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DESIGN OF A LASER PYROMETER FOR THE MEASUREMENT OF UNSTEADY TEMPERATURE DISTRIBUTION DURING LASER WELDING

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Ekanath F. Nikhade

August 1989

Dedicated to my Wife

Mrinalini E. Nikhade

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ABSTRACT

Pyrometers using a single element detector, 3×1 linear array and 3×3 area array were designed for the purpose of measuring temperatures of a spot in a pulsed laser weld-pool. The design is predicated on sampling at rates sufficient to track weld-pool temperature changes introduced by a 5 kHz pulsed laser system. The pyrometer design permits electro-optical interfacing with the Center for Laser Applications' (CLA) Rofin-Sinar-3000 high power CO_2 laser.

For every temperature measurement the pyrometer measures the reflectivity of the target (weld-pool) using a 25 millimeter (mm) aperture optics and a liquid nitrogen cooled Indium Arsenide (InAs) detector. Emissivity is determined from measured reflectivity. A 1.535 μm low power cw laser source is incorporated in the system for this purpose. The detector is highly sensitive and linear over the entire temperature range. It has a passband from 1 to 3.1 μm and converts the optical signal to electrical, which is then amplified and recorded as 12 bit data on the CLA's Masscomp computer.

The pyrometer will scan a strip whose width (100 μm) is decided by the Instantaneous Field Of View (IFOV) of the detector and whose length is governed by the weldment traverse speed and the laser duty cycle. It can measure sample temperatures from 300 °C to 2500 °C with an accuracy of one degree °C.

A calibration black-body and a reference gold coated surface are to be used for calibration of the pyrometer. The emissivity of the target weld-pool is calculated using the reflection calibration. The black-body calibration is the basis for calculation of an overall system constant from which the true temperature of the target is calculated.

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LIST OF SYMBOLS

k:	Kilo (10^3)
Hz:	Hertz
CLA:	Center For Laser Applications
cm:	Centimeter
mm:	Millimeter
μm:	Micrometer
ms:	Millisecond
μs:	Microsecond
IFOV:	Instantaneous Field Of View
°C:	Degree centigrade
°K:	Degree Kelvin
°C/sec:	Centigrade per second
cw:	Continuous wave
SEM:	Scanning Electron Microscope
TEM:	Transmission Electron Microscope
mm^2:	Millimeter square
bb:	Black-body
ϵ:	Emissivity
ρ:	Reflectivity
h:	Planck's radiation constant
k:	Boltzmann constant
c:	Velocity of light
CO_2:	Carban dioxide

$>$:	Greater than
λ:	Wavelength of radiation
S/N:	Signal-to noise ratio
NEP:	Noise equivalent power
D*:	Specific detectivity
$\sim$:	Approximately
μV:	Microvolt
nV:	Nanovolt
pV:	Picovolt
λ_{c0}:	Cutoff wavelength
λ_p:	Peak wavelength
f_c:	Cutoff frequency
A/D:	Analog to digital converter
TWS:	Thumb wheel switch
SHM:	Sample and hold module

CHAPTER I

INTRODUCTION

Materials which exhibit improved properties (e.g. wear, strength, fatigue) at elevated temperatures are required for many engineering applications. These materials are subjected to various forming and joining processes which require high temperatures ($\sim$ 600 °C to 2500 °C) at the joints. Many of the joining techniques such as laser-beam, arc, plasma and electron-beam result in the melting of a small area of the processed part (in the order of few mm^2) followed by very high cooling rates ($\sim 10^5$ °C/sec). The molten pool shape and fluid flow characteristics influence the depth of penetration, porosity, heat cracking, segregation, microfissuring and degree of fusion in the joint. To understand the thermophysical behavior of such a pool during cooling, accurate noncontact and time dependent temperature measurements are required. These measurements have the advantage over conventional contact temperature measurements in that they do not disturb the nucleation or crystallization within the sample, i.e. they are non-intrusive.

The conventional remote sensing techniques used for temperature measurements detect the emitted radiation of the sample and attribute it to the "brightness temperature". Thus two samples having different emissivities but the same total radiant energy at the measuring device will have the same "brightness temperature". Their actual temperature, however, could vary over a wide range due to emissivity differences. To overcome this difficulty of making accurate temperature measurements over a range of temperatures, some designers simplify by using an average emissivity value. But this practice results in only an approximation. An attempt to measure the emissivity as an integral part of temperature measure-

ment is an obvious solution and results of such an effort have been reported [1]. The temperatures measured using this technique have reported good agreement with those measured by thermocouple devices.

Employing the rudiments of the single detector design discussed in reference [1], a pyrometer was designed for noncontact temperature measurements of weld-pools. This system was made to be compatible with the CLA's high power Rofin-Sinar-3000 CO_2 laser system. The objectives of the work were:

1. Design a pyrometer using a single detector that can measure the temperature of a point in the weld-pool during laser welding of a sample with the CLA CO_2 high power laser system.

2. Extend the design by using a linear array of detectors for the temperature measurements of a small strip across or along the weld direction.

3. Extend the design using an area array of detectors for the temperature measurements of a small area on the surface of a weld-pool.

Detailed design of a pyrometer for the temperature measurement of a spot on weld-pool is given. This measurement does not make any apriori assumption about the local emissivity of the target at the measuring spot. Emissivity is computed by measuring the reflectivity of the target spot within the weld-pool area as an integral part of the overall measuring process. This is done for each temperature measurement. For this the pyrometer incorporates 1.535 μm cw laser with chopped collimated beam. During every cycle of a chopper the laser's reflected signal from target is used to compute reflectivity and then the target's emitted signal is used to compute true temperature. Thus every temperature measurement is the true temperature of the of the target.

CHAPTER II

BACKGROUND

An understanding of the theory of solidification processing is necessary to obtain in-depth information about material properties such as wear, strength and fatigue. Present techniques used to study solidification perform measurements on the samples after the processing is complete. Data is typically collected using Scanning Electron Microscopes (SEM), Transmission Electron Microscopes (TEM), Electron Microprobes and other post-facto measurement systems. Data collected by these methods often result in inferences which are unrealistic.

Since the cooling rate of the molten material strongly influences the material properties, it would be beneficial to have the sample's thermal history. The data collected must have meaningful spatial and temperature resolution in the context of solidification theory. If the thermal data is gathered optically thus allowing nonintrusive measurements, a very high data handling rate is required. The work involved in the acquisition of such data is interdisciplinary due to the different areas of expertise involved in the design of an instrument with the appropriate capabilities. The design work reported herein is a result of combining the areas of solidification theory, infrared sensor technology and high speed data storage and retrieval techniques to study material thermal histories during laser processing.

A. Temperatures Experienced During Laser Processing:

Laser processing of materials is fast, clean and reliable. The actual processing occurs over a small area of the order of a few mm^2. The temperatures in the processed parts rise rapidly to the melting point of the material and vary from 700

°C for aluminum to 2500 °C for composite materials. Typically, temperatures fall quickly, at a high cooling rate i.e. $\sim 10^5$ °C/sec. The temperature distribution, in addition to being a function of time, is three dimensional in space. The objective of this thesis project was to design an instrument that would map the temperature distribution of the laser generated molten pool as a function of time and position. To physically measure the temperature distribution, both, as a function of depth of the pool and time was considered impractical. Hence the measurement of the temperature distribution on the surface became the thesis goal. The temporal temperature data can then be related to the weld depth distribution by using an appropriate heat transfer model.

Laser processing of materials can be accomplished in either a continuous wave (cw) or pulsed mode. In the cw mode there is always a high temperature plasma somewhere along the path of the laser beam near the surface of the material being processed. This plasma makes optical temperature measurements at the surface difficult. In the pulsed-laser mode, used for many materials, the plasma disappears within a few microseconds after the laser pulse off-time portion of the cycle is initiated. Thus realistic optical temperature measurements for the material being processed become possible during the off-period of the pulsed-laser mode.

B. Contact Temperature Measurements:

Thermocouples are typically used for contact temperature measurements. The junction of the thermocouple makes physical contact with the object to be measured. If used above 700 °C thermocouples are unstable [2]. In addition, their basic intrusive nature interferes with the system being monitored. This can

disturb some ongoing physical processes such as nucleation and crystallization. Other disadvantages of thermocouples are their limited range of linear response and their typically long time constant (> few ms). Hence thermocouples (and other contact temperature thermometers) are not considered particularly useful for the present application.

If one is compelled to use thermocouples, temperatures can be measured at locations away from the molten pool and analytical models employed to predict the temperature profile of the pool. The reliability of such data would be dependent upon the models' accuracy.

C. Noncontact Temperature Measurements:

For measuring high temperatures, noncontact temperature measurement techniques are normally preferred over contact temperature measurements. The validity of this premise is more relevant in cases where it is necessary to avoid any physical contact of the measuring device with the system. Using noncontact techniques, one typically measures the emitted radiation of the target in a spectral band which is then related to the physical temperature of the radiating surface. These techniques are based on Planck's black-body radiation law or its variation, Wein's law. The mathematical basis of these techniques is explained below.

According to Planck's radiation law [3], spectral radiant emittance from a black-body is given by

$$W(\lambda) = \frac{\epsilon\, 2\pi hc^2}{\lambda^5}\left[\frac{1}{e^{ch/\lambda kT} - 1}\right] \qquad (1)$$

where

$W(\lambda)$ - Spectral radiant emittance from a black-body (Watts cm^{-2} $\mu\mathrm{m}^{-1}$)

λ - Wavelength of the radiation (μm)

h - Planck's constant (6.6256×10^{-34} W sec^2)

c - velocity of light (2.997925×10^{10} cm sec^{-1})

k - Boltzmann's constant (1.38054×10^{-23} W sec $°K^{-1}$)

T - temperature of radiating surface (°K)

Emissivity (ϵ) depends upon type of material, its surface finish, temperature and the spectral band of radiation used for the measurement. For bodies which are not perfectly black, ϵ is less than unity. The band pass emissivity can be written as

$$\epsilon = \frac{\int_{\lambda_1}^{\lambda_2} \epsilon(\lambda) W(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} W(\lambda) d\lambda} \tag{2}$$

where

ϵ - Emissivity of a grey-body within wavelengths λ_1 and λ_2

$\epsilon(\lambda)$ - Spectral emissivity of the radiating surface.

$\epsilon(\lambda)\ W(\lambda)$ - Spectral radiant emittance of a grey body (Watts $cm^{-2}\ \mu m^{-1}$)

λ_1, λ_2 - Limits of wavelength region (μm).

The band pass radiance of a grey body can thus be written as

$$N = \frac{1}{\pi} \int_{\lambda_1}^{\lambda_2} \epsilon(\lambda) W(\lambda) d\lambda \tag{3}$$

where

N - Watts cm^{-2} sr^{-1}

By measuring N, the temperature of the radiating surface can be determined. If one uses an area array detector instead of a single element detector, one obtains the temperature profile of a radiating surface over which the detector array is focused.

Inaccuracies of the noncontact temperature measurements arise primarily due to the following reasons [2]:

- Noise and non-linearity of the detection system.
- Uncertainty in the emissivity values of the surfaces.
- Stray radiation
- Finite response time of the detection system.

These inaccuracies can be addressed and minimized by appropriate selection of components and by optimizing the design. Solid state photon detectors are linear over a wide range of input radiation and have very small time constants (< few 10's of ns). Careful optical design can keep the effects of stray radiation to a minimum. If the emissivity of the surface is known and it remains constant throughout the measurement process, simple noncontact temperature measurements will give the true temperature. This, of course, is dependent upon the particular material. The emissivity depends upon the spectral band of radiation used for the temperature measurements and also varies widely with the material temperature and its surface. For this reason, use of an average emissivity for temperature estimation may be very misleading. It is therefore desirable to have an accurate knowledge of the emissivity for each weld-pool temperature measurement so that the actual temperature of the sample can be computed.

