

# Optimisation of a pulsed IR source for NDIR gas analysers

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*Thermal sources which radiation can be modulated by supplying the heater with alternating voltage are used in gas analysers operating on the basis of absorption of infrared radiation. Suitability of the source for direct modulation (i.e. without the use of a mechanical chopper) can be determined by frequency limit of modulation and energetic efficiency. Two IR source models, which heaters are made of platinum foil, have been studied. The maximum operating temperature of the sources was 1000°C. The models varied with regard to the way of heat transfer. Conduction through layer of gas between the platinum foil and the substrate was a dominating way of exchanging heat for the first source. Cooling of the heater of the second source took place due to the heat conduction in the platinum foil. Frequency limits obtained for the examined thermal source models are 2 and 5-times higher than for microbulbs, respectively, which are a commonly applied infrared source in simple gas analysers.*

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**Keywords:** infrared sources, gas sensors, gas analysis.

## 1. Introduction

Non-dispersive infrared (NDIR) methods have been applied in gas analysis for over half a century. Gas concentration in these methods is determined on the basis of measurement of IR absorption within the range of 3–10  $\mu\text{m}$  wavelengths. In order to acquire adequate measuring accuracy of the concentration, modulation of this radiation is indispensable.

Infrared sources applied in early approaches of NDIR analysers had significant power as they were first of all adapted to systems with opto-acoustic detectors [1,2] characterised by a relatively small sensitivity. The only way of modulation of radiation emitted by such sources was to apply mechanical choppers. Thermal or photon detectors equipped with interference filters are more often put into operation in contemporary analysers. They are characterised by greater sensitivity and that is why they can co-operate with the sources of lower power and small thermal mass. Employing alternating voltage supply for such sources enables obtaining sufficient modulation of infrared radiation intensity. This solution is labelled as direct or electric modulation.

Basic advantage of direct modulation is elimination of the mechanical chopper from the measurement system of the analyser. