Hot filament infrared radiators and pyroelectric single-element detectors for analytical application

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The infrared source and detector are essential components of infrared analysers. They basically determine the system's resolution, its size, energy demand and price.

This paper describes the schematic set-up and the basic characteristics of radiators and pyroelectric single-element detectors that have been developed for the efficient application in the wavelength range 2…15 µm. On the one hand, the infrared sources are housed in a transistor package (TO-39, TO-8), electrical input power < 10 watts and, on the other hand, in a glass bulb with a fitted infrared window, electrical input power 15…30 watts. They are based on tungsten filaments. It is shown that the radiators are optimised for high radiation power and a direct modulation capability with a sufficient modulation depth (50 %) of up to 30 Hz. Calcium fluoride and zinc selenide were chosen as window materials.

In particular for analytical applications, pyroelectric infrared sensors with small responsive elements have been developed, which are characterised by high responsivity, high specific detectivity and an optimised spectral responsivity. As a result, responsivity values

- S_V of (500 K, 10 Hz; 25 °C, $\tau_F = 1$) $\geq$ 6,000 VW^{-1} and
- a specific detectivity D^* (500 K, 10 Hz, 1 Hz, 25°C) $\geq 4 \times 10^8$ cm $Hz^{1/2}$ W^{-1}

have been obtained for $LiTaO_3$ sensors with a responsive area of ∅ 0.5 mm.

1 Introduction

Infrared analysers are used to identify materials or to determine their concentration in mixtures of substances by means of substance-specific absorption bands. Gas analysis [1,2], the analysis of food, biological substances or technical fluids are significant fields of application. The radiation flux coming from the infrared radiator penetrates the sample to be measured, is then analysed spectrally and generates a wavelength-specific signal at the output of the infrared sensor. At present there is a tendency to use more and more thermal sensors with special narrow-band filters (e.g. for CO with a CWL = 4.64 µm, BW = 180 nm) in commercial analytical devices.

The radiation power of the infrared source together with the signal-to-noise ratio (D^*) of the infrared detector at the relevant wavelength λ determine the resolution and the long-time stability of the measurement system. Up-to-date infrared sources are thermal radiators or semiconductor radiators (laser and LED's). Thermal infrared radiators are:

- Metal wire and metal foil sources (miniature lamps, radiators in TO-packages or glass bulbs)
- Thin film sources
- Thick film sources
- Ceramic, SiC and carbon sources.

The thermal radiator's temperature, its emissivity and area determine the radiation power released.

Radiation power at the measurement wavelength λ, radiator size and the electrical input power, direct modulation capability and last but not least the price are issues of major interest for users and system developers. The tests carried out aimed at the development of infrared radiators on the basis of tungsten filaments with the following characteristics:

- High radiation power in the spectral range 2…15 µm
- Glass bulb and transistor package
- Zinc selenide and calcium fluoride windows
- Direct modulation capability < 30 Hz
- Good long-term stability and long life time
- Reasonable price.

Furthermore, pyroelectric single-element sensors will be developed using special sensor technologies [3]. These sensors are characterised by a small responsive area, a high signal-to-noise ratio and a high spectral responsivity in the wavelength range to be measured.