D. The Laser Pyrometer:

Accurate temperature measurements are possible only if the surface emissivity and emitted radiation are both measured simultaneously and accurately. Planck's black-body radiation law can then be used for temperature computations. Attempts to develop a device which could accomplish this were first made

by Allen and Lee [1]. They designed a nonscanning optical pyrometer that did not require apriori knowledge of the surface emissivity of the target for computation of its true temperature. Figure 1 shows four stages of the pyrometer designed to acquire accurate surface temperature of the target using a calibration standard. As shown in the figure, reflectivity was measured using a laser source (0.904 μm) and a photon detector, which also measured the emitted radiation from the target. Once reflectivity is known, emissivity can be calculated using Kirchoff's law. The instrument was calibrated for reflectivity using a 0.99 reflectance gold surface. A black-body furnace was used for radiation calibration. Temperature resolution of the instrument was estimated to be 5 °C at 1300 °C. Figure 2 shows a schematic of the system used by Allen and Lee to calibrate their pyrometer. For temperature measurements, the target is placed in a bell-jar and heated with the RF coil while its temperature is monitored by a thermocouple. The pyrometer takes the measurements of reflected and emitted radiations from the target and data is passed to the computer. True target temperature is calculated using this data and the the calibration standard data.

The mathematical background of how to estimate the true temperature of the target using a reflection standard, black-body radiator and the target's reflectivity and emissivity measurements is given below.

1. Incident Laser Radiation On The Reflection Standard:

To find the target reflectivity, ρ_t, the voltage signal corresponding to the low power laser radiation incident on the weld-pool is required. To account for such a radiation one would generally have to consider the transmission factor for the optical elements involved in the path. This can be eliminated, however, by using

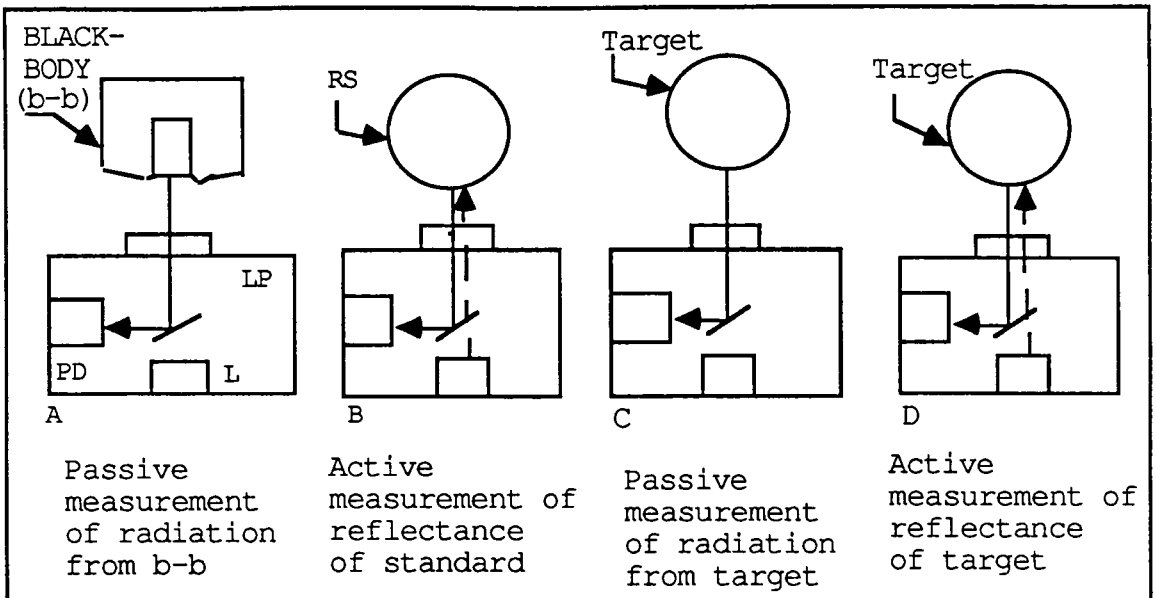


Figure 1. Four Stages Of Laser Pyrometer for Measuring True Surface Temperature Of a Target. (PD- Photo Detector, L-Laser Source, LP-Laser Pyrometer, RS - Reflection Standard.)

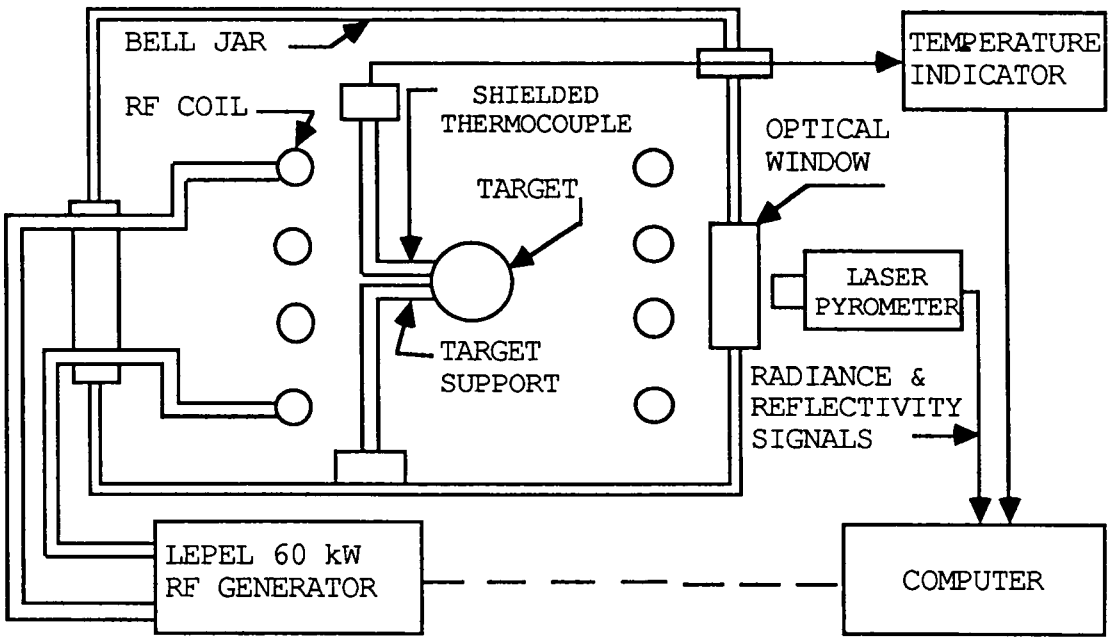


Figure 2. Laser Pyrometer Calibration System Schematic.

a gold reflection standard of known reflectivity.

Since

$$\rho_g = K\frac{V_{lg}}{V_{lc}}$$

where

V_{lc} - laser signal incident on the gold standard.

V_{lg} - laser signal at the detector as reflected from the gold standard.

ρ_g - Reflectivity of the gold standard. (known)

K - The optical system constant.

Therefore the voltage corresponding to the laser radiation incident on the gold calibration standard is

$$V_{lc} = K\frac{V_{lg}}{\rho_g} \tag{4}$$

2. Reflectivity Of The Target:

The reflectivity of the target is measured using the low power cw laser.

Since

$$\frac{V_{lc}}{K} = \frac{V_{lt}}{\rho_t} \tag{5}$$

where

V_{lt} - laser signal at the detector as reflected from the target.

ρ_t - Reflectivity of the target.

From equations (4) and (5) V_{lc}/K can be eliminated, thus giving as the target reflectivity

$$\rho_t = \frac{V_{lt}}{V_{lc}/K} = \frac{V_{lt}}{V_{lg}/\rho_g} \tag{6}$$

The target reflectivity, ρ_t, varies with the spectral band of the radiation used by the measuring system. For a fixed spectral band it varies with the weld material, its surface characteristics and temperature. Hence it must be measured for every temperature computation.

3. Emissivity Of The Target:

Once the reflectivity of the target is obtained, the emissivity of the target, ϵ_t, can be calculated using Kirchhoff's law. Since the molten pool does not transmit energy

$$\epsilon_t = 1 - \rho_t \tag{7}$$

4. True Temperature Of The Target:

From Planck's radiation law, when $e^{ch/\lambda kT} > 1$,

$$W_t(\lambda) = \frac{\epsilon_t c_1}{\lambda^5} \frac{1}{awe^{c_2/\lambda T}} \tag{8}$$

$$= CV_{rt} \tag{9}$$

where

$W_t(\lambda)$ - Spectral radiant emittance of the target

c_1 - First radiation constant ($2\pi hc^2 = 3.3715 \times 10^{-4}$ W cm^{-2} μm^4)

c_2 - Second radiation constant ($\frac{ch}{k} = 1.43879$ μm °K)

C - Instrument constant

V_{rt} - Voltage corresponding to the target radiance.

Hence solving for temperature T one obtains:

$$T = \frac{c_2}{\lambda \log\left[\frac{\epsilon_t c_1}{\lambda^5 C V_{rt}}\right]} \tag{10}$$

Writing the above equation using a system constant, C_{sys},

$$T = \frac{c_2}{\lambda \log\left[\frac{\epsilon_t}{C_{sys} V_{rt}}\right]} \tag{11}$$

where

$C_{sys} = \frac{C\lambda^5}{c_1}$, a constant for the pyrometer. It is a function of wavelength, radiation constant c_1 and the instrument constant C.

In practice, the radiation constant, c_2, and the wavelength of radiation, λ, (or a spectral band to be precise) are fixed. From the radiation measurement of the target, ρ_t and V_{rt} are obtained for each reading.

C_{sys} is known from the black body calibration data in the following way. If the pyrometer is used to measure the radiation of the black body whose precise temperature, T_b (°K), is known then equation (11) can be modified to

$$T_b = \frac{c_2}{\lambda \log\left[\frac{\epsilon_b}{C_{sys} V_{rb}}\right]}$$

where

ϵ_b - Emissivity of the black body (= 1)

V_{rb} - Voltage corresponding to black body radiance at temperature T_b (°K)

Therefore

$$C_{sys} = \frac{1}{V_{rb}\ awe^{[c_2/\lambda T_b]}} \tag{12}$$

Since all the quantities on the right hand side of equation (12) are known, C_{sys} can be found. Once C_{sys} is known, the temperature of an unknown target can be calculated using equations (7) and (11).

CHAPTER III

DESIGN OF THE LASER PYROMETER

The schematic block diagram of the laser pyrometer is shown in Figure 3. The pyrometer is composed of three principal subsystems: electro-optical, calibration and data acquisition. The electro-optical subsystem directly interfaces with CLA's Rofin-Sinar-3000 laser system and converts the optical radiation from the target being processed into an electrical signal. The latter is amplified, digitized and recorded on the Masscomp computer. The calibration subsystem has a radiator black-body and reflection standard. They evaluate system constants and enable derivation of the weld-pool temperature from the acquired voltage data. Interface electronics and the Masscomp computer handle the data acquisition. These subsystems are discussed in detail in the following sections.

