INFRARED DETECTORS

INFRARED IMAGING SYSTEMS

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The problem of infrared detectors is difficult to introduce in a short time. It is a very interesting topics because it involves the problem of thermal fluctuations, and because of the improvements recently obtained with major applications to spectroscopy, astrophysics and imaging systems.

INTRODUCTION.

In any infrared detector the photon energy is transformed into some kind of excitation. There are two types of detectors depending on the use of this excitation [1].

1 - Quantum detectors :

The excitation of the detector leads to an instantaneous change of an easily measurable physical property (i.e. electrical conductivity) which is detected before thermalization, i.e. before thermal equilibrium occurs, i.e. before any change of temperature.

This explains why a germanium photo conductor can be immersed into liquid helium and give a photoconductive signal. The temperature has not to change.

Let us look at two examples of quantum detectors to see how thermal equilibrium is destroyed by absorption of a photon:

Ex. 1 - Photoconductivity (fig.1).

Ex. 2 - Ruby Quantum Counter (fig.2).

The energy levels of Cr^{3+} in Al_2O_3 are given in fig.2.

At 2 K the population of the 2 A level is negligible and nearly no R_2 light is absorbed.
Far infrared quanta at 29 cm^{-1} are absorbed, thermal equilibrium is destroyed and the R_2 wavelength is emitted at 6922 Å. The sensitivity is 1 μw.

Besides photo-conductors and quantum counters we can cite a number of infrared quantum detectors : photo-voltaic cells, photographic plates, electronic bolometers, Josephson junctions, photon-drag detectors etc...

2 - Thermal detectors.

There is some kind of excitation. Electrons or phonons are excited either inside the detector itself or in a thin black layer deposited on the detector. This excitation is not directly detectable. We have to insulate the detector from the heat sink to get, after some time, an increase Δ T of temperature. Now many physical properties, may be all physical properties, are temperature sensitive and we have to choose one of the most sensitive to detect the infrared absorbed energy.

The response needs some time and a thermal time constant $\tau = \frac{\mathcal{C}}{\mathcal{G}}$ is introduced where $\mathcal{C}$ is the heat capacity and $\mathcal{G}$ the thermal losses for a unit temperature difference between detector and thermal sink. The thermal losses are made by radiation, convection and conduction. When they are limited to radiation the order of magnitude for τ is 1 or 2 seconds, at room temperature: the result is that a thermal detector cannot be immersed into the heat sink which should prevent any increase of temperature.

I - NOISE, NOISE EQUIVALENT POWER [3] [4].

When a shutter is placed in front of the infrared detector to stop any infrared radiation from the source, some noise is still observed.

When the detector is opened the noise N is added to the signal S. We define the responsivity as $R = \frac{S}{\emptyset}$. The result is that Responsivity can be normalized by taking noise as a unit. This gives the detectivity $D = \frac{R}{N}$ (w^{-1}).
The inverse of detectivity is the NEP $= \frac{N}{R}$ (w).
The time constant $\tau \simeq \frac{2\pi}{\Delta f}$ and in most cases :

$$D \propto \frac{1}{\sqrt{A}} \quad \frac{1}{\sqrt{\Delta f}}$$; hence a normalized detectivity :

$$D^{*} = D \sqrt{A}. \sqrt{\Delta f} \quad (w^{-1} \text{ cm. } Hz^{1/2}).$$

The problem of noise which is now encountered in every field of physics has been concerning the infrared physicists since the earliest time.

I think it is because the only broad band infrared source since the pioneer work of Rubens until now has been the blackbody, the brilliancy L_ν of it decreases dramatically towards low frequencies : $L_\nu \propto \nu^2 \; T$.

I - 1 - Noise sources internal to the detector.

a - Johnson noise.

Johnson's noise is due to the random motions of the charge carriers. It is given by Nyquist's formula :

$$\overline{e^2} = 4 R k T \Delta f$$

R is the real part of the detector impedance, Δf is the band width. Johnson's noise is a white noise.

b - Thermal noise.

It occurs from temperature variations in the detector. In the case of thermal detectors the signal being sensitive to temperature, fluctuations give a noise. These fluctuation come on one hand by conduction and convection processes. These ones can be avoided. On the other hand they occur by random emission of photons. These ones cannot be avoided and lead to a NEP

(detector photon noise) = $2 \sqrt{2 \alpha \sigma k T_1^5}$. For $T_1 = 300$ K, we get NEP (detector photon noise, 300 K) $= 5.5.10^{-11}$ w.
At 3 K, we should have NEP (3 K) $= 5.5.10^{-16}$ w.

