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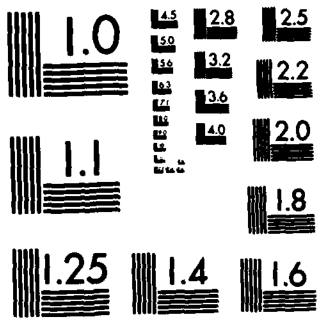
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DEVELOPMENTS IN FAR-INFRARED DETECTION TECHNIQUES

by

Kong Fanping and Lu Yongxiang

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By: Kong Fanping and Lu Yongxiang

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DEVELOPMENTS IN FAR-INFRARED DETECTION TECHNIQUES

Kong Fanping and Lu Yongxiang
The Shanghai Technical Physics Institute, Academia Sinica

I. Introduction

The far-infrared spectral region of wavelengths in the electromagnetic wave spectrum located between infrared and microwaves (wavelengths of 30 micron to 3 millimeters) is an important transition region and many important physical processes are closely related to the radiation phenomena of this spectral region. For example, the pure rotation spectrum with mostly light molecules and the absorption phenomena related to the lattice vibration in solids and other elemenetary excitation processes occur in this spectral region; the electron cyclotron radiation of magnetically-confined plasma under high temperature conditions is also in this region which is the major part of the fusion plasma's energy dissipation formed from these radiations. Aside from these, the astronomy research topics of 3K cosmic background radiation, and the cold celestial bodies, interstellar dust and nebular molecule fine structures etc. of the Milky Way system and extragalactic galaxy, which have caught people's attention are inseparable from far-infrared detection techniques. From the point of view of application techniques, this spectral region has many special features and it blends the principles of traditional microwave techniques and geometric optics.

Because the far-infrared region has wide scientific and technical utilization prospects, it has always received the serious attention and solicitude of scientific workers from various nations. Early, at the end of the nineteenth century, taking Rubens as the representative, German scientists began early investigative research on the far-infrared spectral region [1]. However, because there was a lack of ideal radiation sources and sufficiently sensitive detection devices, the advancements in development research on this spectral region were slow.

From the course of development of infrared and microwave science and technology, people clearly saw that in the research on the production and transmission of electromagnetic radiation and their interaction with substances, sensitive detecting devices play an especially important role. This is especially true of far-infrared radiation which cannot be directly sensed by the human sense organs but people must rely on special sensing elements to transform the far-infrared radiation energy into other physical quantities. It can be said that before the development of sensitive detecting elements, the wide application of far-infrared radiation was impossible. Far-infrared detection is also related to the problems of the effective transmission and coupling of radiation. This is related to the energy weakness of the radiation awaiting detection and the serious atmospheric attenuation. Therefore, conventional microwaves and optical techniques encounter difficulties.

This paper mainly introduces the developments in far-infrared detecting devices and in passing explains the transmission method and coupling structure etc. problems closely related to detectors.

II. Detection Mechanisms

Based on the different forms of interaction between far-infrared radiation and substances, far-infrared detectors can generally be divided into the three major categories of thermal detectors, photoconductive detectors and transprectification detectors. The first two devices were developed on the basis of optical and infrared detectors and the third type directly shifts the response spectrum region of the microwave detecting device towards even shorter wavelength areas.

1. The Thermal Detector

The thermal detector is the earliest used far-infrared detecting device. It was made based on the thermal effects of far-infrared radiation. As regards the structure of the device, there are generally two parts: the absorbent material can absorb far-infrared radiation and the thermometer which is used to indiciate the absorbing temperature rise. In order to raise the sensitivity of the thermal detector and maintain excellent transient response characteristics, the absorbent material of the thermal detector and the thermal inertia of the thermometer both have relatively small control. They are joined by certain thermal resistance and constant temperature sources (the surrounding environment). The response spectrum of the thermal dedetector is determined by the absorbent material and window material and the noise characteristics are determined by the combinbination of the thermometers, thermal inertia, thermal resistance and operating temperature.

The response characteristics of the thermal detector can be analyzed beginning from the common thermal balance equation. Assuming the thermal capacity of the thermal detector (the product of the specific heat and mass) is H, the thermal conduction between it and the constant temperature source is G and the temperature difference is θ, then

$$\eta I = H d\theta/dt + G\theta, \qquad (1)$$

The I here is the power of the received irradiation on the detector and η is the absorption efficiency. If the irradiation power of incidence is sinusoidal range modulated, that is $I=I_\omega e^{j\omega t}$, at this time, the changes of θ are also sinusoidal. Moreover, $\theta = \theta_\omega e^{j(\omega t+\phi)}$. Here, θ_ω and ϕ separately satisfy

$$\theta_\omega = \eta I_\omega (G^2 + \omega^2 H^2)^{-\frac{1}{2}}, \qquad (2)$$

$$\phi = \arctan(\omega H/G). \qquad (3)$$

Because θ_{ω} is actually the maximum temperature rise after the absorbent material sustains irradiation, we can see from formulas (2) and (3) that decreasing thermal conduction G and decreasing modulation frequency ω of the incident radiation (causing $\omega H \ll G$) is helpful to raising the speed of response of the thermal detector.

There are many types of commonly used thermal detectors: the pneumatic Gaolai tube, thermopile, thermoelectric detector as well as the refrigeration type resistance radiation thermometer etc. The Gaolai tube uses thin metallic film as the absorbent material and after the quantity of heat which it absorbed is transfered to the gas in the Gaolai tube, the pressure of the gas correspondingly increases which causes the organic film of the rear wall to expand and the relaxation of the organic film to be directly read out by the optical method. The structure of the thermopile is strong, its performance is stable, its bearing power is high and it often acts as the basis for far-infrared spectral region power calibration. The detector which developed most rapidly in recent years is the thermoelectric detector. This device is made from magneto-electric material which possesses spontaneous polarization characteristics and the output signals form a direct ratio with the rate of change of the material's temperature rise (but it is not the temperature rise itself). Therefore, it possibly shortens the response time to the nanosecond level and the utilization range expands with it. The refrigeration type resistance radiation thermometer is already commonly used in the far-infrared spectral region. Because the operating temperature is low and the noise in the device related to the temperature and its own emission both decrease, the response performance is very good. At present, the synthetic type resistance radiation thermometer is being developed to expand the range of the response spectral region. See Table 1 for the development levels of the various types of thermal detectors.

(1) 种 类	(7) 响应波长范围	响应率 (13)	响应时间（或调制频率范围） (19)	噪声等效功率 NEP (25)
(2) 热电堆(室温)	λ<50 微米 (8)	10^{-1}—10^{2} 伏·瓦$^{-1}$ (14)	10^{-2}—10 秒 (20)	10^{-9} 瓦·赫$^{-\frac{1}{2}}$ (26)
(3) 高莱管(室温)	取决于窗口材料 (9)	10^{3}—10^{6} 伏·瓦$^{-1}$ (15)	5—20 赫 (21)	10^{-10} 瓦·赫$^{-\frac{1}{2}}$ (27) (商品) (31)
(4) 热释电探测器(室温)	取决于探测材料和窗口材料 (10)	10^{2}—10^{6} 伏·瓦$^{-1}$ (16)	10^{-9} 秒 (22)	5×10^{-10} 瓦·赫$^{-\frac{1}{2}}$ (28)
(5) ^{4}He 致冷的半导体测辐射热计 (1.2K)	取决于探测材料、涂层和窗口材料 (11)	10^{3}—10^{4} 伏·瓦$^{-1}$ (17)	5—100 毫秒 (23)	10^{-12}—10^{-13} 瓦·赫$^{-\frac{1}{2}}$ (29)
(6) ^{3}He 致冷的半导体测辐射热计 (0.3K)	取决于探测材料、涂层和窗口材料 (12)	10^{7} 伏·瓦$^{-1}$ (18)	5—100 毫秒 (24)	10^{-14}—10^{-16} 瓦·赫$^{-\frac{1}{2}}$ (30)

Table 1 Performance of typical thermal detectors [2].

Key: (1) Type; (2) Thermopile (room temperature; (3) Gaoli tube (room temperature); (4) Thermoelectric detector (room temperature); (5) ^{4}He refrigerated semiconductor radiation thermometer ; (6) ^{3}He refrigerated semiconductor radiation thermometer; (7) Response wavelength range; (8) Micron; (9) Determined by window material; (10) Determined by detecting material and window material; (11)-(12) Determined by detecting material, coating material and window material; (13) Speed of response; (14)-(18) Volts·watts; (19) Response time (or modulation frequency range); (20) Seconds; (21) Hertz; (22) Seconds; (23)-(24) Milliseconds; (25) Noise Equivalent power; (26)-(30) Watts·hertz; (31) Commodity.

2. The Photoconductive Detector

The photoconductive detector is made based on the electroconductive changes caused by the direct effects of electromagnetic radiation and detecting materials. Because this type of photoconductive effect is always connected to certain excitation processes of electrons in the detecting material, the detecting process often has long wave cut-off characteristics. As regards the widening involvement of the non-intrinsic photoconductive process in far-infrared detection applications, the energy of the far-infrared radiation quantum awaiting measurement must be larger than the detecting material's corresponding energy level distance E_i, that is

$$h\nu = hc/\lambda \geq E_i, \qquad (4)$$

Here, h is the Planck's constant, v is the radiation frequency, c is the speed of light, λ is the radiation wavelength and E_i is the impurity activation energy in the non-intrinsic semiconductor material. From formula (4), we can also directly obtain cut-off wavelength λ_c of the photoconductive process:

$$\lambda_c = hc/E_i. \qquad (5)$$

In the semiconductor detectors, the speed of the photon-generated carriers produced by the incident electromagnetic radiation is $I\alpha\beta$. Within this, I indicates the incident radiation intensity (using the photon number as the unit), α is the absorption coefficient and β is the quantum yield. By using various mechanisms and compound carriers, the compound rates can statistically be indicated as $\Delta n/\tau$ with τ being the carrier's life. Under steady state conditions,

$$I\alpha\beta = \Delta n/\tau, \qquad (6)$$

Because signal voltage V_s of the photoconductive detector forms a direct ratio with $\Delta\sigma/\sigma$ (σ is the material's conductivity), in most situations $\Delta\sigma/\sigma$ is mainly determined by $\Delta n/n$. Therefore,

$$V_s \propto \Delta\sigma/\sigma \propto I\alpha\beta\tau/n. \qquad (7)$$

It can be seen that increasing the incident radiation intensity, using the radiation integrating cavity to raise the absorption coefficient and using high quantum yield material as well as using high resistance material or decreased operating temperature to reduce the background carrier concentration of the detecting materials are all beneficial to strengthening the output signals of the photoconductive detector. Control of the compound mechanism to lengthen the carrier's life no doubt can also increase the signals. However, this takes sacrificing the fast speed response of the detector as the premise and it must be weighed and considered based on the utilization requirements.

At present, the applications of the non-intrinsic photoconductive detector which uses Ge and Si as the base materials are quite widespread. The impurity activation energy in Ge is distributed in the 0.01-0.35 electron volt range, the cut-off wavelength of the response is 3-120 micron, the impurity activation energy in Si is 0.04-0.55 electron volts and the cut-off wavelength of the response is somewhat shorter. Use of the neutral donor captured electron D-state (or neutral acceptor captured hole A+ state) as well as the Rydberg state newly developed detecting devices makes it possible to extend the response wavelength to 0.5 micron. Although the sensitivity of photoconductive detector which is based on the absorption of n type InSb free carriers is inferior to that of the refrigeration type resistance radiation meter, yet its response is fast, its use is convenient and thus it has been given serious attention. Recently, research on the HgCdTe free carrier absorption photoconductive detector can hope to have increases in the area of detection performance. See Table 2 for the development levels of various photoconductive detectors.

(1) 种 类	(5) 响应波长范围（微米）	(6) 响应时间	响应性能 (11)
非本征 Ge (2) Ge:Cu Ge:Ga	2—30 30—120	(7) 典型值100毫秒，重补偿材料有可能达1毫微秒	NEP~2.5×10^{-13} 瓦·赫$^{-\frac{1}{2}}$ (12) NEP~6×10^{-17} 瓦·赫$^{-\frac{1}{2}}$ (13)
非本征 Si (3) Si-As(<20K) (4) Si-As, Si-P, Si-Sb 中*D*-态 (1.6K)	1—23 100—500	同上 (8) 1毫微秒	D^*~2.5×10^{10} 厘米·赫$^{\frac{1}{2}}$·瓦$^{-1}$ (14) NEP~10^{-11} 瓦·赫$^{-\frac{1}{2}}$ (15)
GaAs (4—6K)	100—350	10毫微秒 (9)	NEP~4×10^{-14} 瓦·赫$^{-\frac{1}{2}}$ (16)
InSb (2K)	200—3000	200毫微秒 (10)	NEP~5×10^{-12} 瓦·赫$^{-\frac{1}{2}}$ (17)

Table 2 Performances of typical photoconductive detectors [2].