A. Electro-Optical System:

The optical components of the electro-optical system collect the reflected and emitted radiation from the target and focus it on the liquid nitrogen cooled InAs detector. The specifications of the electro-optical components are determined by the desired pyrometer characteristicsand may be defined as follows:

1. Temperature Range And Temperature Resolution:

To understand the weld-pool characteristics of the family of alloys and composites, a temperature range of 300 °C to 2500 °C is selected with a temperature resolution of 1 °C. The lower temperature range enables gathering data for alloys

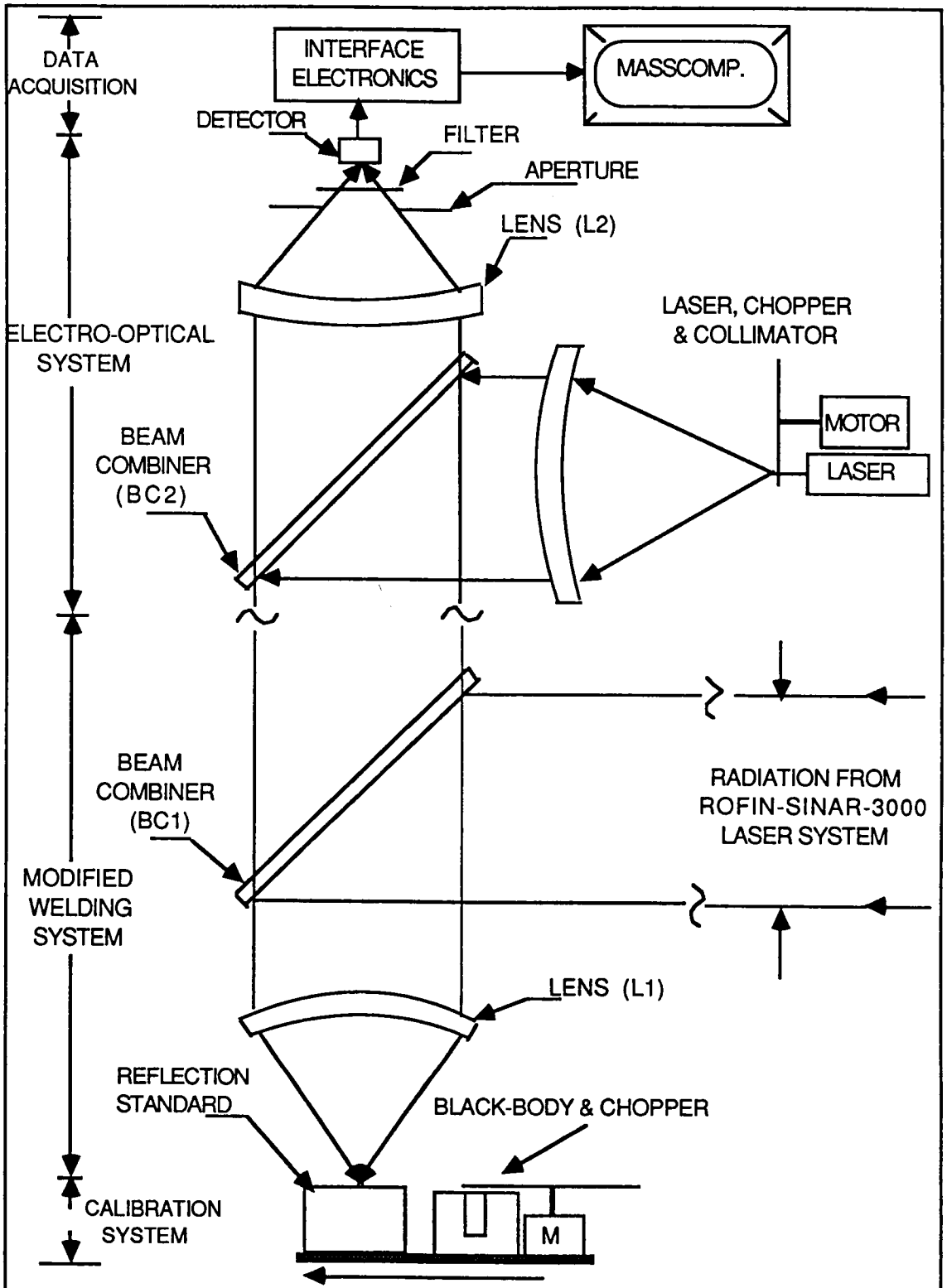


Figure 3. Block diagram of the pyrometer to be integrated with CLA's Rofin-Sinar-3000 laser system.

with lower melting points e.g. aluminum alloys.

2. Spatial Resolution:

Spatial resolution is decided by the minimum area of the weld-pool which will give enough signal to be detectable at the lowest temperature of interest and which will also reveal the meaningful thermophysical characteristics of the weld-pool. Very high spatial resolution ($\sim$ 10 μm or less) is necessary to get the detailed view of the weld-pool needed to understand temperature changes taking place over very short distances. The high resolution need mandates high aperture optics and a high data rate, which in turn requires large data storage capacity. Needless to say, these requirements will also increase the cost of data analysis. It was decided to have the optics of the design pyrometer compatible with the existing optics of the Rofin-sinar CO_2 laser. It was also decided to use the existing Masscomp computer from CLA for data recording and storage. Considering these constraints a compromise spatial resolution of 100 μm $\times$ 100 μm at the weld-pool was selected.

3. Spectral Band Resolution:

The selection of spectral band and spectral resolution depends upon the temperature range of interest, detector availability and cooling limitations. The temperatures involved in this study vary from 300 °C to 2500 °C. For every temperature measurement the reflectivity of the weld-pool is measured using a solid state cw laser. The maximum wavelength of the available laser for reflectance measurement is 1.535 μm with a bandwidth of 5 nanometers. Since reflected and emitted radiation has to be measured in the same wavelength band the spectral

resolution for the emitted radiation A 1-2 μm band initially appears to be an ideal choice for temperature measurements, since this is centered at the 1.5 μm laser wavelength. This band was studied in detail for radiation characteristics and its radiation as a function of wavelength is shown in Figure 4. However very small radiation available from this band at 300 °C rules out the use of this narrow band. If the lower temperature limit to the study of thermophysical behavior of weld-pools were 500 °C then a 1-2 μm band is recommended. For the system developed, however, a 1-3 μm band was necessary to give sufficient signal at 300 °C.

4. Temporal Resolution:

Temporal resolution is the shortest interval in time between two temperature measurements during the cooling of the weld-pool. Since the thermophysical behavior of the cooling weld-pool is an important function of time, high temporal resolution is required. In practice both reflected and emitted radiation are measured during one temporal resolution. This is done by chopping the low power laser radiation. The maximum chopping frequency of the chopper available for this study is 50 kHz, hence, the temporal resolution of the instrument is 20 μs.

B. Components Of The Electro-optical System:

Having specified the general characteristics of the electro-optical system, the components of the system may then be defined. These components include a beam combiner, a lens, a cw laser with collimator and chopper, and an infrared detector with its preamplifier. In a system their performance is interdependent, hence their selection has to be such that it will optimize the output signal. The

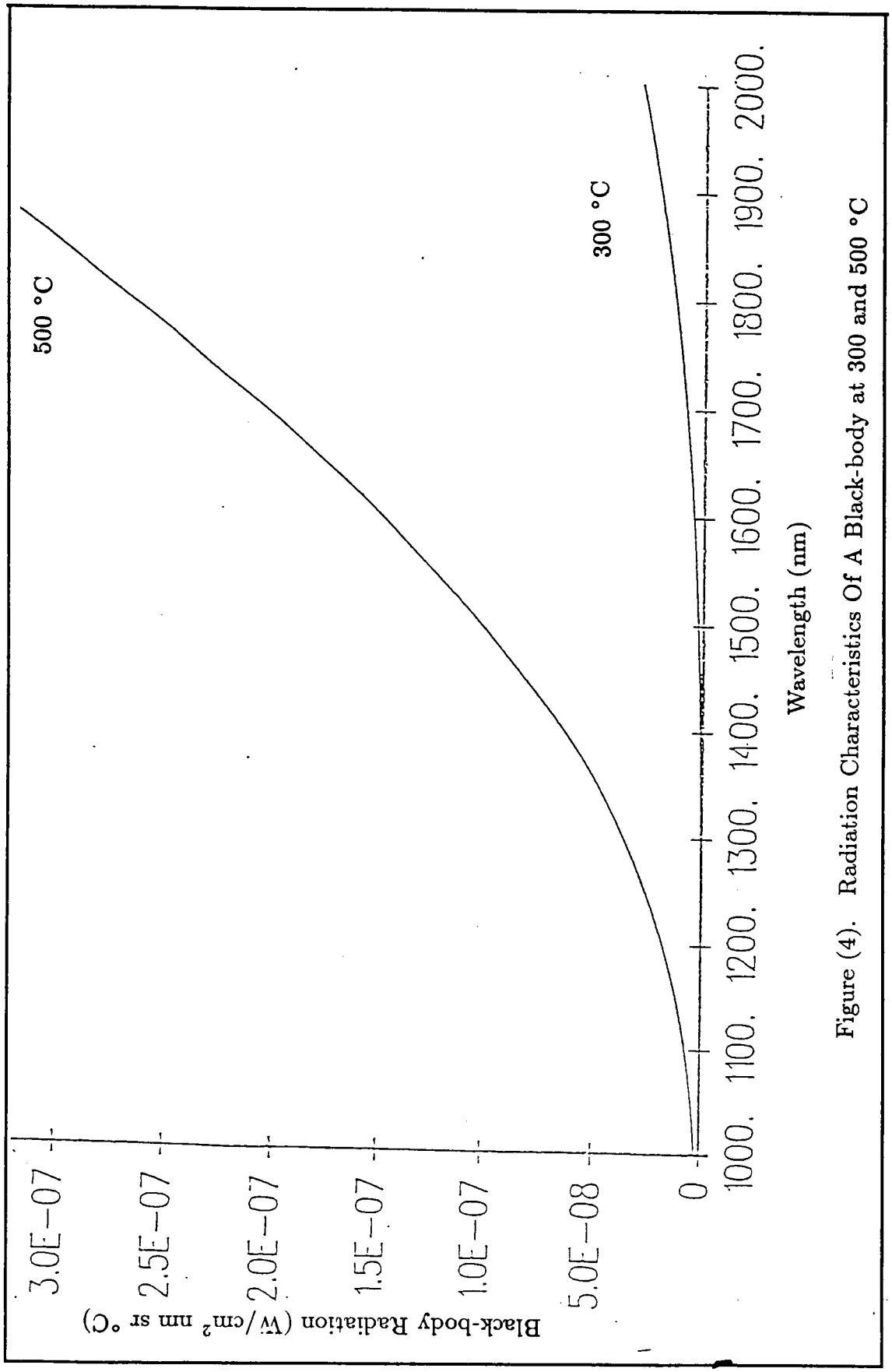


Figure (4). Radiation Characteristics Of A Black-body at 300 and 500 °C

selection and description of the electro-optical components is given below.

1. Beam Combiner BC_1:

The beam combiner BC_1 along with lens L_1 are enclosed in a metallic cone. The high power CO_2 laser radiation is focused through a 2 mm opening onto the target being processed. Argon gas is passed through this cone to prevent the high temperature plasma and metallic vapors from entering the cone. This ensures that no metallic vapors are deposited on the optical elements within the cone. The opening aperture of the cone also sets an upper limit to the maximum target size that the detector can view for temperature mapping.

Since the lens L_1 within the existing CO_2 laser system, is a 25 mm diameter f/2.5 ZnSe lens the beam combiner BC_1 is selected with an effective aperture of 35 mm. It reflects 10.6 μm laser wavelength and transmits emitted radiation from the target including the 1-3 μm spectral band.

2. Beam Combiner BC_2:

This beam combiner reflects energy from the low power cw laser at 1.535 μm to the weld-pool for reflectivity measurements and transmits the reflected and emitted radiation from the weld-pool to the detector. Minimum attenuation for the reflected and emitted radiation reaching the detector is required. Hence a transmissivity of 80% and a reflectivity of 20% is selected.

3. Focusing Lens L_2:

This lens focuses both the emitted as well as the reflected cw laser radiation from the weld-pool onto the detector. A 25 mm effective aperture, was selected to

be compatible with the aperture of the existing system. The lens selected is a f/2.5 ZnSe meniscus type, antireflection coated lens whose spectral passband extends beyond 1-3 μm spectral region. Thus the two lenses L_1 and L_2 are interchangeable and the image and object size are the same.

4. Optical Filter:

An optical filter with 1-3 μm passband is required to be compatible with the requirements. The spectral passband for the EG&G type PA9 detector is 1-3.1 μm. Hence the characteristics of this detector will also function a filter. Therefore, either no filter or a low pass filter with cut off for higher wavelengths at 3 μm can be used.

If thermophysical data beginning at 500 °C is acceptable (this will be the case for steel alloys and composite materials) then the 1-2 μm band is preferable. In this case a low pass filter with a 2 μm cut off for higher wavelengths can be used.

5. Optical Diaphragm:

A diaphragm will be placed between the filter and the lens to assure a field of view of 100 μm by 100 μm and to prevent stray radiation from being measured. A smaller field of view may be chosen by specifying an appropriate window size provided this does not significantly reduce the signal to noise ratio.

6. Detector:

A detector with a high value of specific detectivity (D*) or low value of noise equivalent power (NEP) is required. This allows reasonably sized optics and a

good signal to noise ratio (S/N) at lower temperatures (about 300 °C). Therefore thermal or bolometer type detectors, though low in price are not feasible. Another reason for not considering such detectors is their high time constant which is in the milliseconds range. A fast detector with a time constant in the microsecond range is required.

The detector selected is an EG&G type J12D-M205-R250U. The typical characteristics of this detector are shown in Table 1. It is a liquid nitrogen (N_2) cooled down-looking type InAs detector. Its active area is circular with a 250 μm diameter and spectral passband of 1-3.1 μm. This detector has an NEP of 0.15×10^{-12} Watts/$\sqrt{Hz}$ which corresponds to a D* value of 1.6×10^{11} cm $\sqrt{Hz}$ W^{-1}. The detector is very fast, its time constant being < 10 nanosecond.

7. Matched Preamplifier:

The detector is followed by a low noise preamplifier for further amplification of the electrical signal ($\sim$ few 10's of μV). The noise at the preamplifier input must be less than the detector output noise so that the latter does not degrade the signal to noise ratio at the detector. The maximum signal frequency at the preamplifier input is 100 kHz. Hence the preamplifier selected is an EG&G type PA-9. It has a bandwidth of 100 kHz and noise level of 1.5 nV/ $\sqrt{Hz}$ at 1 kHz. The typical specifications of this preamplifier are shown in Table 2.

The preamplifier output is available at any of the three transimpedence gain levels: 10^7, 10^6 or 10^5. The selection of the gain is made in agreement with the expected weld temperature. Table 3. gives typical values of preamplifier outputs at different temperatures with a gain level of 10^7. It is noted that at around 2000

Table 1. Specifications of J12D-M204 Series InAs Detectors:

Model No.	Active diam (mm)	Detector Temp. °K	λ_{c0} (μm)	A/W at λ_p	NEP (1k Hz) (W/$\sqrt{Hz}$)	f_c Hz
R01M	1	77	3.1	1.5	0.15×10^{-12}	200k
R02M	2	77	3.1	1.5	0.3×10^{-12}	100k

Table 2. Operating Characteristics Of The Preamplifier Type PA-9 at 25 °C

Characteristics		Value	Units
Transimpedance Gain: (Switch Selected)	Hi Medium Low	10^7 10^6 10^5	V/A
Bandwidth (Source Capacitance 1000 pf or less)	@Hi Gain @Med Gain @Low Gain	100 300 750	k Hz
Input Offset Voltage (V_{os})		+2000	μV
Input Offset Current (i_{os})		+0.01	nA
Voltage Noise Density (e_n at 1k Hz)		1.5	nV/$\sqrt{Hz}$
Voltage Noise from 0.1 to 10 Hz		1.0	μV_{pp}
Current Noise Density (i_n at 1k Hz)		0.04	pV/$\sqrt{Hz}$
Power Requirements:		+12 Volts, -12 Volts; (10 mA)	

Table 3. Preamplifier Output At Specified Target Temperatures

Spectral Band width: (1-3 μm)

Scene Area: $100\mu m \times 100\mu m$

IFOV (β): 1.6 milliradian

Optical Transmission: ~ 0.35

Responsivity (A/W): 1.5

Preamplifier Transimpedence Gain (V/A): 10^7

Preamplifier Noise Output: $\sim 0.5\ \mu V$

Least significant bit (A/D): 2.4 mV

Target Temp. (°C)	Radiance (W cm^{-2} sr^{-1})	Power At The Detector (W)	Preamp. O/P
300	5.9×10^{-3}	1.5×10^{-10}	0.79 mV
500	7.98×10^{-2}	20.43×10^{-10}	10.85 mV
1000	2.101	0.538×10^{-7}	0.28 V
1500	11.33	2.9×10^{-7}	1.5 V
2000	32.88	8.417×10^{-7}	4.42 V
2500	69.01	17.67×10^{-7}	9.28 V

°C the signal goes to saturation. Hence a lower gain value should be selected when weld temperatures of 2500 °C are expected.

C. Performance Of The Electro-optical System:

The performance of the electro-optical system with the components selected is shown below.

1. Temperature Resolution And Signal-To-Noise Performance:

To detect temperature difference within one degree centigrade, throughout the range of the pyrometer, the pyrometer must have enough signal to noise ratio (S/N) at the lowest temperature of interest. Hence, for this study, the S/N is calculated at 300 °C.

Another quantity of interest in pyrometric studies is the noise equivalent temperature difference (NEΔT), defined as a threshold temperature difference of the pyrometer at a signal to noise ratio of unity. If the detected temperature difference is less than (NEΔT), the pyrometer will attribute it to noise.

Signal to noise ratio is the reciprocal of NEΔT, that is

$$NE\Delta T = \frac{NER}{\epsilon_s \times \frac{\partial R}{\partial T}} \tag{13}$$

where

NEΔT - Noise equivalent temperature difference (°C)

NER - Noise equivalent radiance (W cm^{-2} sr^{-1})

ϵ_s - Emissivity of the target (assumed 0.4)

$\frac{\partial R}{\partial T}$ - Radiance change per degree centigrade. (10^{-4} W cm^{-2} sr^{-1} $°K^{-1}$ for a black-body at 300 °C.)

The noise equivalent radiance (NER) at the detector output is given by:

$$NER = \frac{NEP\sqrt{\Delta f}}{A_0 \beta^2 T_0} \tag{14}$$

where

NEP - Noise equivalent power of the detector ($W/\sqrt{Hz} = 0.15 \times 10^{-12}$)

Δf - Bandwidth of the amplifier (100 kHz)

A_0 - Effective area of the optics (4.9 cm^2)

T_0 - Transmission of the total optical path (0.25)

β - Instantaneous field of view (1.6 milliradian)

For the EG&G type J12D-M205-R250U InAs detector, noise equivalent power is specified as 0.15×10^{-12} $W/\sqrt{Hz}$. Therefore it is found that:

$$NER = 2.1 \times 10^{-5} \ \ (W cm^{-2} sr^{-1}) \tag{15}$$

$$NE\Delta T = 0.25 \ \ (^\circ K) \tag{16}$$

$$S/N = 4 \tag{17}$$

Thus with 25 mm aperture optics, the system has S/N of 4 to detect temperature change of better than a degree at 300 °C.

2. Spatial Resolution At The Weld-Pool:

The instantaneous field of view (IFOV) at the detector is 1.6 milliradian. The lenses L_1 and L_2 determine the spatial resolution at the weld-pool and in

the present case they have the same aperture and focal length. Therefore, the detector images a field of view of 100 μm$\times$ 100μm. Thus, a spatial resolution of 100 μm is obtained at the weld-pool.

D. Calibration System:

The calibration system comprizes of a black-body source, a standard gold coated reflection surface and a low power cw laser with its chopper.

1. Radiator Black-Body:

The black-body selected has a temperature range of 300 °C to 700 °C. Its temperature can be adjusted and controlled to within one degree. A thermocouple in contact with the black-body indicates its temperature on a digital display.

2. Reflection Standard:

The reflection standard is a gold coated surface with a reflectivity of 0.99 over a wide spectral band within and beyond the 1 to 3 μm range. During calibration the temperature of the reflection standard and the black-body is kept the same. Hence the temperature of this standard can be selected to be similar to that of the black-body.

3. Low Power CW Laser (LPCWL):

This laser should have its central wavelength close to 2 μm and adequate power to give enough S/N for measurement of the lowest anticipated weld-pool temperature. The laser selected is Stantel type LYC8M1. Its central wavelength is 1.535 μm and has an output power of 5 milliwatts.

4. High Frequency Chopper:

A high frequency chopper must be used to record the fast changing values of ρ_t and hence the ϵ_t corresponding to every temperature measurement. The highest frequency chopper available had a chopping frequency of 50 kHz. This enables measurements of ρ_t and ϵ_t for every 20μs. A chopper with a higher chopping frequency ($\sim$ 100 kHz) quite likely will be available in the future and this will reduce the temporal resolution to 10μs . A doubling of data rate will occur but this is acceptable for the Masscomp computer.

5. Collimator:

The collimator is part of the low power cw laser. It collimates the 1.535 μm laser energy to a 25 mm aperture which passes to BC_2 and then to the sample being processed.

E. Data Acquisition System :

The preamplifier, as previously noted, gives sufficient output signal and thus, only a little additional gain is required. An amplifier with a gain of 5 is used. The amplifier signal, after multiplexing, is connected to the Masscomp A/D converter. The synchronizing pulse corresponding to A/D conversion is obtained from the high power CO_2 laser and initiates the data acquisition system during every cycle of its pulsed mode of operation.

The pulse train from the low power cw laser chopper is connected to the control logic. Using this information, the control logic gives command pulses to the A/D converter in the Masscomp to convert the analog data to digital. The digital converted data can be stored on the disk or retained in the random access

memory (RAM) of the Masscomp.

1. Calibration And Weld-pool Temperature Data Sequence:

Figure 5a and 5b show the sequence of recording the black-body calibration and reflection calibration data. The first two words form an unique synchronization code with the first word having all zero bits and the second word having all one bits. The next four words are time data in terms of seconds, minutes, hours and days. Using an enable level set with the thumb-wheel switches, one can insert the initial values of seconds, minutes, hours as well as select any time period from 1 to 366 days. This is followed by six words for either black-body calibration or reflection calibration. From six words of reflection calibration data three values of reflection calibration voltage can be derived. The mean of these voltages will give V_{lg} of equation (6). To keep the design simple six words are written for black-body calibration also, though only three are required in this case. The tenth word is thermocouple temperature data for the black-body calibration. The system also writes one word of house-keeping data during the reflection calibration.

The data recording sequence for weld-pool temperature measurements is shown in Figure 5c. It begins with the synchronization and time code words. The number of words for thermal plus reflection data depends upon the frequency of the high power CO_2 laser and its duty cycle as well as frequency of chopper of the cw laser.

2. Calibration And Weld-pool Temperature Data Control:

Figure 6 shows the control logic for the calibration sequence. Analog data is sampled using Datel SHM45 [5] sample and hold module and the multiplexed

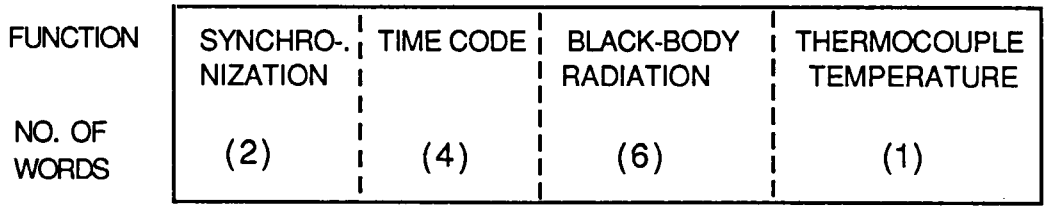


Figure 5a. Black-body calibration data sequence.

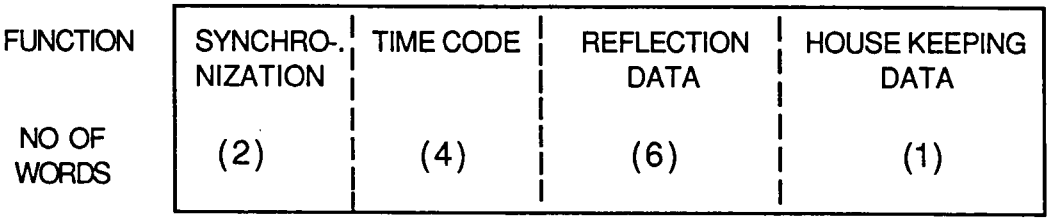


Figure 5b. Reflection calibration data sequence.

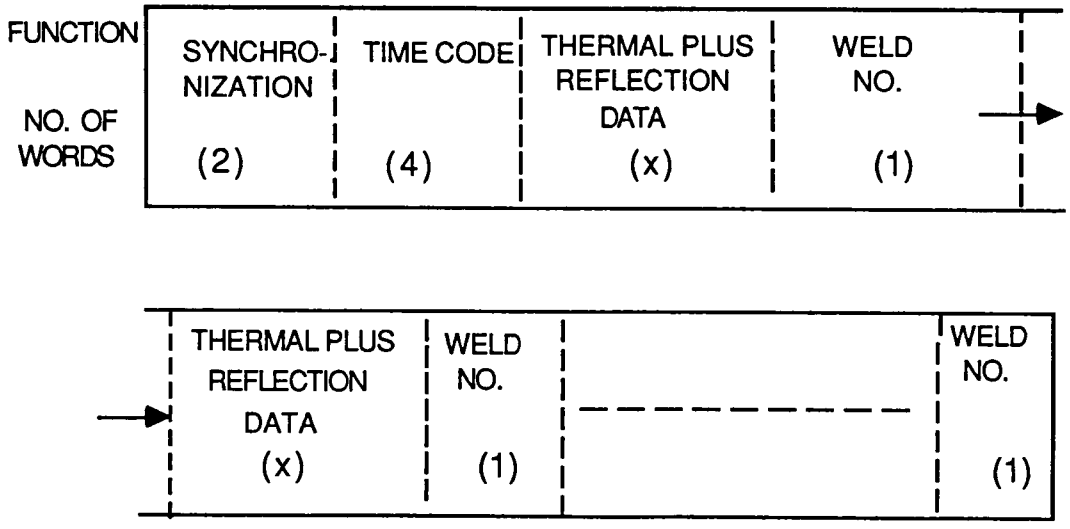


Figure 5c. Target data sequence.

Figure 5. Calibration and target data sequence.

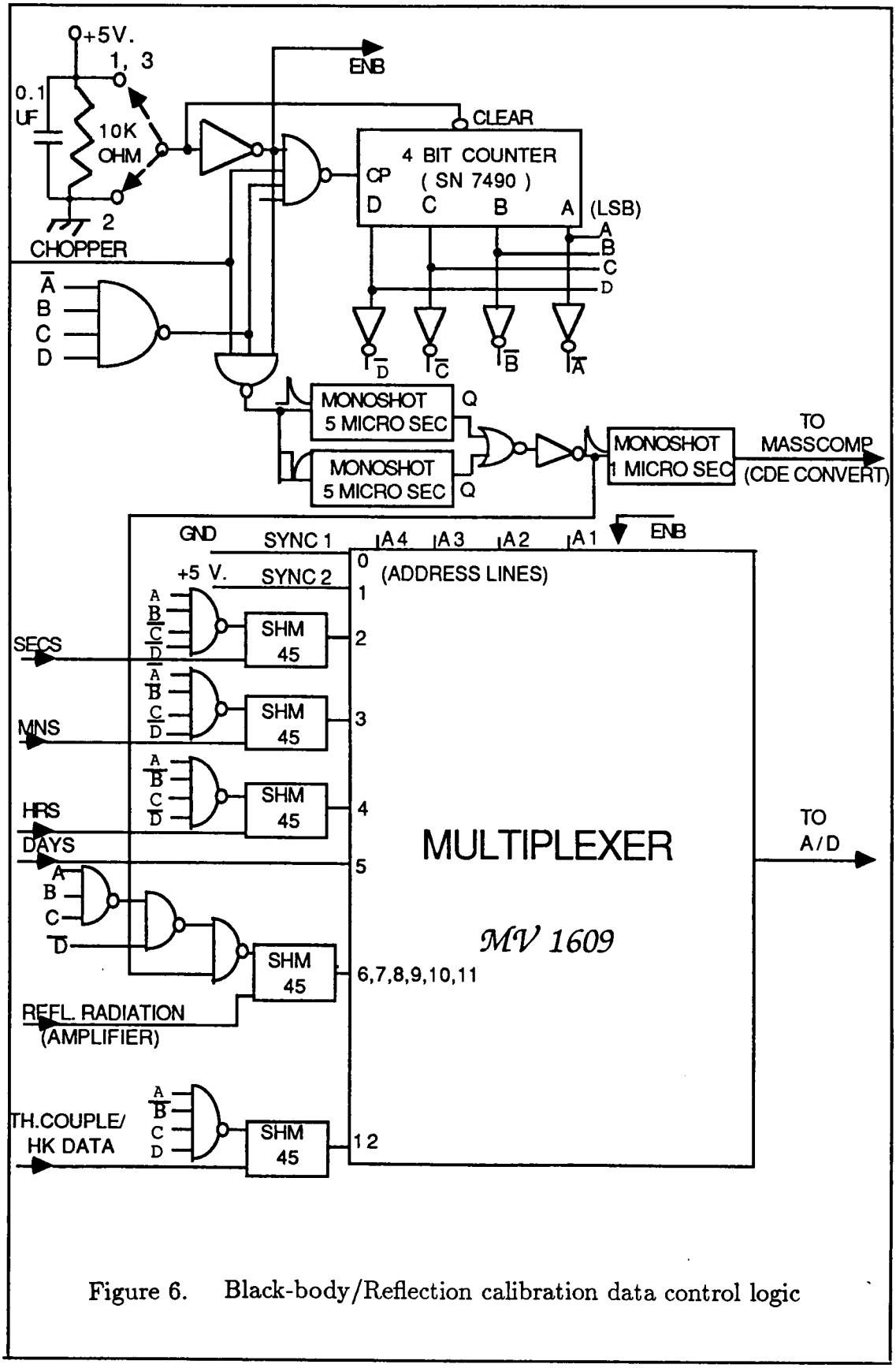


Figure 6. Black-body/Reflection calibration data control logic

analog output is sent to the Masscomp. Switch position 1 of the system is the reset position. Moving the switch to position 2 allows the counter to work and generates the enable level and address bus pulses for the multiplexer, and the command conversion pulses to the Masscomp to convert the analog signal to digital. Since there are only 10 words in the calibration sequence the counter is locked on the eleventh pulse of the chopper from the instant the calibration switch moves to position 2.

Figure 7 shows the control logic for control of data when the weld-pool temperature is recorded. In switch position 1 the counter is cleared and the multiplexer is disabled. In position 2 the counter [5] clear is removed and the multiplexer is enabled. Since the first six words form the synchronization code and the time code, the counter gets locked on the seventh pulse. Subsequently each cycle of the cw laser chopper produces two command pulses to record emitted and reflected data. The CO_2 laser pulse number is printed after each sequence of radiation data corresponding to each welding pulse. This sequence is continued until the welding for a given sample is complete.

3. Clock And Circuit Packages:

Figure 8 shows the amplifier which can be set to a maximum gain of 10. It receives the input from the preamplifier and sends its output to the calibration control or data control. The clock generates seconds, minutes and hours. The initial time can be preset in the clock using thumbwheel switches. Also shown are circuit packages from Datel of 12 bit D/A [5], sample and hold and 16 channel analog multiplexer.

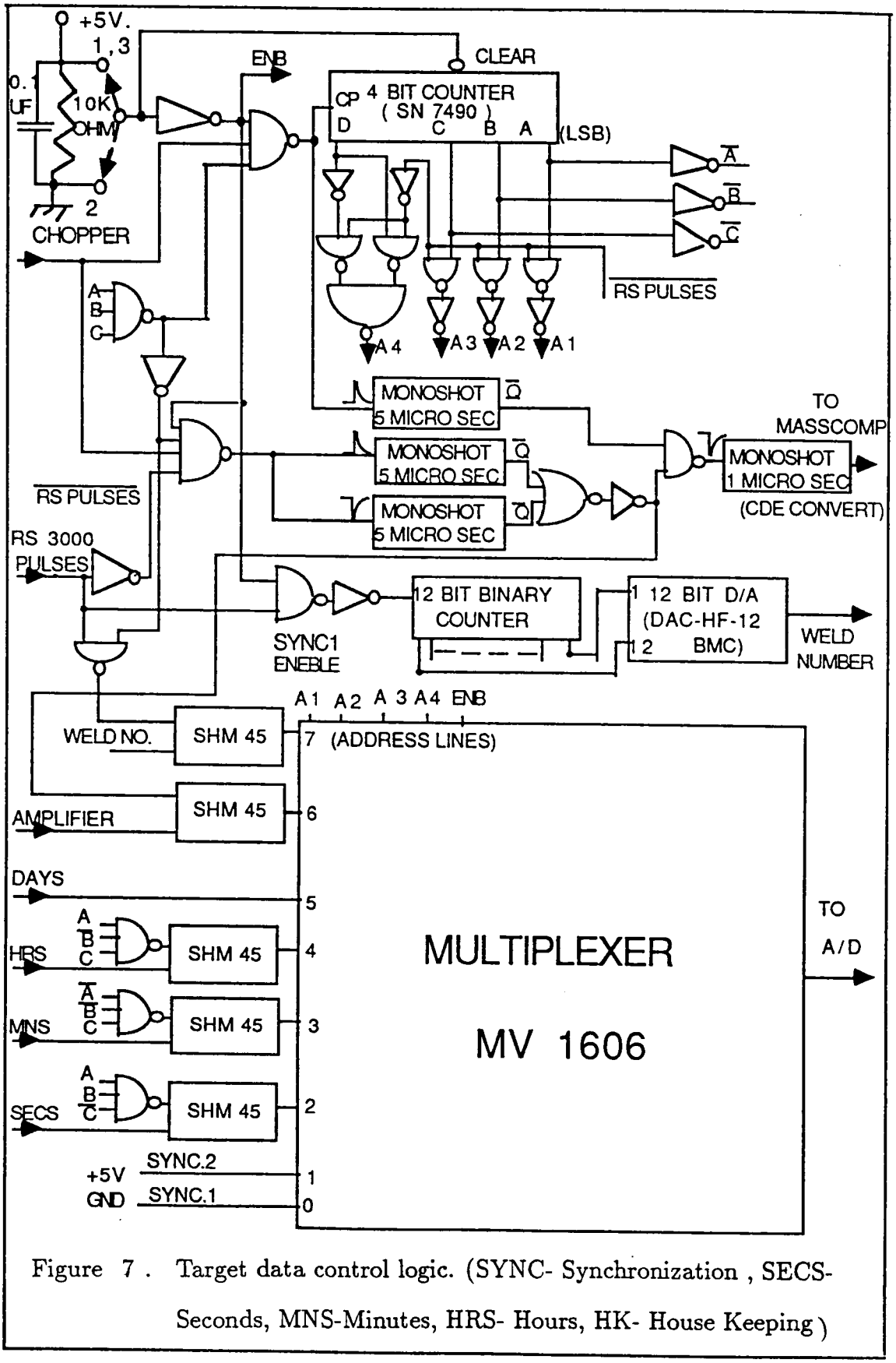


Figure 7 . Target data control logic. (SYNC- Synchronization , SECS- Seconds, MNS-Minutes, HRS- Hours, HK- House Keeping)