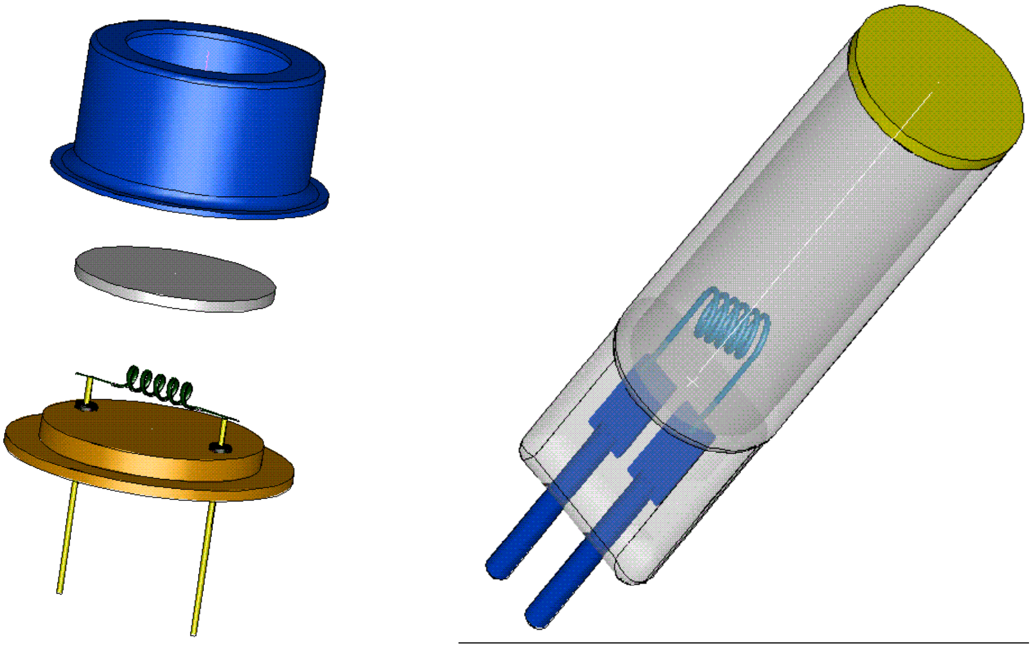
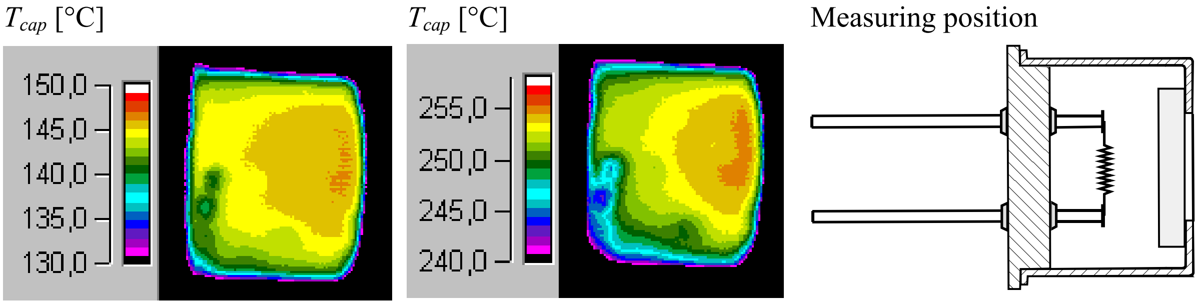


Figure 1: Schematic set-up of infrared sources in a TO package and in a glass bulb

2 Infrared Radiators

2.1 Design and Technology

Figure 1 shows the schematic set-up of the infrared sources in a TO package and in a glass bulb [4]. The TO radiator consists of the TO header with the pins enclosed in glass, the filament and the cap with the infrared window. These packages offer the following advantages: the potential use of the efficient methods and equipment of microelectronics, the large choice of available components and semifinished products and the high flexibility with regard to size and pin configuration of the package. Radiators have been built in the TO-39 package (∅ 8.5 mm × 6.5 mm) and also in the TO-8 package (∅ 14 mm × 7.5 mm). Basic technological steps are adjustment and installation of the filament, the fitting of the IR window in the cap and the sealing of the package. After the filament has been adjusted on the pins, laser beam welding is applied to join the two parts mechanically and electrically. Reliable connections have been achieved for a focus of 0.3 mm, a power value of 0.5 kW and pulse lengths of 2…10 ms. Alternatives are parallel gap welding or spot welding. Fitting the IR window into the metal cap is of decisive importance for the functioning and long-term stability of the radiator. The fitted connection should demonstrate a tightness with leakage rates smaller than 10^{-7} mbar l/s. Problems may occur when the connection is subjected to thermal loads, while the radiator is in operation. Figure 2 shows the measured temperature distribution on the cap surface when a TO-39 radiator is run in the dc mode. It is obvious that the connection between window and cap is very much subjected to thermal stress even for small electrical input power values. The measurements showed that it is necessary to perform a thermal optimisation of the overall set-up to reduce the thermal load of the fitted connection without reducing the radiation power. It is additionally inevitable to use a heat sink (cooling body) to deduct the heat from the package cap in the power range 2…10 W. The temperature range, in which the fitting connection must be stable and tight, is thus –20 °C (storage) … +200 °C. What is likewise important is to compensate the differing expansion behaviour of the two components. Several fitting techniques have been tested (gluing, soldering, welding). Gluing with special epoxies showed the best results. The transistor package is hermetically sealed using a special technique of resistance welding between transistor header and cap in an inert-gas atmosphere.



P = 1.25 W P = 2.8 W

Figure 2: Infrared images of a TO-39 radiator

The glass bulb radiators consist of the glass bulb as the basis, the pins enclosed in glass, the filament and the fitted infrared window (Figure 1). It has been the aim of these tests to develop radiators with an electrical input power of 15…30 watts for specific spectrometric applications. In order to make such radiators in the wavelength range 2...15 µm it is necessary to join the window materials mentioned earlier with the glass bulb ensuring hermetic tightness. Fitting tests have proved so far that gluing and diffusion pressure welding are not suited to provide stable and hermetically tight connections between the infrared window and the glass bulb. Adjusted glass parts and glass solder proved to produce the best joining results. The radiator's dimensions are roughly ∅12 mm x 40 mm. Figure 3 shows images of the two radiator types. Table 1 gives a summary of the properties of the filaments used.

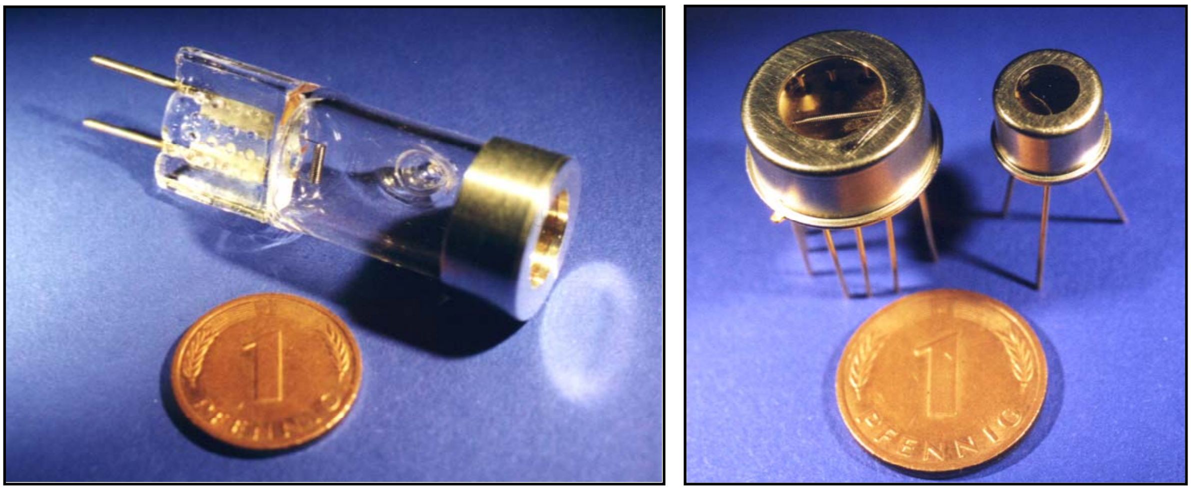


Figure 3: Two different types of infrared radiators

	Filament A	Filament B	Filament C
Maximum power [W]	20	10	6
Wire diameter [µm]	106	42	41
Number of turns	40	90	40
Length of filament [mm]	6.6	6.5	3

Table 1: Properties of used filaments

2.2 Properties

The basic parameters of infrared radiators are their spectral radiant exitance, the modulation depth in the ac mode and the electrical input power. Users and system developers prefer to determine the radiation flux Φ_S being incident on the detector area for a given measuring set-up to be able to compare radiators. Figure 4 shows the principal test set-up used to determine the radiation flux for different radiator types. The radiation flux Φ emitted by the radiator is passed over a test distance of 50 mm onto a aperture with ∅ 1 mm, behind which a gauged pyroelectric detector with a special narrow-band filter is installed. This filter has a central wavelength of 3.98 µm with a band width of 78 nm. This type of filter is frequently used as a reference channel in gas analysis. The radiation flux Φ_S is determined from the known responsivity $S_{V\lambda}$ of the detector and the signal voltage u_S (λ) measured. Since a pyroelectric infrared detector is used, the radiation is modulated with a chopper at 5 Hz. Figure 5 shows the radiation flux Φ_S measured for assembled radiators with various filaments and for different electrical input power values. Two commercial infrared sources (IS1 and IS2) with transistor package have been compared in view of their radiation flux. It has been shown that the radiation power of the radiators developed is sufficiently high for numerous applications. Attention should be paid to the fact that – as the filament temperature rises – the spectral radiant exitance increases but the mean life time of the radiator decreases.

