Polychromatic Reflectometer with Laser Heating for Measuring Thermal Radiation Properties of Materials at High Temperatures[1]

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ABSTRACT

Thermal radiation properties of opaque materials strongly depend on their surface texture. In spite of this fact the methods for measuring reflectivity and emissivity of materials at high temperatures with laser heating technique don't take into account the influence of changing the studied sample surface under the intense laser beam on the results obtained.

In this connection a new reflectometer has been developed to measure thermal radiation properties of materials at high temperatures regardless of changing the sample surface texture during laser heating. The reflectometer based on the pulse diffuse irradiation of the sample surface under powerful laser beam has the vast capacities to measure thermal radiation properties of materials up to temperatures 4000 K and in the spectral range 0,4-1,1 μm with high precision. The principle of the pulse diffuse light probing of the sample surface heated by intense laser radiation to measure its thermal radiation properties at high temperatures has been suggested and realized in the experiment for the first time.

KEY WORDS: diffuse irradiation; high temperatures; integrating sphere laser reflectometer; laser heating technique; light probing; reflectometer; refractory materials; thermal radiation properties.

1. INTRODUCTION

Heating of materials for measuring their thermal radiation properties at high temperatures is being performed using different techniques. Among them the most advanced technique is laser heating technique since it has some unique peculiarities in this field of investigation [1].

There were a lot of attempts to measure thermal radiation properties of materials under intense laser irradiation but only in 1977 this task was correctly solved by Bober et al [2]. The main difficulty of this task was due to the necessity to collect all the radiation reflected from the flat sample probed by a reference light beam during laser heating in order to measure spectral directional hemispherical reflectivity and spectral directional emissivity and to determine the true temperature of the irradiated sample surface. Bober used the directional probing of the sample surface by additional light source and integrating sphere to collect reflected radiation in laser experiment. Temperature measurements were made with a high speed pyrometer working at the probing wavelength.

This method was called as integrating sphere laser reflectometer and became generally accepted instrument in investigation of thermal radiation properties of materials at high temperatures. To extend its capacitics the variants of this method were proposed by other investigators [3-5].

The second approach applied for measuring thermal radiation properties with laser heating technique is based on the specular reflection law [6]. Such an approach is suitable only for the materials with specular reflection surface (for example for molten materials). Up to now there are only two above mentioned approaches for investigation

of optical characteristics of materials at high temperatures with laser heating technique. Unfortunately both methods don't take into account the influence of changing the texture of material surface under powerful laser radiation though this effect is very significant at high temperatures..

Therefore our aim is to show that ignoring this effect may lead to serious experimental errors in measuring optical properties of solids with laser heating technique. Also a new approach has been developed in this area of investigation.

2. REFLECTOMETRY IN LASER EXPERIMENT

In measuring thermal radiation properties of solids at high temperatures with laser technics the flat sample is being heated by powerful laser beam in continuous regime up to high temperatures. Thermal radiation properties are being measured in dynamic regime of sample heating or its cooling when the sample temperature is recorded as a function of time. In this case open surface pyrometry is used for temperature measurements and reflectometry for determining thermal radiation properties.

Usually the traditional reflectometry is based on using the model sample with specular or diffuse reflection surface [7]. Integrating sphere reflectometers are applied for diffuse reflecting samples and specular reflectometers are used for specular reflecting sample (Fig.1). Also the nature of sample surface reflection is fixed in time of the measurements. The perfectly opposite situation is observed in laser experiment.

Optical diagnostics of sample surface heated by intense laser beam is being performed by directional radiation of additional light source. The radiation reflected from the sample surface is recorded by traditional methods or specular reflectometer for

specular sample surface or integrating sphere reflectometer for diffuse sample surface. But the texture of the sample surface heated by powerful laser radiation is being changed during experimental time due to sublimation, solid phase transformations, melting and other processes occuring at high temperatures. It means that the reflection indicatrix of sample surface is being changed during laser heating. The possible behaviour of the reflection indicatrix during the laser heating of the sample surface is presented in Fig.2.

Thus it is shown that the nature of the reflecting surface in laser experiment is not fixed and depend on the measurement time unlike traditional reflectometry.

In spite of great impotance of this fact nobody has taken into consideration this feature of reflectivity measurements in laser experiment up to now.

Therefore let us consider the capacities and limitations of reflectometers in laser experiment from this point of view.

a) Fig.3 shows the measurement scheme of specular laser reflectometer. Before the laser heating the polished sample surface has specular reflecting indicatrix. During laser heating the specular reflecting indicatrix is converted to mixed specular diffuse reflecting indicatrix. Since the reflectance and temperature measurements are made in the same fixed direction and reflection indicatrix is a function of time this manner is not suitable for accurate measurements of thermal radiation properties with laser heating technique. In [6] this scheme was suggested for reflectivity measurements of molten materials. Here it is to be noted that molten materials has mixed specular diffuse reflection surface.

b) Fig.4 shows the integrating sphere laser reflectometer [2]. The sample is placed in the centre of an integrating sphere. With a focused CO_2 laser beam the

temperature of the sample surface is achieved up to 4000 K within 1-100 ms. The reflected portion of the additional light beam directionally incident in the centre of the heated sample area is scattered by the integrating sphere and measured with an appropriate photodetector.

The temperature of the sample surface heated by the laser is determined by means of a fast micropyrometer looking into the integrating sphere. The directional - hemispherical reflectivity $\rho_\lambda(\Theta,2\pi,T)$ of the sample is obtained by additional calibration measurements where the sample is replaced by a perfectly reflecting mirror of the same size. The condition of sufficient opacity of the sample surface and Kirchhoff's law are used to evaluate the spectral directional emissivity $\varepsilon_\lambda(\Theta,T)$

$$\varepsilon_\lambda(\Theta,T) = \alpha_\lambda(\Theta,T) = 1 - \rho_\lambda(\Theta,2\pi,T) \qquad (1)$$

Here α_λ is the spectral absorptance, T is the true temperature of the sample surface.

The main assumption in this method is an assumption of uniform irradiation of the sphere wall. In this case the irradiance measured in any point of the sphere wall is proportional to the reflectivity of the sample studied. Also it was suggested that sample surface was fixed during laser heating. But as shown above this suggestion is not right. Therefore it is necessary to establish the boundaries of the application of the integrating sphere laser reflectometer for measuring thermal radiation properties of the materials at high temperatures.

It is known from the photometric calculations [8] that if the sample is in the centre of integrating sphere and the light beam is incident on the sample surface from the upper part of the sphere then the irradiance of the "lower" hemisphere is found from the formula (Fig.5):

$$E_{\lambda} = \frac{\rho\Phi_0}{4\pi R^2}\left\{\left[1-\sum_{j=1}^{m}\frac{f(\Theta_j)(1-\rho_j)S_j}{AR^2}\right]\frac{\rho^*}{1-\rho'}\right\} \qquad (2)$$

The irradiance of the “upper” hemisphere is equal to:

$$E_{up} = \frac{\rho\Phi_0}{4\pi R^2}\left\{\frac{4\pi f(\Theta)}{A}+\left[1-\sum_{j=1}^{m}\frac{f(\Theta_j)(1-\rho_j)S_j}{AR^2}\right]\frac{\rho^*}{1-\rho'}\right\} \qquad (3)$$

Here $f(\Theta)$ is the reflection indicatrix of the sample surface; Φ_0 - light flux; S_j - area of j-st hole in the sphere; ρ_j - value of the reflectivity of j - absorbing part in the sphere; $A \equiv \int_{\Omega} f(\Theta)d\omega$ - equivalent solid angle; R - sphere radius; ρ - reflectivity of the sample; ρ^* - reflectivity of the sphere coating; ρ' - effective reflectivity of the sphere.

The expressions (2) and (3) show that irradiance of the “lower” hemisphere is uniform over its surface while the irradiance of the “upper” hemisphere is variable and depends essentially on the reflection indicatrix of the studied sample surface. This is true when the reflection indicatrix is fixed in time of measurements. But in laser heating the reflection indicatrix of the sample surface is not fixed in time. So let us consider the influence of sample reflection indicatrix on the results obtained for an integrating sphere laser reflectometer.

The reading N_1 of the photodetector located in the lower hemisphere of the laser integrating sphere reflectometer is proportional to the irradiance of the sphere wall. Using the expression (2) we get (Fig.4)

$$N_1 = cE_{l,\lambda} = c\frac{\Phi_0\rho\ (\Theta,2\pi)}{4\pi R^2}\left[1-\frac{f_1(\Theta_1)S_1}{AR^2}-\frac{f_1(\Theta_2)S_2}{AR^2}-\frac{f_1(\Theta_3)S_3}{AR^2}\right]\frac{\rho^*}{1-\rho'} \qquad (4)$$

Where $f_1(\Theta_1)$, $f_1(\Theta_2)$ and $f_1(\Theta_3)$ are the values of the sample reflection indicatrix in the directions to entrance apertures for probing laser beam and for powerful laser beam

and the value of the sample reflection indicatrix in the direction to outlet for pyrometric measurement, respectively; S_1, S_2 and S_3 are correspondingly the entrance apertures area and the outlet area; c is a constant.

As mentioned above for calibration procedure the sample is replaced by a perfectly reflecting mirror of the same size. In this case the photodetector reading N_2 is determined from the equation

$$N_2 = cE_1 = c\frac{\Phi_0\rho_s}{4\pi R^2}\left[1-\frac{f_2(\Theta_1)S_1}{AR^2}-\frac{f_2(\Theta_2)S_2}{AR^2}\right]\frac{\rho^*}{1-\rho'} \tag{5}$$

Here ρ_s is the reflectivity of a standard sample. Then from Eq.(4) and Eq.(5) we get

$$\rho(\Theta,2\pi) = \frac{N_1}{N_2}\frac{\rho_s\left[1-\frac{f_2(\Theta_1)S_1}{AR^2}-\frac{f_2(\Theta_2)S_2}{AR^2}\right]}{\left[1-\frac{f_1(\Theta_1)S_1}{AR^2}-\frac{f_1(\Theta_2)S_2}{AR^2}-\frac{f_1(\Theta_3)S_3}{AR^2}\right]} \tag{6}$$

For perfectly reflecting mirror, (if $\Theta_1-\Theta_2 \cong 3-5^o$ then $f_2(\Theta_1)\cong 0$ and $f_2(\Theta_2)\cong 0$ one obtains instead of Eq.(6)

$$\rho(\Theta,2\pi) = \frac{N_1}{N_2}\frac{\rho_s}{\left[\,1-\frac{f_1(\Theta)S_1}{AR^2}-\frac{f_1(\Theta)S_2}{AR^2}-\frac{f_1(\Theta_3)}{AR^2}\,\right]} \tag{7}$$

Thus the spectral directional hemispherical reflectivity measured at high temperatures with an integrating sphere reflectometer is given by

$$\rho_\lambda(\Theta,2\pi,T) = \frac{N_1}{N_2}\rho_{s,\lambda}\left[\frac{1}{1-\frac{f_\lambda(\Theta_1,T(t))}{AR^2}-\frac{f_\lambda(\Theta_2,T(t))}{AR^2}-\frac{f_\lambda(\Theta_3,T(t))}{AR^2}}\right] \tag{8}$$

This equation shows that the spectral reflectivity dosn't depend only on the photodetector readings (N_1, N_2). Also knowledge of the temperature dependence of

sample surface reflection indicatrix in the directions to Θ_1, Θ_2, Θ_3 is required to obtain the spectral reflectivity. Up to now all the researchers who used an integrating sphere laser reflectometer [2-5] did not take into account the changing of surface reflection indicatrix f(Θ,T) during laser heating and calculated the reflectivity by a formula

$$\rho_\lambda(\Theta, 2\pi, T) \sim \frac{N_1}{N_2}\rho_{s,\lambda} \tag{9}$$

which is right when the sample surface has specular or diffuse reflection surface and its reflection indicatrix does not change during laser heating.

Such a suggestion may lead to uncorrect results for materials with mixed specular diffuse reflection surface and for materials which strongly change their own reflecting surface under powerful laser radiation.

On the basis on the proposed analysis one may draw a conclusion that the laser reflectometers applied up to now don't take into consideration the changing of the sample surface texture during laser heating and that may lead to great errors of the measurements especially at phase transition points when the sharp change of reflection indicatrix takes place.

Therefore we suggest another approach for measuring thermal radiation properties of the materials at high temperatures with laser heating technique.

In photometry there is a procedure for measuring the optical properties of the materials, regardless of the sample texture. In order to exclude the influence of the reflection surface indicatrix on the results obtained it is necessary to create diffuse hemispherical irradiation of the sample surface [9,10]. Diffuse irradiation of the sample surface heated by laser radiation enables one to measure the spectral reflectivity for any

kind of sample, to eliminate the influence of changing the irradiated surface during laser heating on the results obtained and to get the reliable data on thermal radiation properties of the advanced materials at high temperatures. In this paper we present a new reflectometer with laser heating technique for measuring the thermal radiation properties of materials with arbitrary reflection surface indicatrix at high temperatures.

3. METHOD

Experimental set up is shown in Fig.6. Flat sample is located in the centre of an integrating sphere of 180 mm diameter. The internal sphere wall is coated with 6mm porous fluorocarbon which has ideal reflection and diffuse properties in 0.3-2.5 μm range (according to data of NBS USA). The sphere is provided with two holes for the powerful laser beam input and for the observation of the sample radiance by means of ten wavelength pyrometer operated in 0.4-1.1 μm spectral range.Hermetic sphere provides pressure of the pure inert gas in it about 3 bar to suppress the sample evaporation at high temperatures.

By means of a focused CO_2 laser beam of 1000 W power the sample can be heated up to temperatures above 4000 K during 10-150 ms. The baffles placed near the sample divide the sphere into the upper and lower parts. In the upper part of the sphere three pulse flash-lamps provided with high voltage supply are placed. This location of the flash-lamps provides perfect diffuse irradiation of the sample surface (it will by explained further in detail). The flash-lamps perform the probing of the sample surface by the pulse-diffuse polychromatic radiation in the sample heating with the monochromatic radiation of the powerful CO_2 laser. When one of the lamps starts to operate polychromatic light, multipliedly reflected from the internal sphere wall makes the

diffuse irradiation of the heated sample surface. Pulse polychromatic light reflected from the sample surface is recorded by a ten-channel high-speed pyrometer at the various wavelengths. The pulse reflection signals on the background of thermal radiation of the sample during its laser heating are used to calculate the spectral hemispherical directional reflectivity according to the expression:

$$\rho_\lambda(2\pi,\Theta,\varphi,\mathrm{T}) = \frac{\mathrm{U_i}}{\mathrm{U_{s,\,i}}}\rho_{s,\lambda} \tag{10}$$

where $\mathrm{U_i}, \mathrm{U_{s,\,i}}$ are correspondingly the pulse signals from the pyrometer for the sample and for the standard at i-pyrometer channel; $\rho_{s,\lambda}$ is the spectral reflectivity of a standard with well known reflectivity.

To obtain the spectral directional-hemisperical reflectivity Helmholtz's reciprocity principle is used in the next form

$$\rho_\lambda(2\pi,\Theta,\varphi,T) = \rho_\lambda(\Theta,\varphi,2\pi,T) \tag{11}$$

which is true in case of diffuse irradiation of sample surface.

Spectral directional emissivity is found from the Kirchhoff's law (for the opaque surface).

$$\varepsilon_\lambda(\Theta,\varphi,T) = 1-\rho_\lambda(\Theta,\varphi,2\pi,T) \tag{12}$$

This expression is true in laser heating if the hypothesis of local thermal equilibrium is accepted.

Multichannel pyrometer records not only pulse reflection signals but also radiance temperatures of the sample surface at N wavelengths as well (N is the number of pyrometer channels). So multiwavelength pyrometer simultaneously records both spectral reflectivities and radiance temperatures at N wavelengths. Therefore in

determining the true temperature of the sample surface we use a lot of information which allows us to calculate the true temperature with high accuracy by the following set of equations

$$N \quad \begin{cases} T^{-1} - T_{r,1}^{-1} = \lambda_1 C_2^{-1} \ln\left[1 - \rho_{\lambda,1}(2\pi, \Theta, \varphi, T)\right] \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ T^{-1} - T_{r,i}^{-1} = \lambda_i C_2^{-1} \ln\left[1 - \rho_{\lambda,i}(2\pi, \Theta, \varphi, T)\right] \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ T^{-1} - T_{r,N}^{-1} = \lambda_N C_2^{-1} \ln\left[1 - \rho_{\lambda,N}(2\pi, \Theta, \varphi, T)\right] \end{cases} \tag{13}$$

where i takes the values from 1 to N; C_2 is the second Planck's radiation constant; $T_{r,i}$ - radiance temperature at the i-pyrometer channel; $\rho_{\lambda,i}(2\pi, \Theta, \varphi, T)$ - spectral hemispherical-directional reflectivity at the i-st wavelength; Θ, φ - radial and azimuthal angles respectively, determining the direction of observation of the sample radiance.

Thus the main measured parameter in the method developed is the sample surface radiance and then spectral reflectivity, emissivity and true temperature are determined from the Eq.(13). The sample surface is irradiated hemispherically and viewed directionally. Such manner of the reflectivity measurements enables one to eliminate the influence of changing the sample surface texture during laser heating on the results obtained in the case if the hemispherical irradiation of the sample surface is uniform diffuse one. It can be seen (Fig.6) that central location of the sample with flash-lamp placed in the upper hemisphere permits one to irradiate the lower hemisphere by diffuse surface of upper hemispere. The design of the reflectometer developed is made in such a manner that the light from flash lamp is incident only on the upper hemisphere. Then the secondary diffuse radiators of the upper hemisphere irradiate the internal

surface of the lower hemisphere and uniform irradiation of the lower hemisphere is realized by means of multiplied reflections of the light into the sphere. Uniform irradiation of the lower hemisphere leads to diffuse irradiation of the sample surface. Photometric calculations also confirm this affirmation. Using the procedure of photometric calculations proposed in [8] one may show that the irradiance of lower hemisphere is determined by the following expression (Fig.7).

$$E_{\lambda} = \frac{\Phi_0}{4\pi R^2}\left[1 - \frac{2kS}{AR^2}\right]\frac{\rho^*}{1-\rho'} \tag{14}$$

The irradiance of the upper hemisphere is found from the equation

$$E_{up} = \frac{\Phi_0}{4\pi R^2}\left\{\frac{4\pi f(\Theta)}{A} + \left[1 - \frac{2kS}{AR^2}\right]\right\}\frac{\rho^*}{1-\rho'} \tag{15}$$

Where k is a constant; $S = S_1 = S_2$ - is the area of apertures; Φ_0 is the light energy from the flash lamp; f(Θ) is the photometric body (indicatrix of light source) of the flash lamp.

The expressions (14) and (15) show that the irradiance of the lower hemisphere is constant over its surface but the irradiance of the upper hemisphere is variable and depends on the photometric body of the light source. Thus the photometric calculations confirm that diffuse irradiation of the sample surface in the reflectometer developed is performed by a uniform irradiated hemisphere placed above the sample surface studied.

The principle of the pulse diffuse light probing of flat sample surface heated by concentrated light flux in the imaging furnace was used in our previous developments [11-14] to measure thermal radiation properties of the materials at high temperatures. We have successfully applied these methods for measuring spectral reflectivity and emissivity of the refractory materials in the visible and infrared spectral ranges up to 3000 K. Since the power of the imaging furnace is limited it is very difficult to reach the

temperatures above 3000 K. Therefore the reflectometer developed with laser heating technique enables one to extend essentially the temperature interval in measuring thermal radiation properties of advanced materials.

4. CONCLUSIONS

It is shown that advanced methods for measuring thermal radiation properties of materials at high temperatures with laser heating technique don't take into account the influence of changing the studied sample surface under powerful laser beam on the results obtained. Since these methods are based on reflectometry of the model fixed surface (specular or diffuse one) ignoring the effect of changing the sample surface reflection indicatrix under intense laser radiation may lead to serious experimental errors.

A new reflectometer with laser heating technique based on pulse diffuse irradiation of the sample surface has been developed. Pulse diffuse irradiation of the sample surface studied by an additional light source in laser experiment enables one to eliminate the influence of changing the surface reflection indicatrix during laser heating on the results obtained and to obtain the reliable data on thermal radiation properties of materials at high temperatures. Also such procedure of light probing the sample heated by powerful laser beam permits one to perform the reflectivity and emissivity measurements near high temperature phase transitions including melting point of refractory materials when the sharp change of reflection indicatrix takes place.

The technique operates up to temperatures above 4000 K and in the spectral range 0,4-1,1 μm at ten wavelengths. Uncertainty in reflectivity and emissivity measurements is about ±2%.

Thus due to vast capacities of the method developed it can successfully compete with the method of the integrating sphere laser reflectometer and in some cases it may be more reliable instrument for measuring thermal radiation properties of the advanced materials at high temperatures. This comparison is given in Table I.

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Table I. Comparison the method developed with the method of an integrating sphere laser reflectometer

Component of the method	The method of laser reflectometer	The method developed
1. Heating	One-side heating of the sample by means of powerful laser beam.	
2. The heating source	Powerful CO_2 laser.	
3. Diagnostics	Active probing of the studied surface by means of the additional light source.	
4. Probe type	Low-powered gas laser (monochromatic light in continuous regime with modulation).	Flash-lamp (polychromatic light in pulsed regime).
5. Method of probing	The directional irradiation of the sample surface.	Diffuse irradiation of the sample surface.
6. The main parameters measured	Spectral directional hemispherical reflectivity and radiance temperature.	Spectral hemispherical directional reflectivity and radiance temperature.
7. Amount of information obtained	Simultaneous measurement of $\rho_\lambda(\Theta,\varphi,2\pi,T)$ and T_r at one wavelength.	Simultaneous measurement of $\rho_\lambda(2\pi,\Theta,\varphi,T)$ and T_r at 10 wavelengths.
8. Resources of widening the spectral range	a) successive application of some lasers; b) recording the emission spectrum of the sample.	Recording the spectrum of reflected and emitted radiation from the sample.
9. Method of integration of light fluxes	Integration of the reflected radiation from the sample by means of photometric sphere with well-reflected surface.	Double integration of the incident and reflected radiation from the sample by means of photometric sphere with well-reflected surface.
10. Sources of method error	Influence of dynamic change of the sample surface texture under laser heating on the results obtained.	____

Component of the method	The method of laser reflectometer	The method developed
11. Method of elimination of some sources of error	Use of the relative method of measurements with application of the sample with well known reflection properties.	
11. Method of elimination of some sources of error	_____	a) Diffuse irradiarion of the sample surface enables one to eliminate the influence of dynamic change of the sample surface texture under laser heating on the results obtained. b) Simultaneous multiwavelength sample probing and recording the sample radiance and reflected signals at various wavelengths enable one to increase the accuracy of temperature measurements.
12. Class of studied materials	Opaque materials with diffuse or close to diffuse reflection surface.	Opaque and semitransparent materials with specular, diffuse and mixed specular diffuse reflection surface.
13. Main parameters of the method	a) temperature range is 1300-4000 K; b) spectral range: $\lambda = 0.63\mu m$ and $\lambda = 10.6\mu m$; c) measurement error, $\delta\rho_\lambda = 2 - 3\%$.	a) temperature range is 1300-4000 K; b) spectral range: is $0.4 - 1.1\mu m$ at ten wavelengths ; c) measurement error, $\delta\rho_\lambda = 2 - 3\%$.

FIGURE CAPTIONS

Fig.1. Reflection from model surface: a) diffuse surface; b) specular surface (Φ_0 is the flux incident on the sample; Φ is the flux reflected from the sample).

Fig.2. The possible behaviour of the reflection indicatrix during the laser heating of the sample surface.

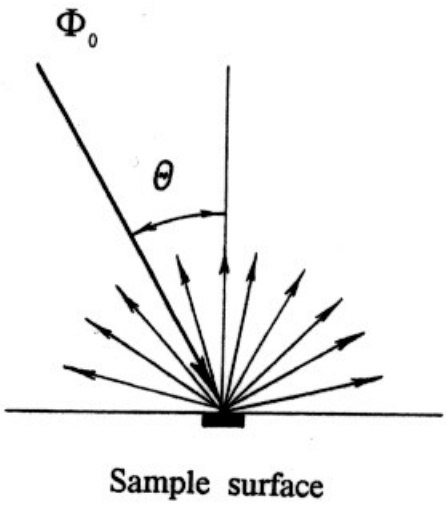
Fig.3. Specular laser reflectometer.

Fig.4. Integrating sphere laser reflectometer.

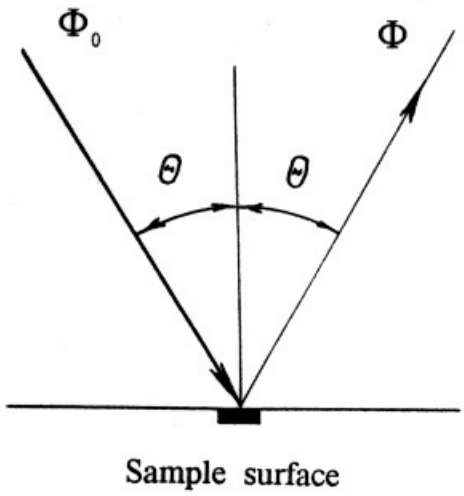
Fig.5. Scheme of photometric calculations for integrating sphere laser reflectometer. (Φ_0 is the flux incident on the sample; f(Θ) is the reflection indicatrix of sample surface; S_1, S_2 are the apertures in the sphere).

Fig.6. Polychromatic reflectometer with laser heating.

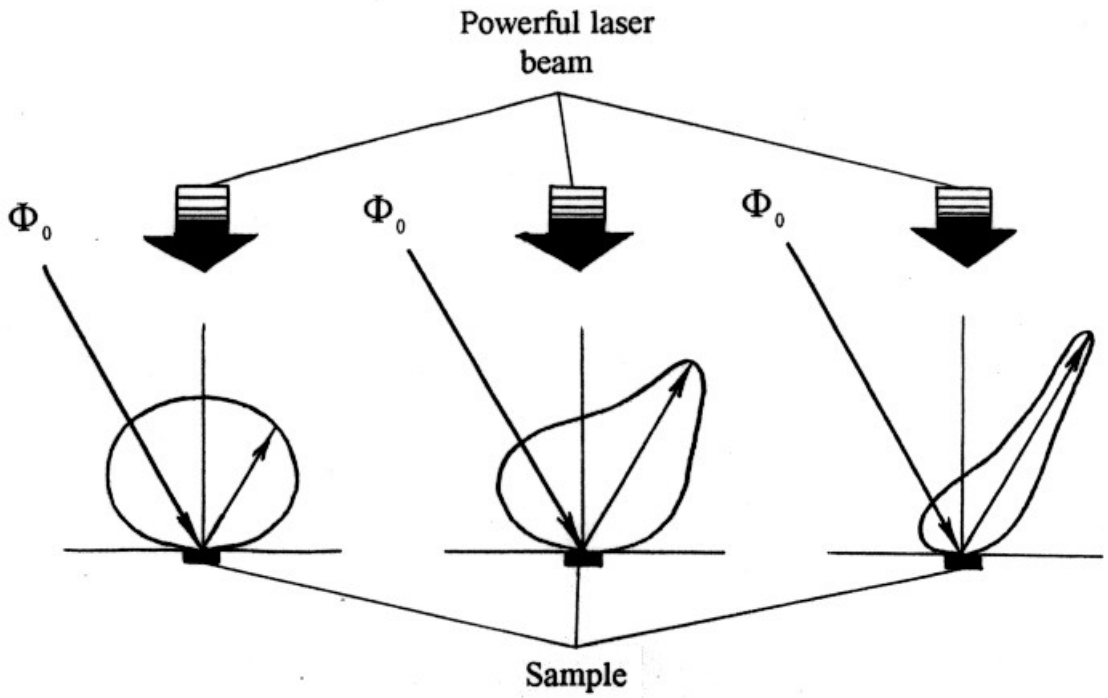
Fig.7. Scheme of photometric calculations for the reflectometer developed. (Φ_0 is the light energy from the flash-lamp; f(Θ) is indicatrix of the flash-lamp).

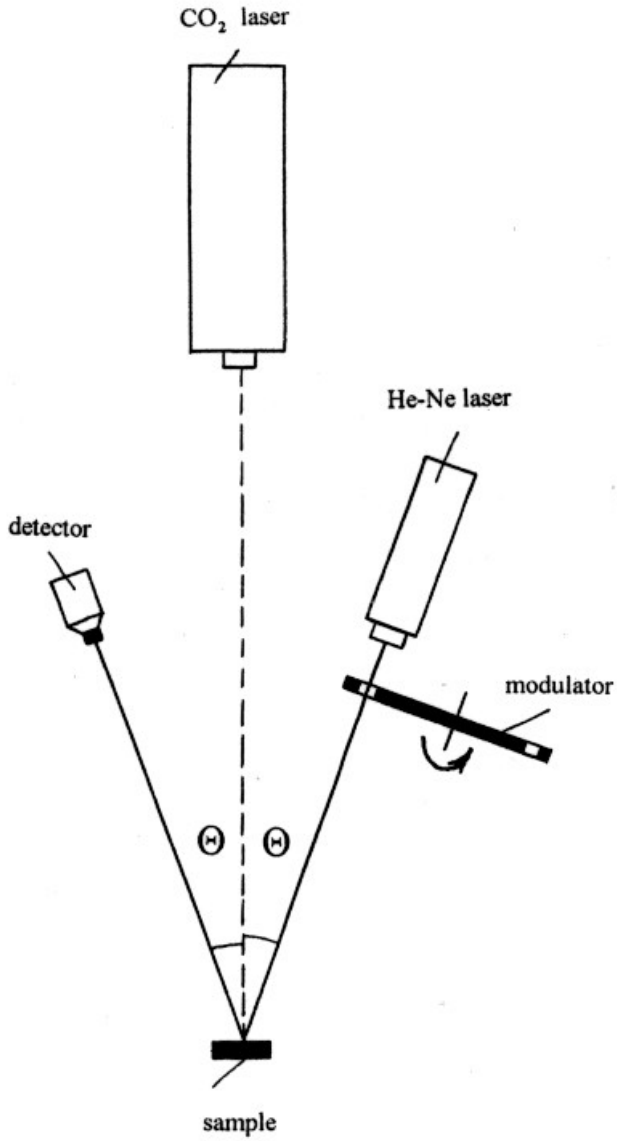

Φ_0
θ
Sample surface

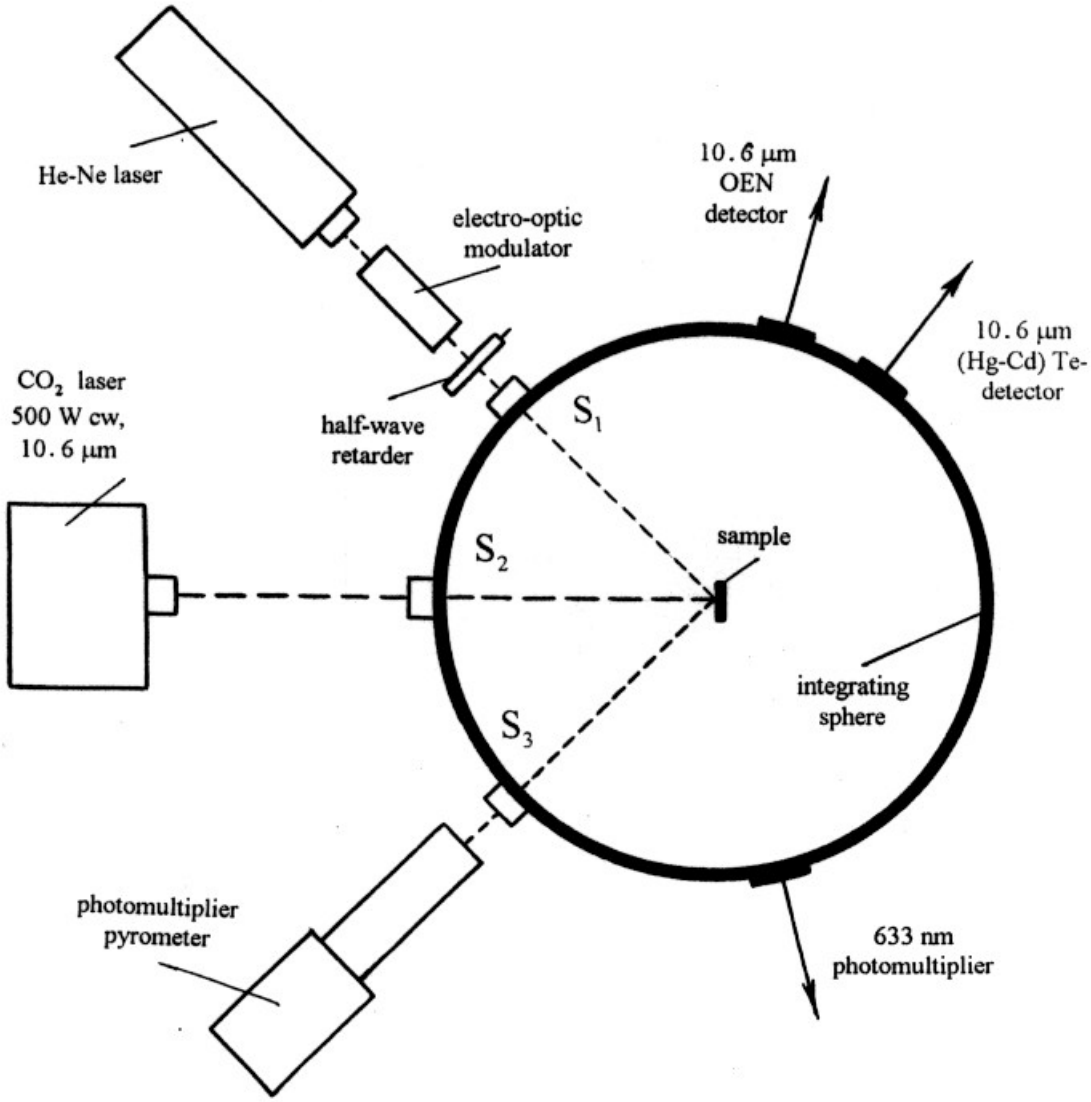
a)

