrained light detected; (b) longitudinal excitation with detection of out-coupled light; (c) any combination of excitation and detection modes can be incorporated into a distributed sensor system.

B. Modulated Reflection Spectroscopy

This notion is an extension of a technique developed to study excitation near the band edges of semiconductor materials [10]. It depends upon the alteration of the energy band structure of a solid in the presence of intense laser light. I will describe specific work on semiconductors but the basic procedure could, in principle, be extended to dielectrics and metals. The experimental set up is described in Figure 4. It utilizes two laser beams. A pump beam at a fixed wavelength above the band gap is modulated. Its excitation of the sample surface is probed by a tunable laser through the band gap energy. Measurement of the differential reflectivity ($\Delta R/R$) of the probe beam gives an analogue signal related to the third derivative of the complex index of refraction. The complex refractive index carries information of the absorption coefficient which changes rapidly near the band edge. By fitting the measured lineshape to a simple model of the absorption coefficient the band gap energy can be determined. Thus the derivative signal isolates the band edge which, in turn, depends upon the sample temperature.

Modulated Reflection Spectroscopy

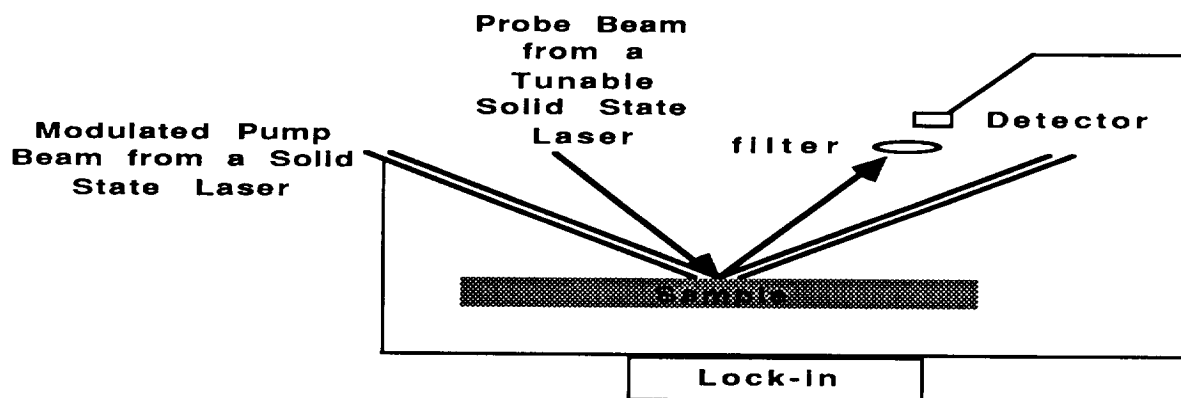


Figure 4. A modulated pump beam alters the band edge near the surface of the sample. This alteration is interrogated by the reflected light from a tunable probe beam. The differential reflectivity ($\Delta R/R$) is related to the third derivative of the complex refractive index.

Using this technique (with a broadband probe beam instead of a tunable laser) non-contact temperature measurements of GaAs up to 610 C have been made with an accuracy of ± 10 C [11]. Using a laser probe should improve the accuracy of this measurement.

This technique has several advantages. First, by measuring a derivative quantity it is insensitive to background behavior and is sensitive to the feature measured, the energy gap location. It measures a quantity which is not dependent on the emissivity. Furthermore, since it is an ac measurement other information such as the phase shift of the reflected light is available.

C. Thermal-Quantum Detectors

This idea for this measurement arose from an analysis of the thermodynamic efficiency of radiation detectors. Radiation detectors can be divided into two broad categories: thermal devices, which convert the energy of each photon absorbed to internal heat and quantum devices which count individual photons having energy above a threshold. This distinction in operation has a significant effect on the thermodynamic efficiency of each type of device when it is used to measure blackbody radiation [12].

Not all of the radiant energy emitted from a blackbody source at a constant temperature T_S and subsequently absorbed by a quantum detector at constant temperature T_R can be converted into a detectable signal (usable work in the thermodynamic sense). Some of the radiant energy absorbed by the receiver is converted to heat, some is reradiated and the remainder is converted to usable energy. The basic limitation on the amount of energy converted to usable work is a consequence of the second law of thermodynamics and it involves the flux of free energy [12]. An upper bound on

the efficiency of this conversion assuming that all of the available free energy is converted to usable energy was derived by Landsberg and Malinson [13]. This bound is given by a polynomial function of the ratio of the temperatures $x = T_R/T_S$ as

$$\eta_{\max} = 1 - \frac{4}{3} x + \frac{1}{3} x^4$$

However, in quantum devices not all of the free energy available in the radiation field can be converted into usable work because of the basic limitation of the detecting device itself. Figure 5. shows the maximum efficiency for the conversion of energy from a blackbody source by a device having a threshold energy $E_0 = h\nu$ and maintained at a temperature T_R .