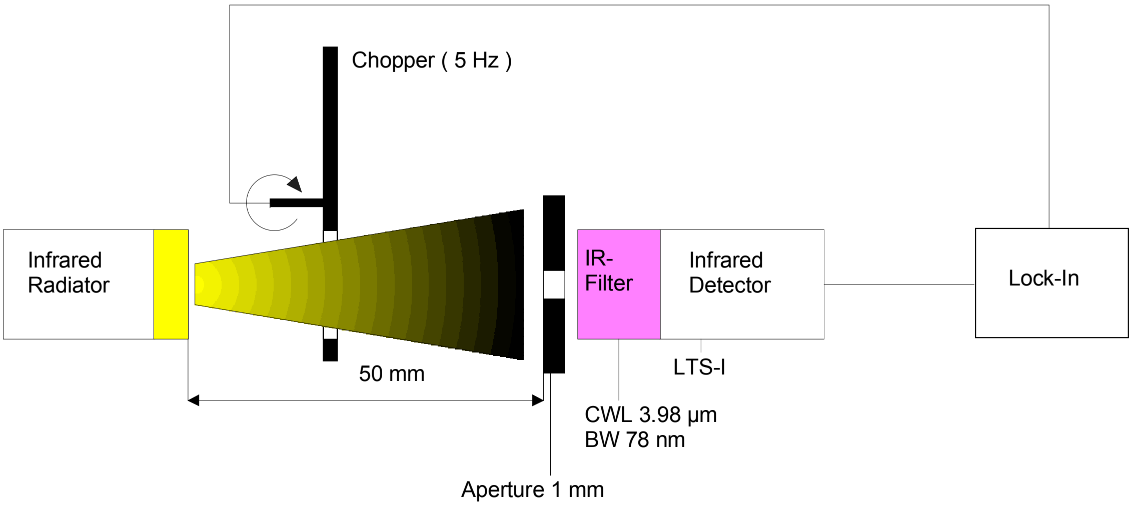


Figure 4: Measuring device for the comparison of different radiators

The term modulation depth m describes the radiator behaviour for direct electrical modulation. The modulation depth results from:

$$m = [\Phi_{Smax} - \Phi_{Smin}] / \Phi_{Smax} \times 100\ \% \qquad (1)$$

Figure 6 shows that the modulation depth m for a TO-39 radiator with filament C is a function of the frequency for different electrical input power values. The thermal time constant decreases as the filament temperature rises and the obtainable modulation depth increases at a constant frequency. Modulation depths larger than 60 % have been obtained in the technically interesting frequency range *f* < 20 Hz at an electrical input power of approximately 2.8 W.