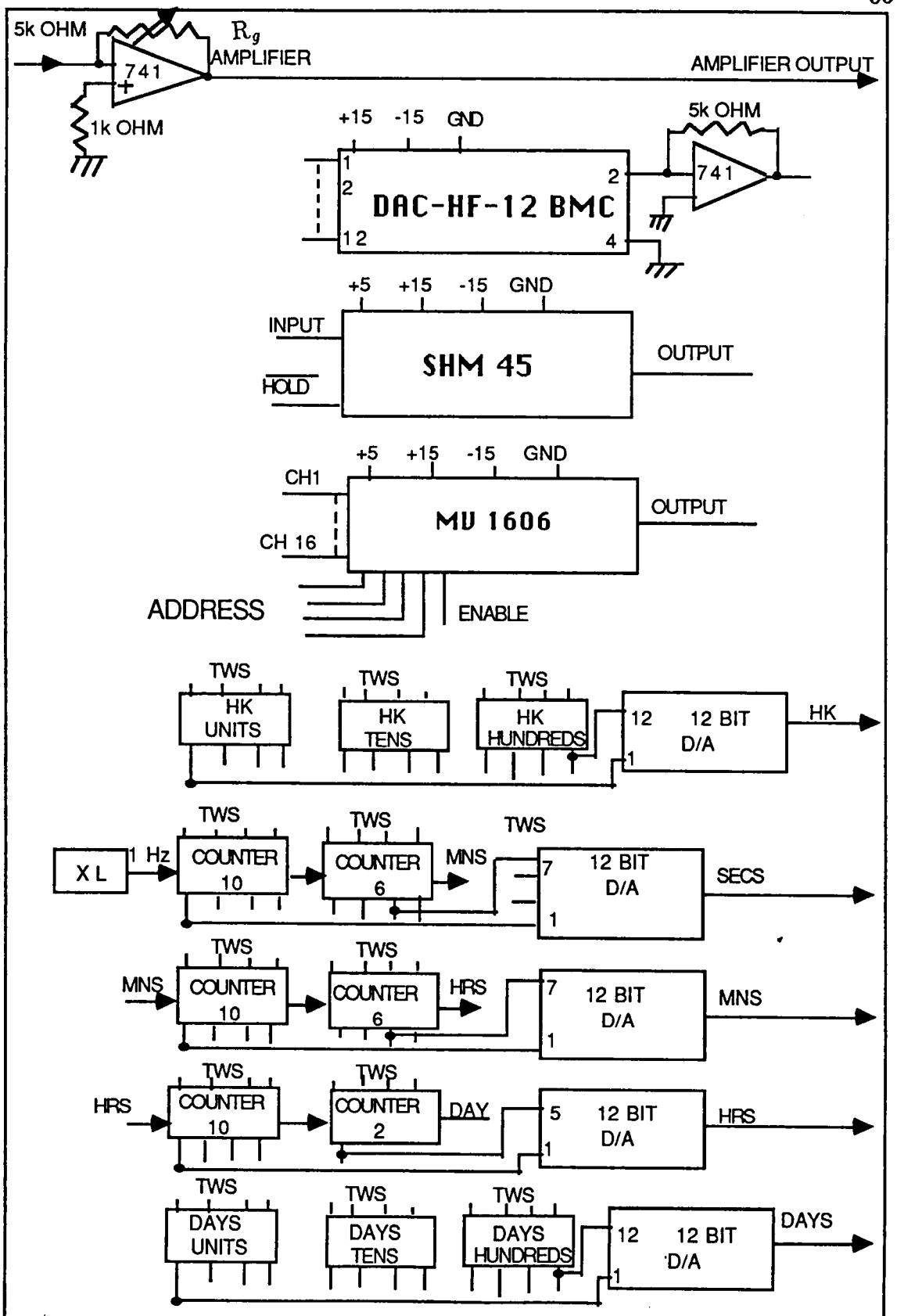


Figure 8. Clock and circuit packages.

4. Data Rate:

The data rate of the pyrometer depends on the chopping frequency or the detector dwell time and remains fixed for a particular chopping frequency. Since the chopping frequency selected is 50 kHz, it gives a data rate of 100k bytes per second, each byte being a 12 bit word.

5. Data Storage:

The Masscomp computer, available in the CLA department is selected for data acquisition and as a storage medium. It can accept the data at the rate of 400k samples per second and store the data in random access memory (RAM) or on hard the disk. The disk has a storage capacity of 3.2 Mega bytes.

CHAPTER IV

SYSTEM IMPLEMENTATION

The noncontact temperature measurement pyrometer is designed to integrate the electro-optical and the data acquisition subsystems with the CLA's Rofin-Sinar-3000 laser system. Before actually operating the instrument for temperature measurements it has to be calibrated by using a black-body radiator and reflectance standard. Recalibration is also recommended after processing of the sample is complete. This will ascertain if metallic vapors entering the cone degraded the optical quality of the electro-optical system, specifically lens L_1, which is in immediate proximity to the material being welded.

A. Modification Of The CLA CO_2 Laser:

As shown in figure 9, the Rofin-Sinar-3000 CO_2 laser uses a flat mirror and lens combination to focus the beam onto the target. In a modified system for pyrometric temperature measurements (Figure 10), the flat mirror is replaced by a beam combiner, BC_1, which reflects 10.6 μm laser radiation and transmits the lower wavelength radiation emitted by the sample being processed. This modification is required so that the detector of the pyrometer can have an unobstructed view of the processed sample undergoing solidification, without overly complicating the optical design. Except for this, there is no change in the components of the original welding system. The electro-optical system of the pyrometer is integrated with the laser system on the top of the beam combiner, BC_1.

The lens, L_1, is a 27.5 mm diameter, f/2.5 zinc selenide (ZnSe) lens. This

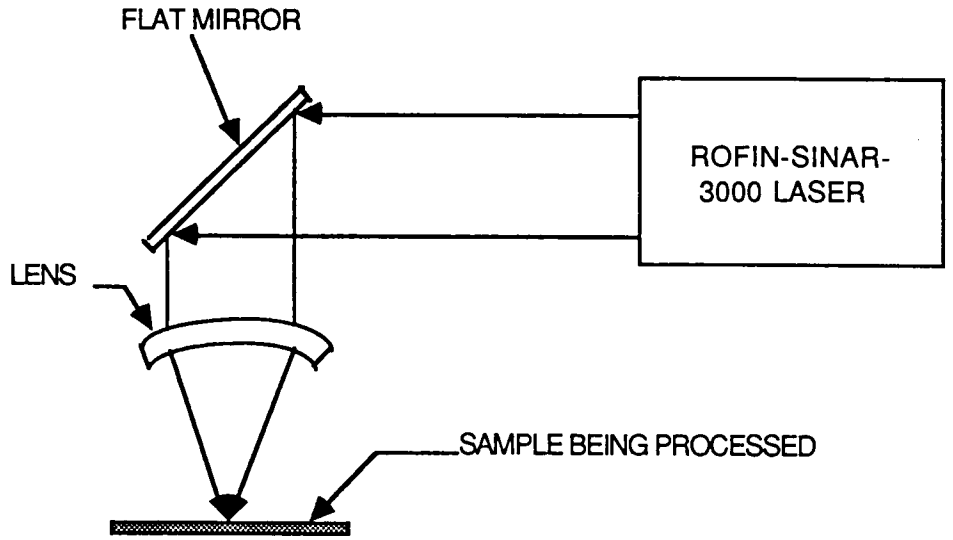


Figure 9. Optical layout of existing welding system using Rofin- Sinar-3000 laser system

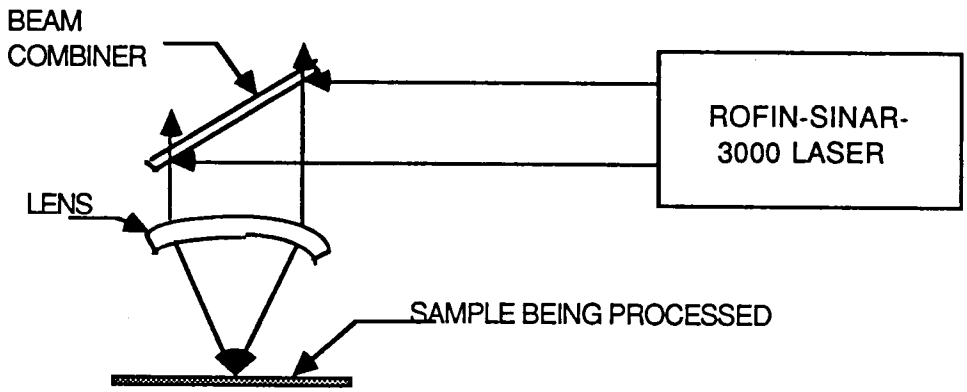


Figure 10. Optical layout of modified welding system using Rofin-Sinar-3000 laser system

lens is enclosed in a metal cone. Argon gas can be passed through this cone from feed tubes to suppress the high temperature plasma and prevent metallic vapors from entering the cone. The final inner diameter of the cone, close to sample being processed, is 2 mm.

B. Calibration And Operating Procedure:

The indium arsenide detector is cooled with liquid nitrogen. Black-body and reflection standards are set at the desired temperature. When the detector as well as the calibration standards have reached a steady state of temperature, the system is ready for calibration. Pulses from the chopper are checked to determine that they are properly fed to the electronics unit and then to the Masscomp computer.

1. Reflection Calibration:

With the high power CO_2 laser OFF and the LPCWL ON, the reflection unit is checked for alignment. If alignment is satisfactory, the LPCWL chopper is started. When the chopper blocks the laser radiation, the pyrometer will record the emitted radiation from the gold standard, otherwise the combined emitted and reflected radiation is recorded. From these two readings the voltage corresponding to only the reflected radiation from the standard (V_{lg}) is obtained. Since reflectivity of the standard (ρ_g) is given, the terms in equation (6) are known and the reflectivity of the target can be calculated by knowing the corresponding reflected voltage (V_{lt}), since

$$\rho_t = \frac{V_{lt}}{V_{lc}/K} = \frac{V_{lt}}{V_{lg}/\rho_g} \tag{6}$$

2. Black-Body Calibration:

Next, black-body calibration is done to determine the system constant C_{sys}. The black-body is aligned with the detector. Its temperature T_b (°K) is noted. When the chopper is turned on the voltage corresponding to the emitted radiation (V_{rb}) and the combined emitted and reflected radiation will be recorded. Only V_{rb} is required for black-body calibration as seen from equation (12).

$$C_{sys} = \frac{1}{V_{rb}\ e^{[c_2/\lambda T_b]}} \tag{12}$$

Thus system constant C_{sys} is then known.

3. Operating Procedure And Determination Of Target Temperature:

After the reflection and black-body calibrations are completed, the sample being processed is placed below the high power CO_2 laser beam and processed using the pulsed laser mode. While the sample is being processed readings of reflected and emitted radiation are recorded during the off period of the laser cycle. From the recorded signals, the voltages corresponding to the emitted radiation (V_{rt}) and the reflected radiation (V_{lt}) are known. Since V_{lg}/ρ_g and C_{sys} are already known, target temperature can be computed from

$$T = \frac{c_2}{\lambda\ \log\left[\frac{\epsilon_t}{C_{sys} V_{rt}}\right]}$$

The amount of data stored in the computer for the samples being processed varies with sample's velocity (15 mm/s to 150 mm/s) as well as with frequency (10 H_z to 1 kH_z) and duty cycle which is normally more than 50 percent for the

CO_2 laser. By using these parameters the amount of data to be collected and stored on the Masscomp can be estimated.

C. Data Acquisition And Storage:

The data acquisition system consists of digital and analog electronics, and a Masscomp computer. The preamplifier has gain enough to cover the full dynamic range of the A/D converter and its bandwidth is limited to 100 kHz. Hence an amplifier with a maximum gain of 5 is used to cover the full dynamic range for the measurement of lower temperatures. The resistance R_g of the amplifier is a lock-in potentiometer so that a particular gain can be selected and kept fixed. Separate digital control logics are used for calibration data and weld-pool temperature acquisition data. The synchronizing pulse corresponding to the A/D conversion obtained from high power CO_2 laser, initiates the control logic electronics during every welding pulse. The chopped cw laser pulses are routed through control logic, which give the command for the A/D converter to digitize the voltages corresponding to the emitted and the combined emitted and reflected radiation. The digital data can be stored on disk or in the RAM of the Masscomp computer.

1. Typical Data Available At 1 kHz Laser Frequency:

The chopper frequency determines the rate at which reflectivity and emissivity measurements can be made to obtain the actual temperature of a target. The velocity of welding (0.25 mm/sec to 25 mm/sec) decides the amount of overlap of temperature data. In laser processing, the amount of heat involved is confined in a very small area and cooling rates are very high. The number of temperature measurements made on a target depends on the frequency and duty cycle of the

high power CO_2 laser as well as chopping frequency of the the cw laser. Table 4 shows data typically available from the pyrometer using a single element detector when the frequency of the processing CO_2 laser is 1 kHz, its duty cycle is 50 percent and the chopping frequency of the low power laser is 50 kHz. The number of temperature measurements for every pulse of the CO_2 laser is 25. The thermophysical history of solidification of the sample undergoing cooling is recorded from 1500 °C to 1450 °C in the first case and from 700 °C to 650 °C in the second case. This type of data will be recorded and stored on the Masscomp.

2. CO_2 Laser Frequency Required To Get Maximum Cooling Range:

Examination of Table 4 shows that at 1 kHz frequency of the CO_2 laser, the data does not correspond to the complete cooling range (from melting point till 300 °C) of the sample being processed. Table 5 gives the frequency of the processing CO_2 laser if one is interested in the thermophysical history till the sample is cooled to 300 °C. It is seen that the processing CO_2 laser has to operated at very low to give data useful in understanding thermophysical behavior. At CLA, some inconel processing are done at such low frequencies so such data is actually be seen in practice.

System Parameters:

Detector time constant: < 10 ns

Cooling rate: $\sim 10^{5}$ °C/sec

Base temp.: 1500 °C

Laser velocity: 25 mm sec^{-1}

Chopping frequency at cw laser: 50 kHz

Spatial resolution: 100 μm $\times$ 100 μm

Table 4. Typical data available at 1k Hz laser freq. (Cooling time < 500 μ sec.)

Temperature Range	Temperature Drop in 20 μs	Temp. Measurements in 500 μs
1500-1450 °C	2 °C	25
700-650 °C	2 °C	25

Table 5. Parameters to get maximum cooling range.

Temp. Range	Laser Freq.	Time Available	Temp. Drop in 20μs	Measurements per cycle
1500-300 °C	41.7 Hz	$<$ 12 m sec	2 °C	600
700-300 °C	125 Hz	$<$ 4 m sec	2 °C	200

CHAPTER V

DATA REDUCTION

The pyrometer collects emitted and reflected radiation from the target and converts it into voltage data which is then stored on the Masscomp computer. This voltage data bears the signature of the target in terms of the thermophysical parameters: reflectivity, emissivity and temperature. Though one can derive these parameters from the stored voltage data it is preferable to store the target information in terms of the thermophysical parameters.

A. Reflection Data:

Using equation (6) one can write

$$\rho_t = \frac{V_{lt}\ \rho_g}{V_{lg}}$$

where reflectivity of the standard (ρ_g) is given and the reflected laser signal from the standard (V_{lg}) is known from the calibration data. Thus the reflectivity, ρ_t, can be computed for every voltage measurement of a processed sample and then stored.

B. Emissivity Data:

Emissivity data of the target is computed from the equation

$$\begin{aligned} \epsilon_t &= 1 - \rho_t \\ &= 1 - \frac{V_{lt}\ \rho_g}{V_{lg}} \end{aligned} \tag{18}$$

Hence for every value of the reflected laser signal from target (V_{lt}), the emissivity of the target (ϵ_t) can be computed and stored.

C. Temperature Determination:

The temperature of a weld-pool is determined using equation (11). For better understanding of the temperature estimation, equations (6), (7), (11) and (12) are repeated here.

$$\rho_t = \frac{V_{lt}}{V_{lc}/K} = \frac{V_{lt}}{V_{lg}/\rho_g} \tag{6}$$

$$\epsilon_t = 1 - \rho_t \tag{7}$$

$$T = \frac{c_2}{\lambda \log\left[\frac{\epsilon_t}{C_{sys} V_{rt}}\right]} \tag{11}$$

$$C_{sys} = \frac{1}{V_{rb}\, e^{[c_2/\lambda T_b]}} \tag{12}$$

Inserting the value of ρ_t from equation (6) in equation (7) and then substituting for ϵ_t in equation (11) the temperature of the weld-pool can be written.

$$T = \frac{c_2}{\lambda \log\left[\frac{1}{C_{sys} V_{rt}} \times (1 - \frac{\rho_g V_{lt}}{V_{lg}})\right]} \tag{19}$$

The calibration constant C_{sys} is known from equation (12), since V_{rb} and T_b are measured and λ and c_2 are known. ρ_g is known and V_{lg} is found from the reflection calibration. The radiation constant, c_2, and central wavelength of the emitted radiation (λ) are known from experimental choice. Hence executing the computation on the right hand side of equation (19) for each set of values of reflected laser radiation (V_{lt}) and emitted radiation (V_{rt}), yields the temperature data which may be stored.

CHAPTER VI

DESIGN USING ARRAY DETECTORS

The design of a pyrometer using a single element detector to map the temperature of a sample undergoing laser processing is presented in detail. The drawback to the use of the single element pyrometer is that it measures a 0.1 mm line width on a weld-pool while the width of a weld-pool itself is about 3 mm. Hence, to get a wider perspective of the weld-pool area undergoing solidification, larger line width needs to be mapped at the weld-pool. This can be done using a linear or an area array type detector at the focal plane of a lens focusing the weld-pool radiation. However array detectors are much more expensive and the focusing lens has to be of high and uniform optical quality over a larger field of view. To take this into account a simple arrangement of array detectors is proposed. These array detectors map simultaneously, a line width of three pixels for a linear array and an area of 3×3 pixels for an area array. The challenges introduced by these systems can be reasonably met both costwise and technically. The systems proposed are compatible with the CLA's RS-3000 CO_2 laser welding system for the weld-pool temperature measurement and with the Masscomp computer for data recording.

A. Pyrometer Using A Linear Array:

Figures 11 and 12 show two ways of temperature mapping using a three element linear array detector, kept at the focal plane of a lens collecting the weld-pool radiation. Figure 13 shows the data acquisition system. The detector configurations of Figure 11 and 12, being perpendicular and along the sample's

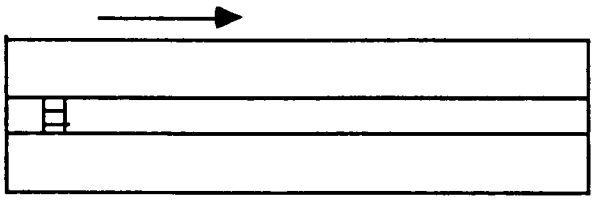


Figure 11 . Temperature mapping of the sample perpendicular to the sample's velocity of propagation

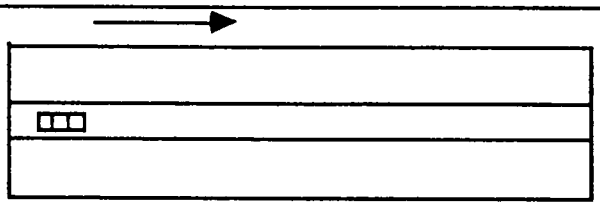


Figure 12 . Temperature mapping of the sample along the sample's velocity of propagation.

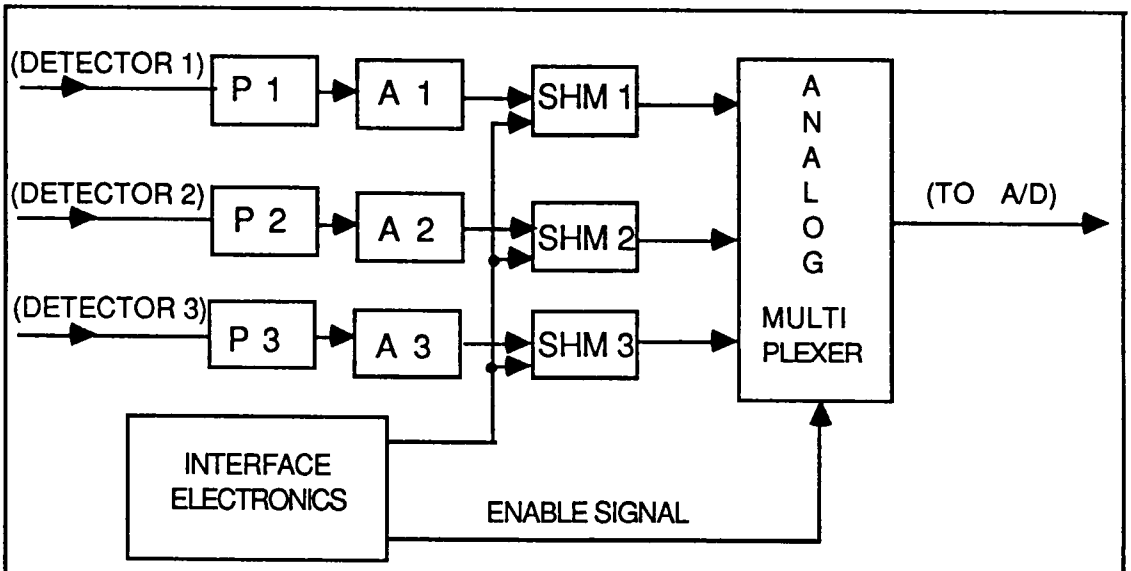


Figure 13. Block diagram of electronics for converting data from 3 element linear array into single stream data

velocity of propagation, are expected to give different temperature profiles. There is, however, no change in the electronics configuration.

1. Electro-optical System:

Assuming the specifications of the single element pyrometer for spatial resolution and noise equivalent temperature difference (NEΔT), a three element linear array will give a scan line having a width of 0.3 mm when the array is perpendicular to welding velocity. Hence the focusing lens has to be of high optical quality over this field of view. The energy calculation then remains the same.

2. Data Acquisition System:

The data acquisition system for a pyrometer using a linear array detector is explained using Figure 13. Since the maximum data rate of the Masscomp is 400 kilosamples per second, this allows a maximum chopping frequency of 66 kHz, thus giving a temporal resolution of 15.15 μs. The signals from three detector-preamplifier devices are separately amplified and then sampled at the same instant of time in three sample and hold devices, thus assuring instantaneous voltage signals from three detectors. These signals are available at the multiplexer and are sequentially read out and recorded on the Masscomp computer as 12 bit digital data.

B. Pyrometer Using An Area Array:

Figure 14 shows a temperature mapping using a 3 $\times$ 3 element area array detector, placed at the focal plane of a lens collecting weld-pool radiation and Figure 15 shows its data acquisition system. The 9 pixels are mapped, three

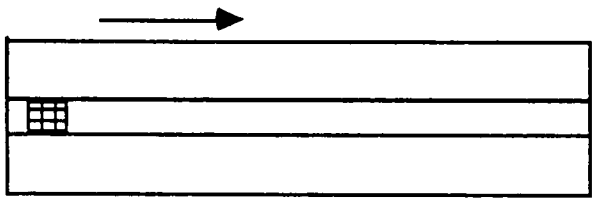


Figure 14 . Sampling the weld surface for temperature using 3 by 3 area array of detectors

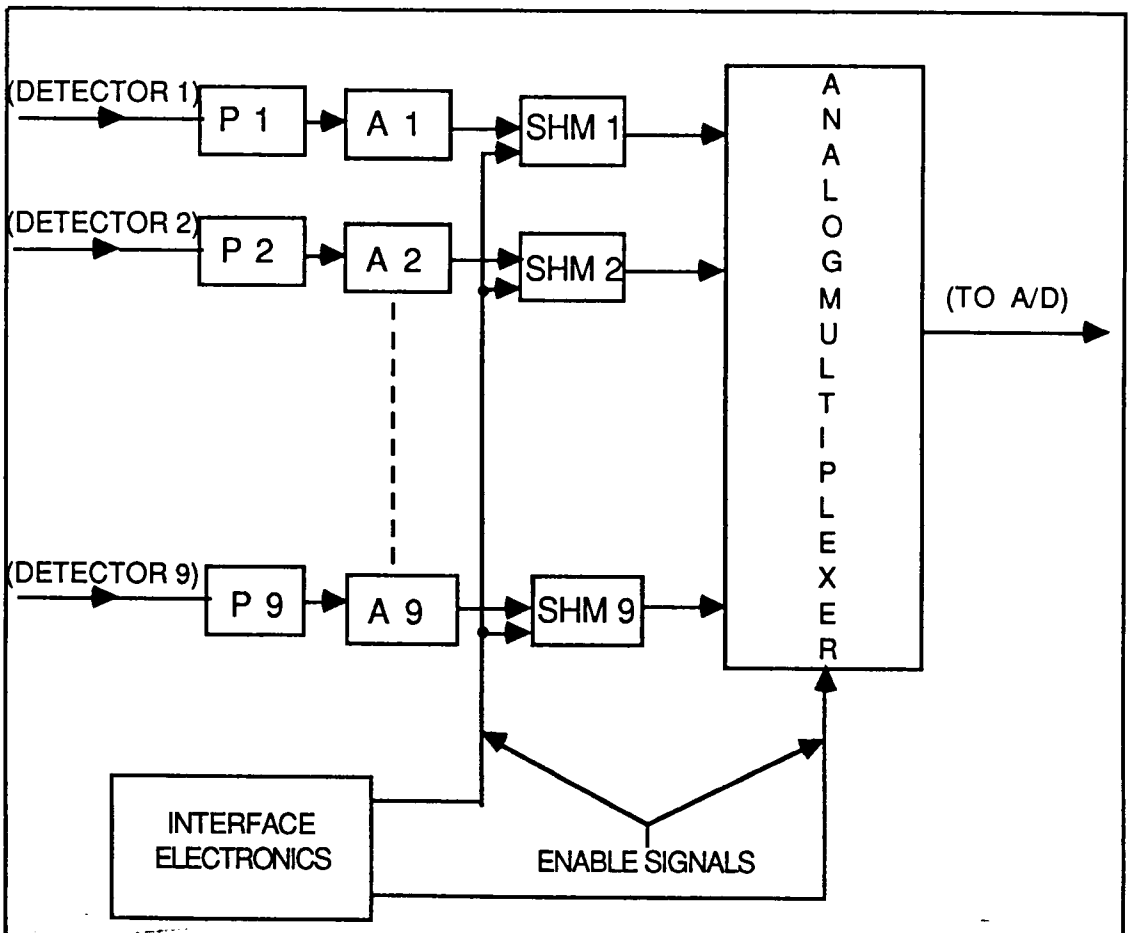


Figure 15. Block diagram of electronics for converting data from 3 by 3 area array detectors into single stream data.

perpendicular to the weld direction and three along the weld direction. Thus the combined effect of a perpendicular (Figure 11) and parallel (Figure 12) linear array detector is available as a single detector.