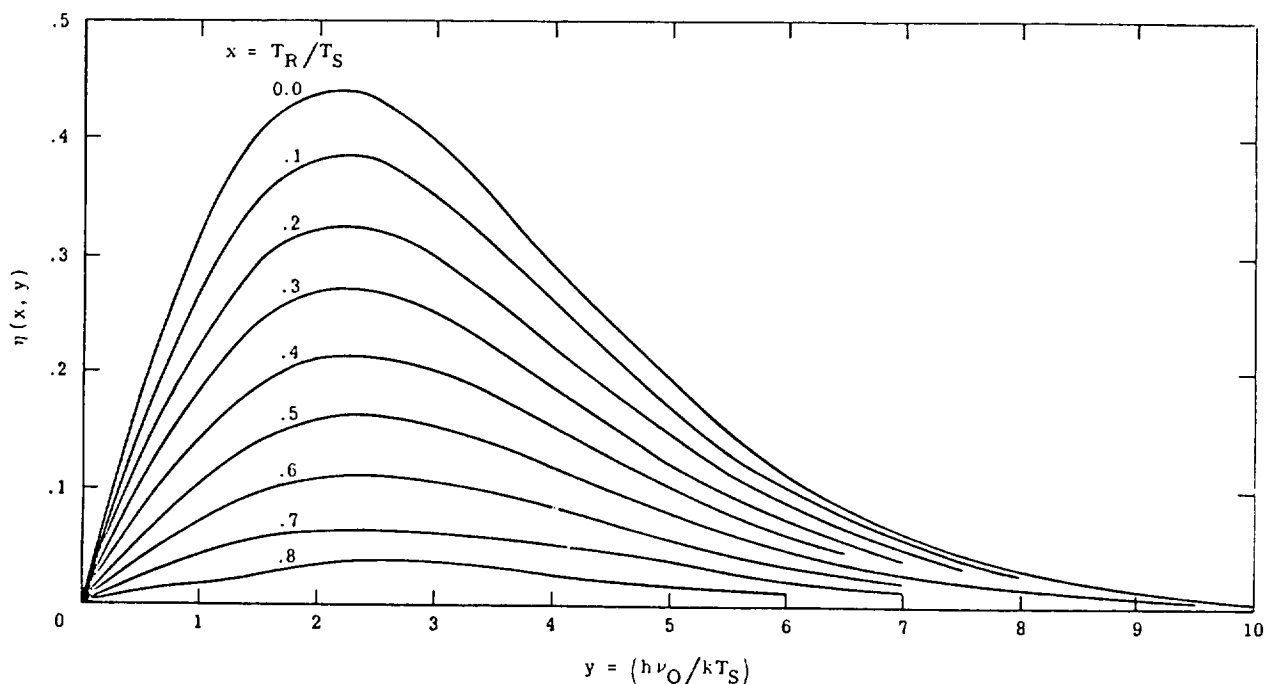


Figure 5. Maximum efficiency for the conversion of energy from a blackbody source at temperature T_S by a device having an energy threshold E_0 and maintained at a temperature T_R , η_{\max} , expressed in terms of the dimensionless parameters $x = T_R/T_S$ and $y = E_0/kT_S$.

In summary then, a thermal device converts the net radiant energy flux incident upon it into heat which is measured as the bolometer signal while a quantum device can detect only the net radiant free energy flux. The difference between these two fluxes depends on the source temperature. This suggests that by comparing the signals from a thermal detector adjacent to a quantum detector one can determine the temperature of the source.

Conclusions

Solid state laser technology is rapidly developing to the point where individual tunable solid state lasers can be designed to meet specific needs. This flexibility in the sources of coherent radiation provides an opportunity for thermal metrology. These developments parallel developments in electro-optics and optical fiber technology. Together they enable new measurement strategies to be designed. In this paper we have described the characteristics of the current generation of diode pumped solid state lasers and suggested how they may be utilized to enable new non-contact temperature measurements.

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