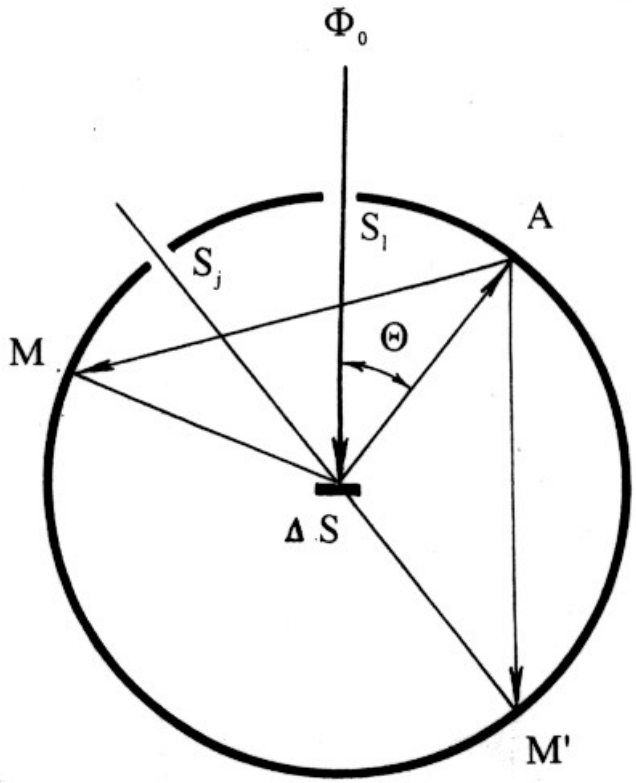

Φ_0
Φ
θ
θ
Sample surface

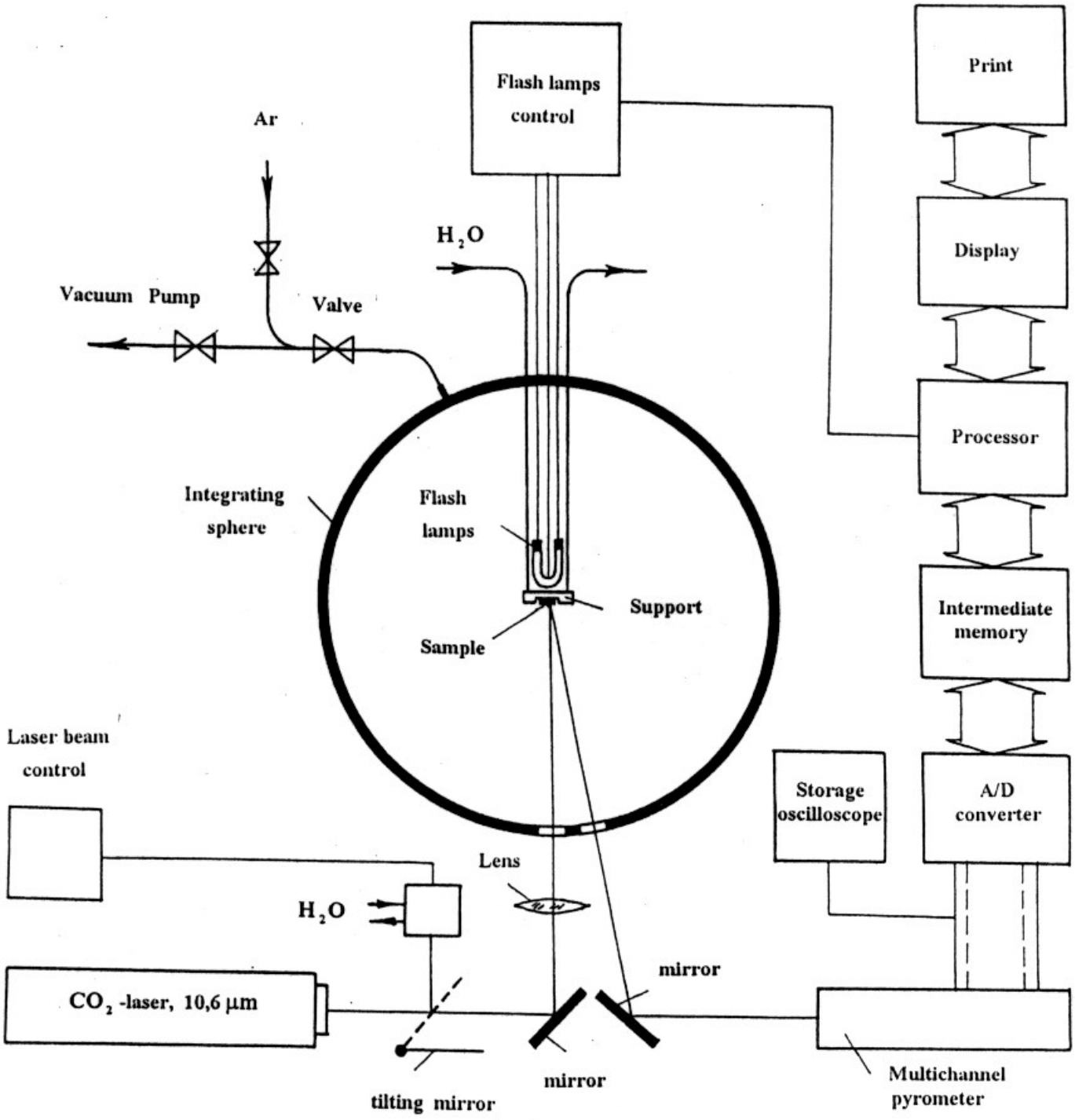
b)

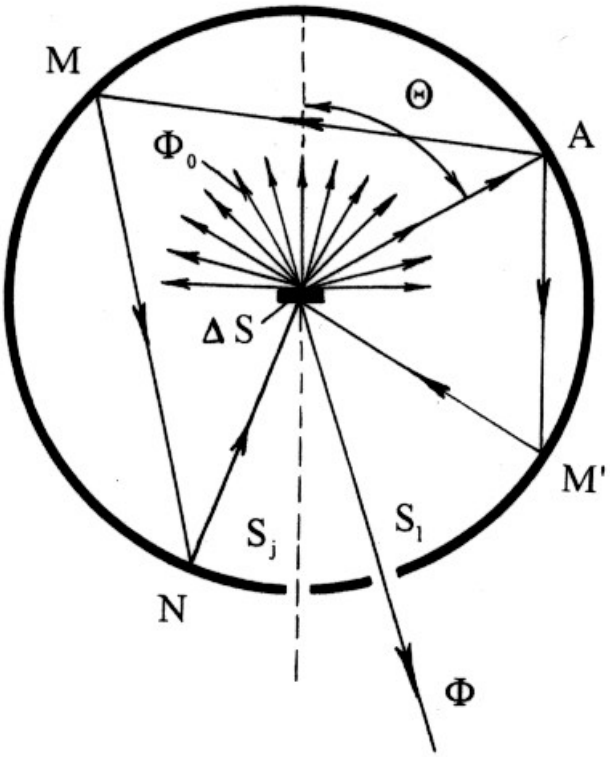

Powerful laser
beam
Φ_0
Φ_0
Φ_0
Sample


CO_2 laser
He-Ne laser
detector
modulator
Θ
Θ
sample


He-Ne laser
electro-optic
modulator
10.6 μm
OEN
detector
10.6 μm
(Hg-Cd) Te-
detector
CO_2 laser
500 W cw,
10.6 μm
half-wave
retarder
S_1
S_2
S_3
sample
integrating
sphere
photomultiplier
pyrometer
633 nm
photomultiplier


Φ_0
S_1
A
S_j
M
Θ
ΔS
M'


Flash lamps control
Print
Display
Processor
Intermediate memory
A/D converter
Storage oscilloscope
Ar
H_2O
Vacuum Pump
Valve
Integrating sphere
Flash lamps
Support
Sample
Laser beam control
Lens
H_2O
mirror
CO_2 -laser, 10,6 µm
mirror
tilting mirror
Multichannel pyrometer


M
Θ
A
Φ0
ΔS
M'
Sj
Sl
N
Φ