3.1 PT Imaging

Photothermal techniques, which employ localized optical excitation require laser scanning if different regions of a sample are to be analyzed in a systematic manner. This method of PT scanning or imaging enables the depiction of the spatial distribution of thermophysical properties of the material under consideration. The dependence of the PT signal on the surface and subsurface features of electronic and non-electronic solids has led to many advances in non-destructive evaluation (NDE) of materials via PT imaging [1-6].

In late 1970's, PA imaging was proposed as an outcome of the celebrated Rosencwaig-Gersho theory, which showed that variations in the thermal effusivity of different media or layers influence the amplitude and phase of the signal. In 1978, Wickramasinghe et al. realized the first PA microscope operating at 840 MHz, which was a well refined application of the PA elastic wave generation method proposed by Gutfeld and Melcher in 1977. They successfully imaged the chromium pattern on a glass strip. In 1978, Wong et al. demonstrated a PA microscope operating at 2 kHz employing gas microphone detection and they investigated the cracks that plague silicon nitride ceramic materials. The first systematic analysis of PA imaging with the support of a three-dimensional thermal diffusion model was presented by Thomas et al. in 1980. A one-dimensional theory for general TW depth profiling was introduced by Ospal and Rosencwaig in 1982, which provided expressions for the surface temperature as a function of the thermo-elastic response of the subsurface. Using infrared detection scheme, Busse in 1982, depicted subsurface holes in an aluminium specimen and compared the result with that of PA
imaging. A three-dimensional model for PT depth profiling was suggested by Ospal et. al in 1983, which found application in the thickness measurement of transparent and opaque thin films with high spatial resolution. TW scattering from a closed slanted crack was investigated both theoretically and experimentally by Grice et. al. in 1983 and they compared PA and OBD response in the light of NDE applications [7-13].

By 1990, different PT imaging techniques based on OBD, PTR and MOR were proposed for the subsurface microscopy of fibers, films, coatings, composites, optical components and semiconducting materials and devices. Advances in inverse problem theory accelerated the industrial importance of PT tomography. Meanwhile, time domain transient thermal NDE yielded the complete PT response spectrum of a test sample eliminating the need for finding the optimum frequency as done in the frequency domain analysis. Transient IR detection gained industrial acceptance and has been in use for large area analysis; excitation is with flash lamps, detection being done with an IR camera, which is frame synchronized by lock-in principle [14-20].

The last decade witnessed swift emergence of PT imaging in key areas like biomedical tomography, semiconductor metrology, depth profilometry, slice tomography etc. Imaging of blood vessels, skin abnormalities and mammography are a few areas where this unique technique succeeded as an alternative to radio wave methodologies. Depiction of buried device layers, surface and subsurface defects in wafers, cleanness and contamination of substrates and spatial variation of transport parameters have been realized with extreme spatial resolution using semiconductor PT diagnostics tools. Depth profilometry has found widespread applications in the thermophysical analysis of inhomogeneous media [21-30].

In PT imaging, the sample is scanned across the modulated pump in a sequential manner to expose the entire area of interest to radiation and the PT signal from each point is collected for further analysis. The scanning process can be
accomplished either by moving the sample across the pump or by sweeping the laser spot over the stationary sample. Each method has its own merits and flaws depending on the detection scheme employed. This chapter deals with the design, development and performance evaluation of a completely automated PT scanner in the stationary-laser configuration.

3.2 Design and Development of the PT Scanner

The PT scanner in our imager is an assembly of

1. A modulated laser diode (LD) for optical excitation
2. An X-Y translation stage with micrometer vernier
3. Two computer controlled stepper motors for stage scanning
4. Interface circuits and associated software for automating the scanner and
5. PA, OBD and PTR detection units

The details of each module is discussed below

3.2.1 Design and Development of a Modulated Diode Laser

Laser diodes are efficient substitutes of gas lasers in the sense of physical size and power consumption. The progress in semiconductor technology during the last decade has yielded LDs of excellent beam and spectral qualities comparable with those of other laser sources and many of the optical research fields exploit them successfully. Even so, these devices have not yet gained considerable role in PT experiments as optical pump. In the development of our PT imager, the use of a LD is beneficial in reducing the cost, physical size and power consumption. Again, the feasibility of direct modulation eliminates the need of an external optical chopper [31-33].