I - 2 - Background noise.

The photon noise due to fluctuations in background emission is equal to $2\,(2\,k\,T_2^{\,5}\;\alpha\sigma)^{1/2}$ and leads to a maximum detectivity D^* (Background limited) $= \dfrac{1}{(2\,k\,T_2^5\,\alpha\,\sigma)^{1/2}}$ which could be observed with quantum detectors since the thermal noise does not affect them. This noise cannot be avoided with quantum detectors but it is limited to the photons which have the right wavelength to be detected ($\lambda < \lambda_0$) or to photons transmitted by a suitable filter. This noise can also be reduced with thermal detectors when they have to look at a reduced wavelength interval. Cold filters are introduced.

In conclusion the ideal detectivity of a thermal detector is limited by photon noise both in the detector at temperature T_1 and in the background at temperature T_2 and

$$D^{*\text{ideal}}_{\text{thermal detector}} = \frac{1}{2(2\,k\,T_1^5\;\alpha\,\sigma\,)^{1/2} + 2(2\,k\,T_2^5\;\alpha\,\sigma)^{1/2}}$$

α being the absorption coefficient, σ and k the Stefan and Boltzmann constants respectively.

Fig.3 gives D* vs background temperature T_2 for two chosen detector temperature $T_1 = 290$ K and $T_1 = 77$ K. It is seen that for both detector and background at 290 K, D^*ideal $= 2.10^{10}$ w^{-1}cm $Hz^{1/2}$.

Lowering the background temperature (or the detector temperature) down to zero gives only an improvement factor of $\sqrt{2}$.

Fig.4 gives D^*_{ideal} vs λ for a thermal detector : it is a constant equal to 2.10^{10} w^{-1} cm $Hz^{1/2}$ as we have seen it.

For a photoconductive detector where λ is the limit of sensibility, the background noise is limited to photons with wave-length shorter than λ and detectivity increases as λ is reduced. As far as detectivity is concerned, quantum detectors operated at room temperature are better than thermal detectors for $\lambda < 10$ µm. It is seen however that, they are far from the background limit (i.e. PbS).

II - COMPARISON OF THERMAL AND QUANTUM DETECTORS.

We have seen that with cold filters the detectivities of both detectors are comparable. Of course the sensitivity range is reduced in both cases.

The time constant $\tau = \frac{\mathcal{C}}{\mathcal{G}}$ of thermal detectors is higher. It can be decreased in two ways :

- increase $\mathcal{G}$: but detectivity is reduced
- decrease $\mathcal{C}$: either reduce thickness d ($\mathcal{C} \propto d$) or decrease temperature ($\mathcal{C} \propto T^3$).

III - INDIRECT DETECTIVITY (HETERODYNING).

It is easy to show that assuming same noise in both detections we have :

$$\frac{D^*_{\text{heterodyne}}}{D^*_{\text{direct}}} = \sqrt{\frac{\emptyset_L}{\emptyset_S}}$$

($\emptyset_L$ = local power; $\emptyset_S$ = signal power).
However the best advantage is to obtain a high spectral resolution. Heterodyne detection translates the problem of spectral resolution into a lower frequency domain where it is easier to build very narrow filters. With direct detection, high resolution must be obtained by the use of very long pathlength differences before detection and this becomes difficult with band-width less than 0.01 cm^{-1} [7].

IV - APPLICATIONS TO IMAGING.

IV - 1 - The pyroelectric vidicon.

The pyroelectric detector has a good detectivity at room temperature, uncommon high speed for a thermal detector and a great variety of possible configuration. For instance a very thin plate of a pyroelectric crystal can be cut perpendicular to the pyroelectric axis and receive an infrared

image. It gives a relief of temperature and thus a relief of polarization, (i.e. bound charges). These charges can be read with an electron beam as in a classical vidicon. We made the first proposal in 1963 [6]. It has taken 10 years to get useful images [8] [9].
The best results up to now are obtained with triglycine sulfate (TGS) single crystal plates. This is the Pyricon. The images show a 200 × 200 spatial resolution (5 lines pair per mm), a 0.5 K thermal resolution on the object with 10 images per second.
Improvements are still expected and TV in the dark is close to be competitive with visible TV.

IV - 2 - Infrared surface detection.

We shall cite :

1) the evaporography which gives an image every 10 s by specific evaporation of a liquid on the hot spots of the infrared image.

2) the Marangoni effect. In the "panicon" [10] a thin oil film deposited on a solid base has its thickness modulated by the unfalling infrared radiation. It is not a problem of evaporation but surface deformation due to local variation of surface tension which is very temperature sensitive. The Marangoni effect is faster than evaporography.
The Marangoni effect has been made more sensitive by Mr Loulergue and Mr Levy from the "Institut d'Optique" [9] recently by using liquid-liquid interface.
They claimed to get 5 images per second with 5 lines/mm on the bolometer and a thermal resolution of 0.5 K on the object.

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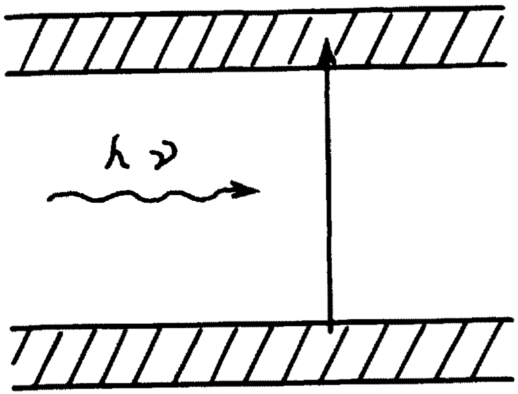
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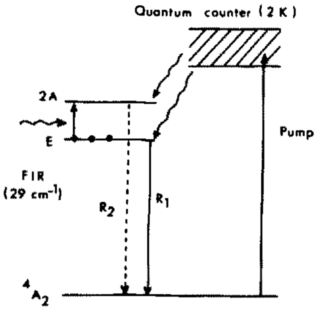
Quantum counter (2 K)
2A
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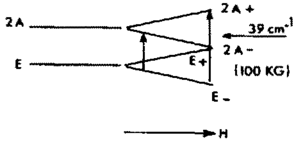
FIR
(29 cm^{-1})
R_2
R_1
Pump
$^4A_2$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E
2A +
39 cm^{-1}
2A -
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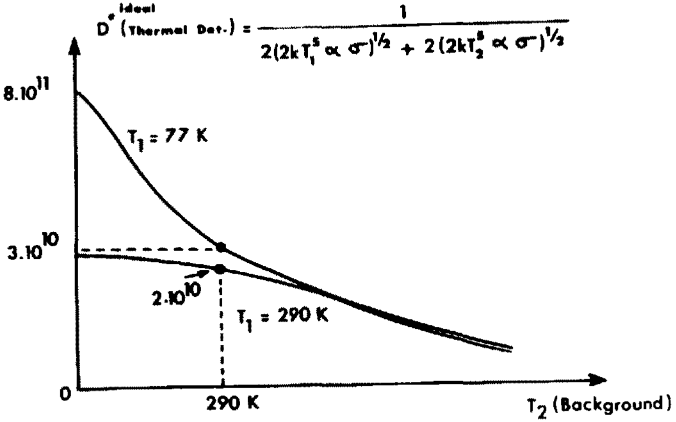
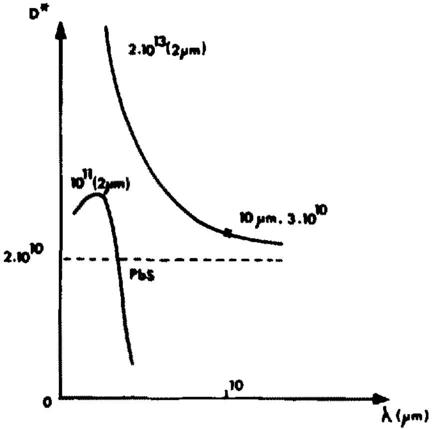
E+
E -
H


$D^{*\,ideal}_{(Thermal\ Det.)} = \frac{1}{2(2kT_1^5 \propto \sigma)^{1/2} + 2(2kT_2^5 \propto \sigma)^{1/2}}$
8.10^{11}
$T_1 = 77$ K
3.10^{10}
2.10^{10}
$T_1 = 290$ K
0
290 K
T_2 (Background)


D*
$2.10^{13}(2\mu m)$
$10^{11}(2\mu m)$
$10\ \mu m,\ 3.10^{10}$
2.10^{10}
PbS
0
10
λ (μm)