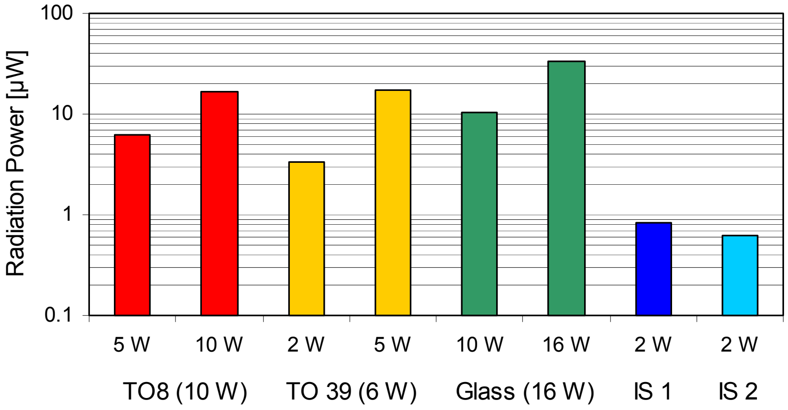


Figure 5: Measured radiation power for different radiator types

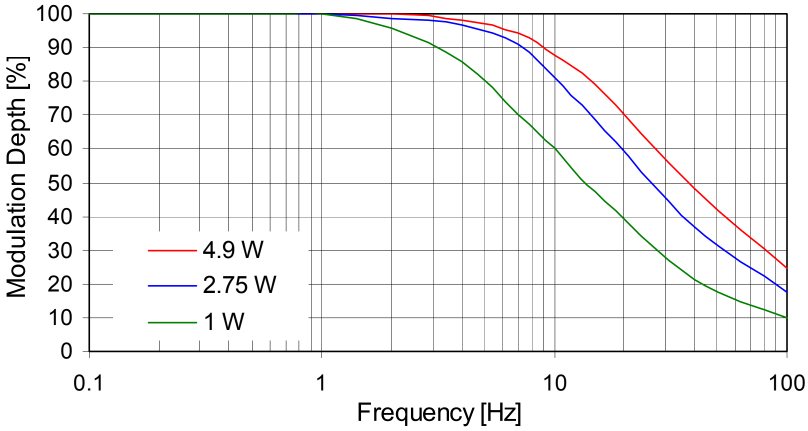


Figure 6: Modulation depth vs. frequency

3 Pyroelectric Detectors

3.1 Design

An essential benefit of pyroelectric infrared detectors on the basis of $LiTaO_3$ is that they show properties that are long-term stable and reproducible [5]. The responsivity depends only very slightly on the ambient temperature compared with other thermal detectors. Figure 7 gives the principal set-up of a detector in the voltage mode. The detector consists of the $LiTaO_3$ chip and a low-noise preamplifier. Both components are housed in a TO transistor package with an infrared-transmissive window. In accordance with the application, broad-band materials or special interference filters for precisely defined wavelength ranges are used as infrared windows.

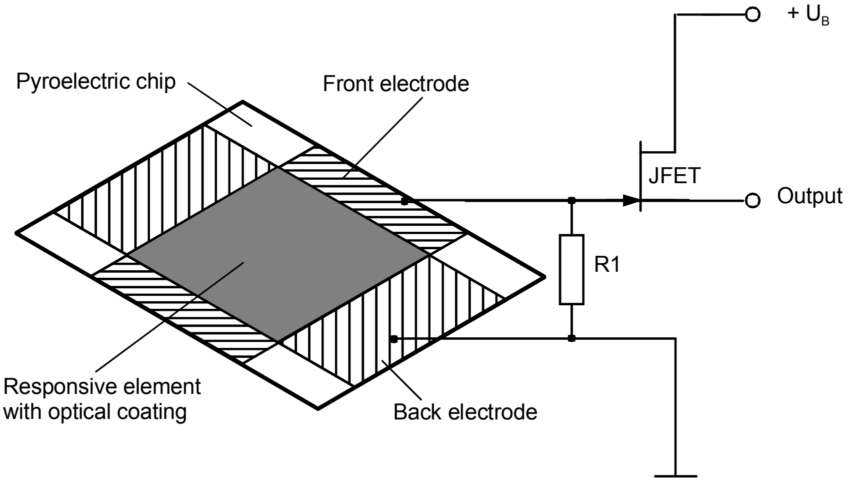


Figure 7: Fundamental set-up of single-element detectors

3.2 Properties

Essential detector parameters are the responsivity S_V and the specific detectivity D^* as a measure for the signal-to-noise ratio. The chosen detector configuration is given by:

$$S_V \sim \alpha / A_S \tag{2}$$

and

$$D^* \sim 1 / d_P^{1/2} \tag{3}$$

with:
- α absorption coefficient of the responsive element,
- A_S size of the responsive element,
- d_P thickness of the responsive element.

The research staff at the Institute for Solid State Electronics have developed and introduced numerous technologies[3] in order to improve the parameters of $LiTaO_3$ detectors and to adjust the detector layout to the application in the best way. These technologies include photolithographic patterning of the responsive elements on the $LiTaO_3$, mechanical and chemo-mechanical polishing to a thickness of app. 20 µm, ion beam etching for the further reduction of the thickness d_p of the responsive element to less than 5 µm and for the three-dimensional patterning of the chips. They also include the evaporation of highly absorbing metal black coatings for the wavelength range 0.8…15 µm and the production of custom-made anti-reflection coatings on the responsive element [5]. The photolithographic patterning of the front and back electrode on the pyroelectric chip allows responsive elements of some dozen square micrometers (arrays) to be easily produced. Most often it is useful to choose element areas of ≥ ∅ 0.25 mm for the application of single-element detectors in infrared systems. Table 2 gives an overview of the essential properties of pyroelectric single-element detectors. The responsivity decreases at chopper frequencies of $f \geq 10$ Hz at $1/f$. The temperature coefficient of the responsivity is ≤ + 0.07 % / K. Figure 8 shows the measured frequency dependence of the specific detectivity for different detectors. Figure 9 demonstrates the spectral responsivity $S_{V\lambda}$ for detectors of the same geometry with a metal electrode, an 3…5 µm antireflection coating and a metal black coating. The absorption coefficient of the responsive element obtained with the metal black coating is about 0.95 in the wavelength range 1…15 µm. The disadvantage of black layers is that metal masks have to be used to pattern them. Thus the lateral resolution is reduced. The antireflection coating is a $\lambda/4$ layer made of silicon-rich silicon nitride [6]. A PECVD has been used to evaporate it. It is designed for a wavelength of 4 µm. These coatings may be patterned photolithographically.