LDs are current operated devices whose optical output is proportional to the forward current. As the forward current is increased, lasing action starts at a critical current \( I_0 \) (Fig. 3.1) called ‘threshold current \( I_0 \)’ and thereafter the current-power
linearity is maintained until the guaranteed maximum operating current \( I_m \) is reached. Above this value the device is permanently damaged. These devices are highly delicate in the sense that exceeding the maximum permitted current even for a microsecond can damage them. Usually, spikes associated with ordinary power supplies are very dangerous in this regard. Even with battery operation, the ON/OFF current surge is found to destroy LDs. So they are powered using a constant current source (LD driver), which is insensitive to the input overshoot.

![Diode Circuit Diagram](image)

**Fig. 3.1** *Variation of output power against the forward current of a laser diode.*

The most important driver design parameter is the maximum constant current it can supply, which is a function of the diode forward resistance. Fig. 3.2 is the circuit diagram of the designed modulated LD driver. Circuits around U1, U2 and Q1 form a grounded-load constant current source whose output current is:

\[
I_L = \frac{R_f V_1}{R_i R_s} \quad (A)
\]

3.1

This current drives the LD [34]. Shunting MOSFET Q4 causes sinusoidal negative modulation of optical intensity without exceeding the preset peak power of the LD.
Usually, output power of LDs increases with temperature and stabilization of optical intensity against temperature is necessary in scientific applications. One method is to use thermo-electric coolers to stabilize the diode temperature. As a more convenient and economical method, LDs are fabricated with a built-in photodiode (PD) whose reverse current is proportional to the laser intensity. This current is sampled and used as an error signal for correcting the laser current in a negative feedback manner. This scheme is called automatic power control (APC). At low modulation frequencies (typically a few Hz), the integration time required by the sampling circuit is long, leading to large overshoots in the laser current, which may permanently damage the diode. Since some PT applications involve low frequency excitation, the APC control is not found suitable. In our scheme, the error signal is recorded and correction is applied on the data. U3 and U4 sample the PD current for correction. The load current is adjusted using V1 and threshold current

**Fig. 3.2**  Constant current laser diode driver. All current determining resistors are of 0.1% tolerance.
(DC bias) using V2. The soft-start circuit (Q2 and Q3) ensures protection from ON/OFF transients.

Fig. 3.3 *Spectral response of the laser diode at 30 mW power, recorded at 28 °C using Ocean Optics PC 1000 spectrometer.*

Fig. 3.4 *Thermal drift in the output power, which is set to 30 mW at 20 °C.*
The maximum possible diode current is about 200 mA with the present circuit and it can be delivered up to a load of about 60 Ω. We have used LNCQ-05 PS (Panasonic) LD (660 nm, 70 mW) whose operating current is 75 mA and threshold current is 35 mA. At 1 kHz, about 95% sinusoidal modulation is achieved with 0.4 V (peak to peak) signal when V1 is 2V. Over a frequency band of 1 Hz to 50 kHz, the total harmonic distortion is below 2%, at 100 kHz it is about 3.5% and is about 6% at 150 kHz. A multi-element glass lens with numerical aperture of 0.476 is used for collimation (Optima LDM 3756). For extreme safety of the LD, the circuit should be powered with a battery and Q4 should be replaced with a linear opto-coupler. We have used a battery powered signal generator to bypass the later.

The operating current is adjusted using a 10 turn wire-wound potentiometer fitted with a vernier calibrated against laser power. In Fig. 3.3, spectral characteristics of the output are shown and the output drift with temperature is recorded over 20-50 °C (Fig. 3.4). The unit has been continuously operated for 240 hours at 25 (±3) °C and the maximum drift observed is about 4%; stability is maintained within 0.1% on applying correction. The beam aspect ratio is 1.3 and the beam size specified everywhere in this thesis is the average of the two diameters.

3.2.2 Automated Sample Scanner

In our PT imager, we have adopted the scheme of scanning the sample in the X-Y plane against a stationary laser beam. The advantages of this method over scanning laser technique are (1) in OBD and PTR, the distance between the point of excitation and the detector remains fixed, (2) fixed pump shaping optics (focusing lens or beam expander) can be used and (3) the angle of pump incidence remains unchanged, during scanning. Its major drawback is that the movement of the platform induces considerable sample vibration leading to undue noise in PA detection [35, 36].
The translation stage is a conventional commercial unit. Two stepper motors of 1.8 degree/step are used for its automation as shown in Fig. 3.5. The platform is fixed and the motors are controlled through the printer port of a computer. The scanner interface circuit is shown in Fig. 3.6.

Fig. 3.5  **Sample scanning stage, controlled using stepper motors.**

Fig. 3.6  **Circuit of the printer port interface for motors and ADC.**
All the three registers with base addresses 378 H (data register), 379 H (status register) and 37A H (control register) available at the printer port are used for the automation of the scanner. We have used an 8-bit analog to digital converter (ADC) to read the lock-in outputs. The data is read as two nibbles through 379 H. Input selection (in-phase/quadrature) and nibble selection are controlled through 37A H. The data register 378 H provides an 8-bit data, each nibble of which controls a stepper motor. For ±2.000 V full-scale input, the ADC sensitivity is about 0.015 V. The translation stage displaces through 500 µm for 360 ° rotation along the X and Y direction yielding a spatial resolution of 2.5 µm with the used motors [37].

3.2.3 Software for Scanner Automation

Sample scanning is accomplished in such a way that the laser beam is first located at a point with coordinates (x=0, y=0) and the PT signal is recorded. Then the beam irradiates the next point (x=1, y=0). If there are M such points in the X direction and N points in the Y direction, then the last point on this line scan is (x=M-1, y=0). Now the spot is located at (x=M-1, y=1) and retraced along the X direction. This action is repeated for irradiating the entire area of interest of the sample. The program accepts step resolution and distance to be traced along X and Y directions and the lock-in time constant. The later is used for setting the delay between each step; 5 times the time constant is set as the delay to ensure sufficient settling time.

The program is written in Turbo Basic and compiled as ‘Imager.exe’ file. The PT data is saved in the file named by the user and is stored as ASCII data.

CLS
SCREEN 9
LOCATE 12,42
COLOR 9
PRINT "PHOTOTHERMAL IMAGER CONTROL PROGRAM"
COLOR 2

LINE (13,0)-(635,315), 13,B
LINE (20, 4)-(300, 310), 14, B
LINE (18,2)-(302,312),11, B
LINE (310,2)-(630,50), 11, B

LINE (30, 10)-(290, 50), 3, B
LOCATE 2, 6
PRINT "X-Resolution (µm)"

LINE (30, 60)-(290, 100), 3, B
LOCATE 6, 6
PRINT "X-Distance (µm)"

LINE (30, 110)-(290, 150), 3, B
LOCATE 9, 6
PRINT "Y-Resolution (µm)"

LINE (30, 160)-(290, 200), 3, B
LOCATE 13, 6
PRINT "Y-Distance (µm)"

LINE (30, 210)-(290, 253), 3, B
LOCATE 17, 6
PRINT "Time Constant (s)"

LINE (30, 260)-(290, 303), 3, B
LOCATE 20, 6
PRINT "Output File Name [ASCII]"

LOCATE 3, 7
INPUT a10%
LOCATE 7, 7
INPUT b10%
LOCATE 10, 7
INPUT c10%
LOCATE 14, 7
INPUT d10%
LOCATE 18, 7
INPUT Z
LOCATE 21, 7
INPUT Y$

OPEN Y$ FOR OUTPUT AS #1

r10%=a10%/10
x10%=b10%/a10%-1
y10%=c10%/10
z10% = d10% / c10% - 1

p10% = 0

1 gosub adc

p10% = p10% + 1
n10% = 0
10 n10% = n10% + 1
m10% = 0
20 m10% = m10% + 1
out &h378, 90
delay 0.2
out &h378, 86
delay 0.2
out &h378, 85
delay 0.2
out &h378, 89
delay 0.2
if m10% < r10% then
goto 20
else
gosub adc

end if
if n10% < x10% then
goto 10
else
end if
if (p10% - 1) < z10% then
gosub yscan
else
end
end if

gosub adc
50 p10% = p10% + 1
n10% = 0
100 n10% = n10% + 1
m10% = 0
200 m10% = m10% + 1
out &h378, 89
delay .2
out &h378, 85
delay .2
out &h378, 86
delay .2
out &h378, 90
delay .2
if m10%<r10% then
goto 200
else
gosub adc
end if
if n10%<x10% then
goto 100
end if
if (p10%-1)<z10% then
gosub yscan
goto 1
else
end
end
end
end
end
end
yscan:
o10%=0
30 o10%=o10%+1
out &h378, 153
delay .2
out &h378, 169
delay .2
out &h378, 105
delay .2
out &h378, 89
delay .2
if o10%<y10% then
goto 30
end if
return

adc:
W = 0
Design and Development of an Automated PT Scanner

\[ W = W + 1 \]

\[ \text{OUT \&H37A, 2} \]
\[ \text{delay } Z \]
\[ A = \text{INP(\&H379)} \]

\[ \text{OUT \&H37A, 6} \]
\[ \text{delay } Z \]
\[ B = \text{INP(\&H379)} \]

\[ \text{OUT \&H37A, 1} \]
\[ \text{delay } Z \]
\[ C = \text{INP(\&H379)} \]

\[ \text{OUT \&H37A, 4} \]
\[ \text{delay } Z \]
\[ D = \text{INP(\&H379)} \]

\[ A1\% = A \text{ AND } 16 \]
\[ \text{IF } A1\% = 0 \text{ THEN } A2\% = 0 \text{ ELSE } A2\% = 1 \]

\[ B1\% = A \text{ AND } 32 \]
\[ \text{IF } B1\% = 0 \text{ THEN } B2\% = 0 \text{ ELSE } B2\% = 1 \]

\[ C1\% = A \text{ AND } 64 \]
\[ \text{IF } C1\% = 0 \text{ THEN } C2\% = 0 \text{ ELSE } C2\% = 1 \]

\[ D1\% = A \text{ AND } 128 \]
\[ \text{IF } D1\% = 0 \text{ THEN } D2\% = 0 \text{ ELSE } D2\% = 1 \]

\[ P = (8 \times D2\% + 4 \times C2\% + 2 \times B2\% + A2\%) \]

\[ E1\% = B \text{ AND } 16 \]
\[ \text{IF } E1\% = 0 \text{ THEN } E2\% = 0 \text{ ELSE } E2\% = 1 \]

\[ F1\% = B \text{ AND } 32 \]
\[ \text{IF } F1\% = 0 \text{ THEN } F2\% = 0 \text{ ELSE } F2\% = 1 \]

\[ G1\% = B \text{ AND } 64 \]
\[ \text{IF } G1\% = 0 \text{ THEN } G2\% = 0 \text{ ELSE } G2\% = 1 \]

\[ H1\% = B \text{ AND } 128 \]
\[ \text{IF } H1\% = 0 \text{ THEN } H2\% = 0 \text{ ELSE } H2\% = 1 \]
Q = 128 * H2% + 64 * G2% + 32 * F2% + 16 * E2%

R = P + Q
U = ((4 * R) / 256) - 2

I1% = C AND 16
IF I1% = 0 THEN I2% = 0 ELSE I2% = 1

J1% = C AND 32
IF J1% = 0 THEN J2% = 0 ELSE J2% = 1

K1% = C AND 64
IF K1% = 0 THEN K2% = 0 ELSE K2% = 1

L1% = C AND 128
IF L1% = 0 THEN L2% = 0 ELSE L2% = 1

S = (8 * L2% + 4 * K2% + 2 * J2% + I2%)

M1% = D AND 16
IF M1% = 0 THEN M2% = 0 ELSE M2% = 1

N1% = D AND 32
IF N1% = 0 THEN N2% = 0 ELSE N2% = 1

O1% = D AND 64
IF O1% = 0 THEN O2% = 0 ELSE O2% = 1

P1% = D AND 128
IF P1% = 0 THEN P2% = 0 ELSE P2% = 1

T = (128 * P2% + 64 * O2% + 32 * N2% + 16 * M2%)

X = S + T
V = ((4 * X) / 256) - 2

locate 2,41
COLOR 4
PRINT U, V

WRITE #1, U, V

return
3.2.4 PA Detection Unit

The imager is equipped with PA, OBD and PTR techniques and the details concerning the development of each are discussed.

The PA cell is of non-resonant type made up of aluminum plates (P1 and P2) as shown in Fig. 3.7. The pressure sensor is a miniature condenser microphone (M) used in mobile phones (Motorola T190). The glass window (G) for illuminating the sample (S) is glued to the upper plate to which M is attached. The upper and lower plates are separated using a rubber ring (R) [38, 39].

![Cross-section of the PA cell used for our investigations.](image)

3.2.5 OBD Setup

The change in the refractive index of a heated material or the fluid in contact with it can be written as:

\[
\frac{\Delta n(r,t)}{n_0(r,t)} = \frac{1}{n_0(r,t)} \frac{dn(r,t)}{dT} \Delta T(r,t)
\]

The deflection of an infinitesimally narrow probe beam passing through a refractive index gradient is given by:

\[
D = \frac{1}{n} \frac{dn}{dT} \int ds \nabla T(r,t)
\]
which has two components, normal ($D_n$) and transverse ($D_t$). The transverse component is zero at the center of the pump where the temperature gradient is zero. This component also vanishes for one-dimensional heating. The normal component is sensitive to the heat flow normal to the sample surface. For one-dimensional illumination of an opaque semi-infinite sample for which the transverse component vanishes, the normal component is:

$$D_n = (1 - R(\lambda))I_0 \frac{L}{n} \frac{dn}{dT} \frac{\sigma_f}{2k\sigma} \exp(-\sigma_f z)$$

in which $L$ is the interaction length of the probe in the refractive index gradient, $\sigma_f$ is the thermal wave number of the heated fluid medium and $z$ is the vertical offset of the probe beam. For fixed interaction length, the parameters strongly influencing the magnitude of deflection are the refractive index coefficient, the thermal diffusivity that determines $\sigma_f$ and the probe offset. Usually, using carbon tetrachloride ($\text{CCl}_4$) as the medium is found to amplify the signal 1000 times compared to air. The detection of the probe beam deflection is done using a quadrant photodiode (RS 652-027), in a differential manner to minimize probe intensity fluctuations [40, 41].

Fig. 3.8 Schematic diagram of the OBD technique for the detection of photothermal signal.
Following conventions, we tried with a low power helium-neon (He-Ne) laser (Oriel, 632.8 nm, 0.95 mW) as the probe. In our PT analyzer, its inclusion imposed the following problems:

1. The beam diameter is about 700 µm, which required tight focusing if the pump is well focused as in PT microscopy. Therefore, the beam diverges to large angles and the detector has to be kept close to the sample to accommodate the probe totally. This necessitated the use of a costly optical filter to block the pump component.

2. The power consumption of a He-Ne laser is high and

3. The unit has built in power supply (2000-3000 V) and keeping it close to the pump (diode laser) may cause damage of the later.

As a solution to the above problems, we propose a simple, inexpensive and novel type of OBD probe unit with a laser pointer (Fig. 3.9).

![Fig. 3.9](image)

*The probing technique developed for our PT imager.*

Most of the laser pointers we examined have a narrow waist (100-500 µm diameter) 10-50 cm away from the collimating lens. Also, the beam divergence is comparable with that of a He-Ne laser. The availability of a well-constricted waist and small divergence without the use of additional optical components make them suitable for the use as a probe beam. Generally, laser pointers are intended for interrupted uses only and they cannot maintain constant output intensity for a long
time. We have observed that the intensity falls abruptly after 2-3 minutes of continuous powering. We have studied the output stability for different currents and observed that at a critical current the intensity remains steady for a long time. Most of the pointers we tried had been preset (by the manufacturer) to consume about 15 mA and the critical current was found within 7-10 mA. Below this value the intensity increases first and shows an oscillatory response for continuous operation. Since the manufacturing details of these devices are not available, we are unable to account for the mechanism at present.

The pointer we have selected has a waist of about 100 µm located 22 cm away from the collimator. We removed the built in driver and powered with a current regulator similar to that used in the pump laser. The critical current is found to be 7.2 mA and the output (0.2 mW) stability is found to be within 2% over 24 hours of continuous operation. In order to avoid a pump filter, the detector is placed 3 m away from the sample and the probe is focused to the detector. The quadrant detector has metallurgical separation of 200 µm between active elements. This passive region is considerably large in the case of a focused spot (<500 µm diameter) and is a cause of poor sensitivity when the intensity is low. As a solution, we have used a front-coated prism with sharp edge (about 40 µm) of angle 145° and two photodiodes each of active diameter 2 mm. Compared to the quadrant cell, the prism arrangement is more economical too.

A conventional PTR unit is employed for radiometry and its details are given in chapter 4.

3.3 Spatial Resolution of the PT Imager

As discussed in section 3.1, PT imaging is a well-explored technique as a means of subsurface microscopy of bulk and layered samples of practical importance. Principal features of PT imaging are:
1. The subsurface probe depth is limited to one diffusion length for amplitude while phase imaging extends the depth by more than 50%.

2. Vertical, closed cracks are not detectable in PA imaging, but are seen in OBD and PTR techniques.

3. The resolution of PT imaging is not determined by Raleigh criterion. Unlike most other microscopies such as optical, electron and ultrasonic, thermal wave images are formed in the extreme near field limit rather than the Fraunhofer limit.

4. Spatial resolution is determined by the pump and probe beam size and the depth and geometry of the defect (object) below the surface.

Inherent factors limiting the spatial resolution of our system are the limited pump power (low signal level) and the vibration of the unit (the imager is placed on a wooden table instead of a vibration isolated platform). Recent developments in PT microscopy have extended spatial resolution to nano-metric scale and such a high resolution is not practicable with our unit [5, 42]. The lack of a vibration independent reference and the facility to fabricate and manage micro structured samples make the exact determination of resolution impossible. So we concentrate to applications, for which the available resolution of our imager is sufficient.

We have made an attempt to check whether the imager can resolve a subsurface structure of 200 µm size. The selection of this size was on the basis of the availability of sample fabrication facilities and possible pump and probe dimensions. The sample (Fig. 3.10) was prepared by fabricating two rectangular pits (0.5x0.4 cm) separated by 200 (±25) µm in a brass piece (2x1x1 cm) such that the depth of each pit is 100 (±25) µm below the surface.

Early investigations on the resolution of PT imaging revealed that TW scatterers influence the signal considerably and their depth beneath the surface is a measure of the geometry of the image formed. As the depth increases, the scatterers modify the signal over a broader range and this happens if the thermal diffusion
length is large. This implies that at higher frequencies, the resolution is high provided that the object lies within a thermal diffusion length. Again, resolution is enhanced as $\mu/A$ increases ($A$ is the separation between the image and object planes).

![Sample used for resolution studies.](image)

We have made line scans, using mirage effect detection (normal component) in which the pump is focused to about 50 $\mu$m with 5 $\mu$m step size, over the defect at 60, 120 and 240 Hz modulation frequencies. The surface layer is thermally thin up to 1114 Hz. The PT amplitude response is plotted in Fig. 3.11. At 60 Hz, the thermal diffusion length in brass is about 430 $\mu$m and there is an extended region of TW scattering. At 240 Hz, diffusion length is about 215 $\mu$m and the scattering effect is smaller. Consequently the image becomes more geometrical at higher frequencies and resolution increases. Surface scanning was done at 25 Hz for which the thermal diffusion length in brass is about 670 $\mu$m. The surface plot is given in Fig. 3.12. According to the Rosencwaig-Gersho theory, the PT signal from the excavated region (thermally thin) strongly depends on the properties of the backing material, which is air in this case. In a qualitative manner, air offers considerable resistance to heat flow and therefore there is a rise in the PT signal compared to that from
Fig. 3.11  *PT amplitude response of the subsurface defect at different excitation frequencies.*

Fig. 3.12  *Spatial variation of the PT signal in thermally thin and thick regions.*
the region of separation. Air, a low effusivity medium compared to brass, gives rise to constructive interference due to TW reflection in this region.

Half power width of the curves gives the value of the wall thickness. It is clear from the analysis that 200 µm is resolvable and this value is taken as the resolution of our imager. The detected signal contains contributions not only from changes in the material parameters but also from scattering of PT waves from near field subsurface flaws. The widening of the curves is due to the separation between the object and image planes (near-field effect). At a given frequency, the image becomes more geometrical as this separation decreases so that the near-field image is captured [43, 44].

3.4 PT Imaging of Laminated Samples

Subsurface images can reveal poor adhesion, corrosion and voids in the substrate in the case of laminated specimen. For an optically opaque and thermally thin coating, the resulting PT signal is contributed by interference of thermal waves from the surface and subsurface boundaries. The reflection (R) and transmission (T) coefficients of a boundary of two materials are given by:

\[ R = \frac{1-b}{1+b} \]  \hspace{1cm} 3.5

\[ T = \frac{2}{1+b} \]  \hspace{1cm} 3.6

where \( b \) is the ratio of the thermal effusivities of the media. Since the resultant of the interfering waves depends on R and T, the thermophysical properties of the backing strongly influence the signal. In the case of substrate corrosion or the presence of air gaps, the spatial variation in the effusivity appears as a thermal image [45, 46].

For corrosion imaging, a surface polished soft iron piece (2x1x0.5 cm) was masked with an insulation tape and 5 holes were made on the mask using hot needles. The specimen was kept in water for a month, taken out and lightly polished
Fig. 3.13 (a) PT amplitude image of subsurface corrosion.
Fig. 3.13 (b)  PT phase image of subsurface corrosion.
after removing the tape. The sample was then spray painted to have a black enamel layer such that the corroded regions were optically unseen. Since the standard values of the thermo-physical parameters of the enamel were unavailable, a trial and error method was employed to confirm that the layer was thermally thin at 25 Hz. OBD detection scheme in which the probe and pump focused to about 100 µm was employed. Both amplitude and phase images (Fig. 3.13 a & b) reflect corroded regions. The phase analysis is sensitive to the layers lying deeper than one diffusion length and the higher contrast of Fig. 3.13 (b) may be due to the response of deep lying regions of wider corrosion.

3.5 Conclusions

An automated PT scanner, which uses stationary pump laser configuration, has been designed and developed. The maximum scan area is 5x5 cm² and resolution is 2.5 µm. The optical pump is a diode laser with maximum power of 70 mW at 660 nm, which can be modulated over a frequency range of 1 Hz to 150 kHz. This direct modulation eliminates the use of a costly electro-optic/acousto-optic light modulator. The scanner is equipped with PA, OBD and PTR detection units. The pump consumes about 2 W electrical power and is so flexible that its inclination can be altered over 180°. A simple probe unit has been devised for OBD detection, which replaces the conventional setup that employs a gas laser and differential photodiode. Software and necessary electronic hardware have been developed for automating the scanner through the printer port of a personal computer. Low pump power and the lack of a vibration isolated table limit the spatial resolution and we have observed that subsurface structure of 200 µm size can easily be resolved. The near-field effect in TW image formation has been demonstrated and the principle has been applied to the imaging of subsurface corrosion in painted layers.
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