1. Electro-optical System:

Again, assuming the specifications of the single element pyrometer for spatial resolution and NEΔT, a 3 $\times$ 3 area array will give an image size of 0.3 mm $\times$ 0.3 mm at the focal plane of the focusing lens (Figure 3). Hence this area has to be aberration free. The energy calculation then remains the same.

2. Data Acquisition System:

The data acquisition system for a pyrometer using an area array detector is shown in Figure 15. Given that the maximum data rate of the Masscomp is 400 kilosamples per second, this allows a maximum chopping frequency of 22 kHz and a temporal resolution of 45.45 μs. The signals from nine detector-preamplifier devices are separately amplified and then sampled at the same instant of time in nine sample and hold devices, thus assuring the instantaneous voltage signals from nine detectors. These signals are available at the multiplexer and are sequentially read out and recorded on the Masscomp computer as 12 bit digital data.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATION

In chapter 3, a detailed design of a single element pyrometer for temperature measurements of a weld-pool and details of its electro-optical and data acquisition subsystems were presented. In chapter 6 this design concept was extended to obtain the temperature of a wider area of a weld-pool by using linear or area array detectors. In all the designs, every temperature measurement of a weld-pool is done considering the surface emissivity, thus making every temperature estimate a true temperature. The design systems are mechanically interfaced with Rofin-Sinar-3000 laser welding system and temperature data is recorded on Masscomp computer. The pyrometer design using array detectors images a wider area of the weld-pool compared to the pyrometer design using a single element detector. Though the temporal resolution for an area array (45.45 μs) is poor compared with a single element detector (20 μs), the area array pyrometer has greater potential for detecting welding faults like microfissures.

A. Conclusions :

The designs presented can measure temperatures over a range of 300 °C to 2500 °C with a spatial resolution of 100 μm $\times$ 100 μm and a temperature resolution of one degree centigrade. The temporal resolution is found to be 20 μs for a single element pyrometer, 15.15 μs for a pyrometer using a linear array and 45.45 μs for a pyrometer using an area array detector. The data rates are 100 kilosamples per second for a single element pyrometer and 400 kilosamples per second for the either the linear or area array pyrometer.

The reason for limiting the spatial resolution to 100 μm was to study the solidification properties of materials at low temperatures (300 °C). The design clearly shows the possibility of increasing the spatial resolution by increasing the optical aperture without adversely affecting the CO_2 laser's welding properties. Also the spatial resolution could be increased by extending the lower temperature limit, say to 500 °C.

The present design is valid for the pulsed-laser mode of operation only. It is not possible to temperature map the weld-pool in the cw mode due to the high temperature plasma present between the weld-pool and the high power laser beam. No attempt has been made to solve this problem.

B. Recommendation:

Fabrication of a pyrometer based on one of the designs presented is recommended. The single element pyrometer is the most simple to make. However the fabrication of a pyrometrer using an area array would give more representative temperature of the weld-pool area. The only verification needed is to determine the lens aberration characteristics which could be tolerated at the image field of view. Once this is confirmed an appropriate lens may be selected and a pyrometer using an area array may be constructed. The electronics is fairly easy and manageable. At present the only high cost item is the beam combiner BC_1. Its cost estimate varies from $ 7,500 to $ 15,000. However this area needs more market survey and more detailed study to find an alternate way for achieving the function of this beam combiner. The Masscomp computer is available within CLA.

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APPENDICES

APPENDIX A

CLA CO_2 LASER

The Center For Laser Applications has Rofin-Sinar-3000, RF excited, fast axial flow, industrial CO_2 laser. This laser has maximum power of 3.6 Killo Watts and can be operated in cw or pulsed-laser mode. Figure A1 shows the schematic diagram of a laser. In Figure A2 this schematic is achieved in RS 3000 by using 4 separate laser tubes and coupling them optically. This enables better control of laser operation.

The laser, though named a CO_2 laser, actually uses a gas mixture (50 % He + 10 % CO_2 + 40 % N_2) at 95 torr, to hvae a sustaied laser action. The gas mixture enters the laser tube from the inlet. The exhaust from the gas mixture, after the laser action, is pumped out from the outlet, purified, cooled, refurbished and recirculated in the laser tube at constant pressure. Thus the gas inside the tube is maintained at constant pressure. RF power at 27 MHz is applied to the laser tube through RF coil which heats the gas mixture and creates the necessary excitation for laser action in the tube. The rear mirror of the laser tube has 98% reflectance and the output coupler has a reflectance of 65%.

When RF power is applied to the laser tube, sufficient number of CO_2 molecules are transferred to an excitation state at a higher energy level. They remain in this state for a very short time and settle to the lower energy states called metastable states, due to comparatively larger duration of these states. For the case of CO_2 there are two metastable states. During this transition from higher to lower energy level, CO_2 molecules emit multiples of quantum energy (integral multiples of $h\nu$). Due to two metastable states, energy is emitted at two wavelengths, namely 10.6 μm and 9.6 μm. The bulk of the energy emitted from a CO_2 laser is at 10.6 μm. This energy is coherent and almost monochromatic ($\Delta\lambda$ = few nanometers) due to laser characteristics. The intensity of the laser beam is increased by optimizing the length of the laser tube and giving an optical feedback by using two parallel semireflecting mirrors at the two ends of the tube.

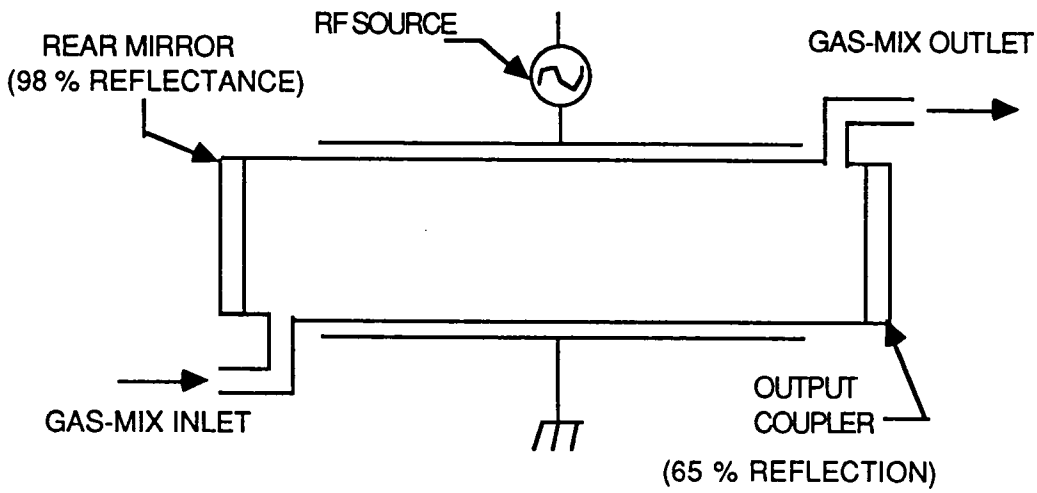


Figure A1. Schematic diagram of Rofin-Sinar-3000 laser system

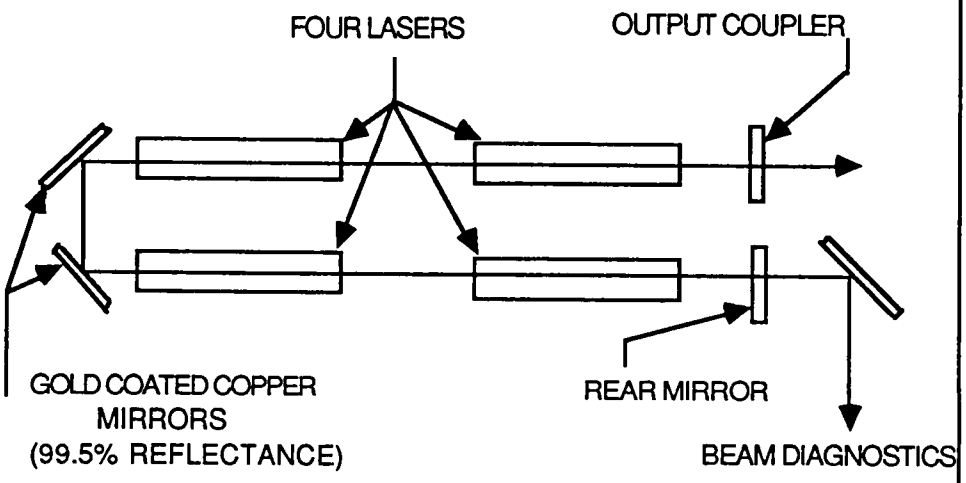


Figure A2. Realization of Rofin-Sinar system using four optically coupled CO_2 lasers

In the Rofin-Sinar-3000 laser system, instead of using a single tube for laser action, 4 separate laser tubes are optically coupled as shown in the figure A2. Table A1 gives the characteristics of the laser system.

Table A1. Characteristics Of CLA's Rofin-Sinar-3000 Laser System

Parameter	Value
Wavelength	10.6 μm
Maximum Output Power	3.5 kWatts
Peak Power	20 kWatts
Beam Diameter	20 mm
Beam Divergence	2 milliradian
Beam Polarization:	45° From The Laser
	Circular At The Welding Head
Modes	TEM 00, TEM 01, TEM 10

APPENDIX B

COMPONENT LIST WITH ESTIMATED COST

List of the important components with their estimated cost is given below.

Table A2. Estimated cost of the components.

Item	Cost ($)
Beam Combiner BC_1	750
Beam Combiner BC_2	7,500
Low Power Laser	1,500
Chopper Assembly	1,500
Collimating Lens	750
Focussing Lens	750
InAs detector	1,500
Matched Preamplifier	1,500
Calibration Black-body	1,200
Reflection Standard	2,000
Electronics Components	2,000
Total	20,950

VITA

Ekanath F. Nikhade was borned in Seloti, Maharashtra, India. After completing Primary and Secondary education he completed M. Sc. in Physics from Nagpur University, Nagpur, India. After working as a lecturer in Physics at D. N. College at Nagpur he joined I.I.T. Bombay in 1965 for M. Tech. in Applied Electronics where he designed and fabricated an instrument for corrosion studies, under the title "Design And Performance Of Transistorised Potentiostat". From 1967 till 1982 he worked with the Space Applications Center at Ahmedabad, India, where he designed and built various electronic and electro-optical instruments for remote sensing applications. In 1982 he joined the Brazilian Space Agency where he worked on developing electro-optical sensors.

He joined University Of Tennessee Space Institute at Tullahoma in January 1987 and in August 1989, completed all the requirements to graduate with a Master Of Science degree in Engineering Science.