Key: (1) Type; (2)-(3) Non-intrinsic; (4' ,-state in Si-Sb; (5) Range of response wavele :h (micron); (6) Response time; (7) Typical val is 100 milliseconds, repeat compensation m ial can reach 1 nanosecond; (8) The same as ove, 1 nanosecond; (9)-(10) Nanosecond; (11) Response performance; (12)-(17) Watts·hertz.

3. The Transrectification Detector

The transrectification detector with far-infrared spectral region is actually an extended development of the microwave detecting device. It can respond to incident electromagnetic radiation induced current and can put out signals using certain nonlinear detection effects. Most transrectification detectors use the point contact structural form and the area control of the contact node points is within several cubic micron. This type of structural design can decrease the value of the device itself and the parasitic capacity and not cause a serious bypass device current. However, the stability of the point contact structure is poor and its operating life is short. The response time of the transrectification device is very short and it is especially suitable for utilization situations with very high modulation frequency or as the mixer in a heterodyne detection system.

As a device for video frequency detection or heterodyne mixing detection, the longest structural utilization time of the metallic semiconductor contact is between W and P-Cu and various semiconductor materials (Si, Ge, GaAs, InSb). This type of structure possibly has many detecting mechanisms, yet in the application of the far-infrared spectral region, most are of the Schottky barrier type. The selection of the material is determined by the application, yet up until recently there were still no quantitative results to appraise which type of material as well as which doping level was the ideal state. In recent years, use of the electron beam etching technique has enabled the Schottky barrier diode and "Super Schottky" diode (using superconducting metal to replace the regular metal for making the contact wire) to have successful reports. There has also been widespread research on another transrectification detector with an MIM structure. Its nonlinear electronic properties are based on the results of electron tunnel effects. The Josephson junction has a broad future in the field of far-infrared detection applications. The interaction of its internally produced oscillating current and current induced by external radiation reveal many unique properties. Because of the Josephson junction oscillating superconductive current's intrinsic inductance and superconductor characteristics, when the quantum energy of the incident radiation exceeds the superconductor's energy gap, the strength of this type of effect weakens and inferring from the basic parameters of existing superconductor material, the Josephson junction is mainly suitable for radiation detection of wavelengths above 200 micron. Moreover, devices with point contact structures are the most sensitive. See Table 3 for the development levels of the various transrectification detectors.

(1) 类 型	(6) 材 料	(9) 响应波长(毫米)	(10) 输入耦合方式	(18) 响应率(伏·瓦$^{-1}$)	(19) 视频 NEP (瓦·赫$^{-1/2}$)
(2) 金属-半导体点接触(300K)	(7) 金属-Ge W-GaAs	1 0.337	(11) 过模波导 (12) 触须天线	10^{4}	3×10^{-4} 2×10^{-8}
(3) 光刻肖脱基二极管(300K)	(8) n 型 GaAs	0.496 0.119	(13) 触须天线 (14) 触须天线	10 0.4	10^{-6} 10^{-7}
(4) 金属-金属点接触(300K)	W-Co W-Ni	0.337 0.337—0.389	(15) 触须天线 (16) 触须天线	1 10^{-4}	
(5) 点接触约瑟夫森结(≤4K)	Nb-Nb	2.5	(17) 触须天线	5×10^{8}	3×10^{-10}

Table 3 Performances of typical transrectification detectors [2].

Key: (1) Type; (2) Metal-semiconductor point contact; (3) Photoetched Schottky diode; (4) Metal-metal point contact; (5) Point contact Josephson junction; (6) Material; (7) Metal; (8) Type; (9) Response wavelength (mm); (10) Input coupling mode; (11) Excess mode waveguide; (12)-(17) Cat-whisker antenna; (18) Speed of response (volts·watts^{-1}); (19) Video frequency NEP (watts·hertz$^{-1/2}$).

III. Transmission Problems

The far-infrared spectral region can be understood as the region of overlapping of the classical optical technique and the classical microwave measure. The difficulty of the effective transmission measure and coupling mode of far-infrared radiation is: the waveguide is commonly taken as the major means of microwave transmission. Thus the resistance loss of the waveguide and the relaxation loss of the dielectric waveguide is due to the fact that the rise of the operating frequency has very great changes in the far-infrared region. Aside from this, when the operating wavelength is shorter than 2 millimeters, the processing of the small-sized waveguide as well as the assembly of the functional elements both have serious difficulties. Although the excess mode waveguide to a certain extent can alleviate the loading requirements in the areas of loss and size, yet the radiation field distribution of the waveguide section is quite complex and there are many difficulties caused by mode type mixing. The situation is more serious when counting chromatic dispersion. Therefore, the development of the directional transmission technique of the structure has already become the most hopeful choice of the far-infrared spectral region. However, not counting the pure light ray optical design of the wave effect, it is necessary that the linearity of the optical element be more than two quantity levels higher than the operating wavelength. For example, for a 1 millimeter wave, if the diameter of the lens or reflector at the least is not smaller than 100 millimeters, this can guarantee that the system has high performance. However, it is naturally inconvenient to assemble such a large element on a laboratory instrument and it is also not practical to use on an astronomical telescope for the same reasons. Therefore, well known microwave measures and optical methods encounter hard to overcome problems in the far-infrared region. In order to resolve the transmission and coupling problems, submillimeter wave optics and quasi-optics were produced. Martin and Lesurf [3], based on the transmission characteristics of Gaussian light beams, implemented the optical method for the far-infrared spectral region. The quasi-optical double beam interferometer spectrometer has a designed structure which is compact, performance is excellent and it can effectively transmit far-infrared radiation. The size of the entire system is about 200 millimeters and the maximum optical path difference is 40 millimeters which is equal to a resolving power of 0.1 centimeters^{-1}.

IV. Coupling Structure

As mentioned above, when the traditional optical and microwave techniques are directly used for the detection of far-infrared radiation, they encounter difficulty. The photoconductive detector is a type of mixer with excellent performance but its response is a little slower. As nonlinear elements, the

Schottky barrier diode and MIM junction have the advantages of relatively large bandwidths and room temperature operation. However, the volume is very small and requires a certain type of feed structure so as to effectively couple the energy to the diode. When the operating wavelength is reduced, due to the skin effect, the resistance loss of the metal waveguide becomes very large and therefore, in a broad sense, the antenna is the best coupling structure for far-infrared radiation. To date, the far-infrared antennas which have been used with relative success is the tungsten cat-whisker (Fig. 1). With the addition of an angle reflector, we can improve the directionality of the antenna (Fig. 2). There is also the double angle conical cavity designed by Gustincic et al (Fig. 3).

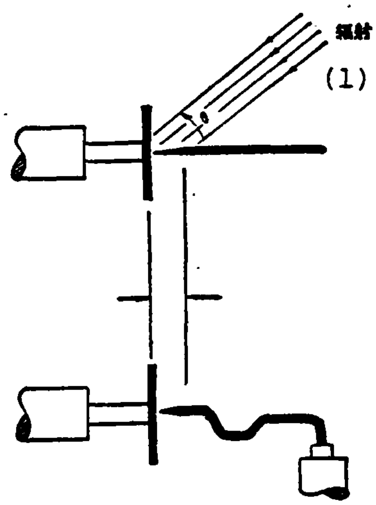

Fig. 1 The cat-whisker antenna.
Key: (1) Radiation.

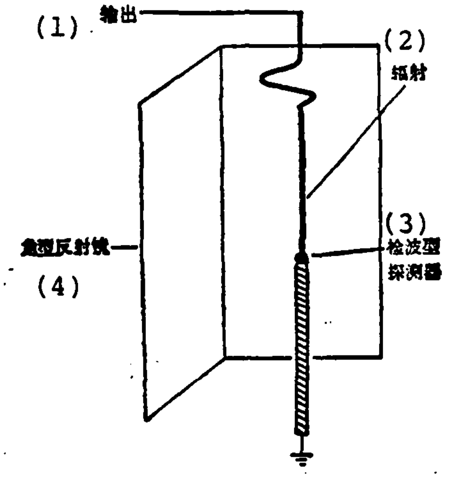

Fig. 2 The free space antenna.

Key: (1) Output; (2) Radiation; (3) Transrectification detector; (4) Angle reflector.

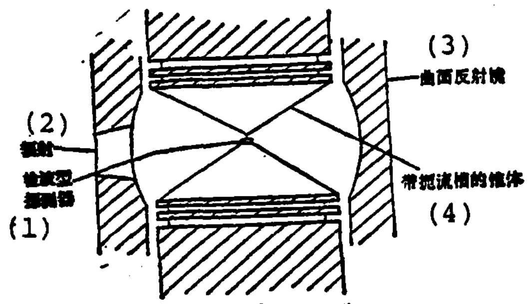

Fig. 3 The double angle conical cavity.

Key: (1) Transrectification detector; (2) Radiation; (3) Curved surface reflector; (4) Cone with choke groove.

The various coupling techniques are still in the early stages of development and we are still unable to make quantitative comparisons of their performances. The greatest drawbacks of this type of antenna are: (1) the antenna model very much resembles the common long-wire antenna. When the operating wavelength is shorter than 2 millimeters, the effective area of the antenna is reduced (in direct ratio to λ^2) and the material characteristics of the tungsten in this spectral region cause the performance of the nonlinear diode to noticeably worsen; (2) it uses the point contact mode and therefore the mechanical stability is poor; (3) the directionality is not good.

The improvements already made are the use of the micro-electronic technique to set the plane antenna in the middle of the dielectric to make it into a sandwich bread shape. Figure 4 is a schematic of the Schwarz V plane antenna set into a quartz medium.

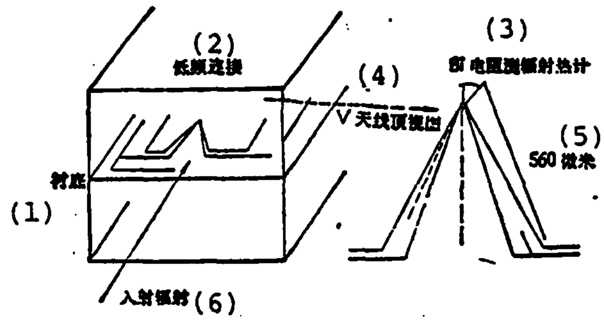

Fig. 4 The infrared V antenna.
Key: (1) Substrate; (2) Low frequency connection; (3) Bi resistance radiation thermometer; (4) Top view of V antenna; (5) 560 micron; (6) Incident radiation.

It has single lobe antenna characteristics, high gain, wide frequency band and the mechanical stability is far better than that of the point contact device. This V antenna can be coupled with various types of detectors [4]. When it is used in conjunction with the Bi resistance radiation thermometer, in the 119 micron area, measured antenna gain g is 8 decibels [5,6]. Based on the same principles, the integration of the manufactured parallel wire transmission line and the 400 unit Bi resistance radiation thermometer has already been successful. The total operating area is 1 centimeter^2, the coupling rate in the 1 millimeter area is 60%, the device's detecting rate is

$D^* \simeq 4 \times 10^8$ centimeters·hertz$^{1/2}$·watts^{-1} and the response time is 2×10^{-7} seconds (Fig. 5). Research on the integration of the Schottky barrier diode and the SIS detector is being carried out [7].

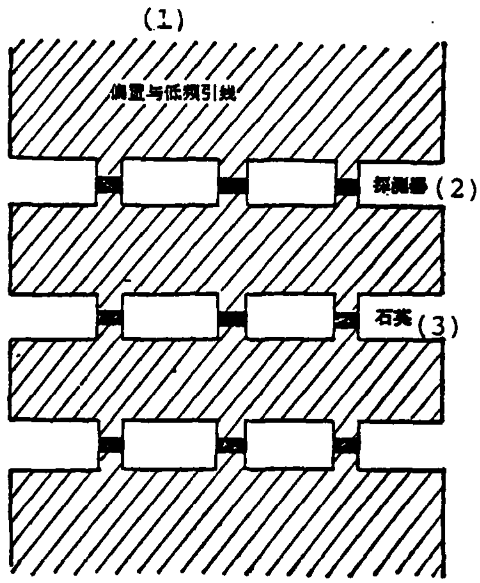

Fig. 5 Integration of the parallel wire transmission line and the 400 unit Bi resistance radiation thermometer.

Key: (1) Bias and low frequency lead wire; (2) Detector; (3) Quartz.

V. Conclusion

The far-infrared detecting technique is a comprehensive utilization technique andthe research developments in inter-related disciplines will provide it with new mechanisms and methods. Research on strengthening the interaction of the far-infrared radiation and substances thus seeks even more sensitive and functional detectors, perfecting the quasi-optical system design theory so as to satisfy ever widening utilization requirements, using microprocessing techniques, developing plane array detecting devices and gradually realizing integration with antennas, waveguides and radiation sources. All of these are not too distant development directions worthy of serious attention in research on far-infrared detecting techniques. It can be predicted that research developments on far-infrared detecting techniques will carry with them even wider applications.

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