Type of detector	LT	LTS*-I	LT-I	LTS*-I	LT-I	LTS*-I
d_P [µm]	20	5	5	5	5	5
A_S [mm^2] or ∅ [mm]	2 × 2	2 × 2	∅ 1	∅ 1	∅ 0.5	∅ 0.5
S_V [V/W]	380	500	1,200	1,800	4,500	7,200
D^* [10^8 cm Hz$^{1/2}$ W^{-1}]	5	**12**	6	9	3	5

Table 2: Properties of single-element detectors based on $LiTaO_3$ [500 K, 10 Hz, 25 °C, 1 Hz bandwidth, $\tau_F = 1$], S* black coating, τ_F window transmission, A_S size of the responsive element

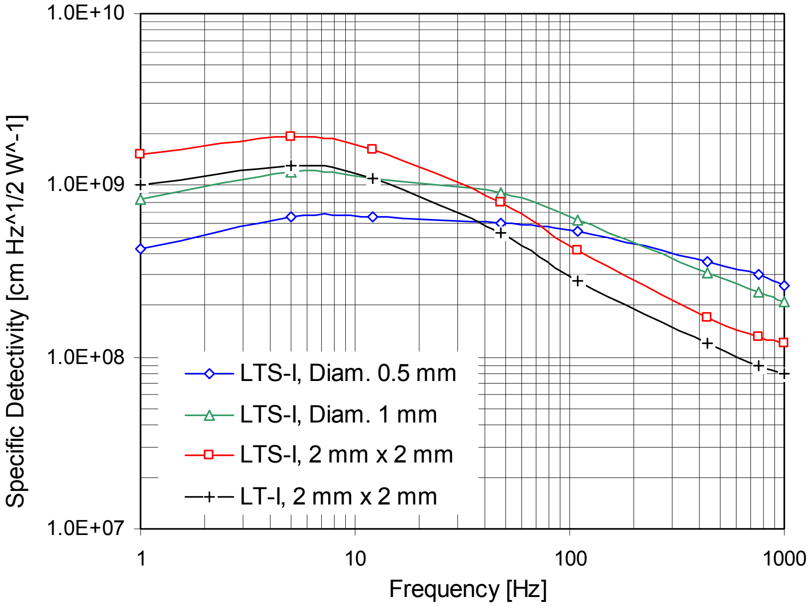


Figure 8: Frequency dependence of the specific detectivity for different single-element detectors

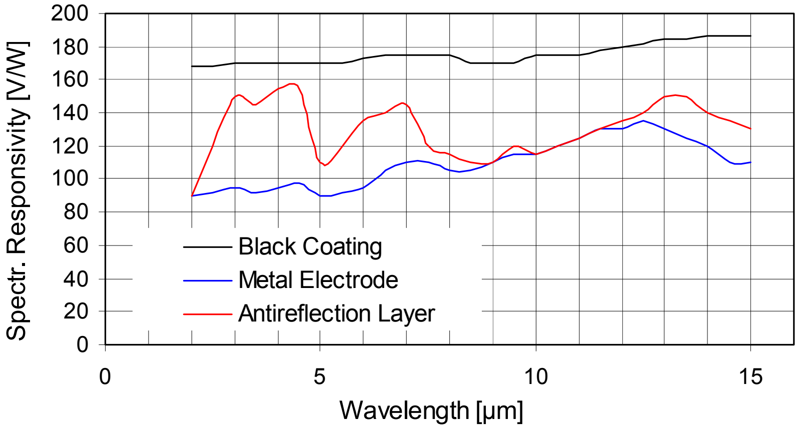


Figure 9: Comparison of spectral responsivity of single-element detectors with different absorption layers and KRS-5 window at 15 Hz

4 Conclusion

First prototypes of thermal infrared radiators in the TO transistor package and in the glass bulb have been set up and measurements have been carried out to evaluate them. The properties measured clearly show that the radiators have a good radiation power and that they may be modulated directly up to some hertz. Further tests will focus on the long-time stability of the sources and also on the further improvement of the radiation power at a constant electrical input power by using optical components (spherical mirrors) and special inert gases.

Precisely adjusted detector technologies allowed pyroelectric single-element detectors to be developed, whose characteristic features are a very high signal-to-noise ratio and a high spectral responsivity. Since the technology is very flexible, highly user-specific detectors may be manufactured at comparatively low costs.

The radiators developed are typically used in the infrared analysis and the spectrometry. Furthermore, the pyroelectric infrared sensors may be utilised in interferometers, pyrometers and in special security systems.

5 Acknowledgements

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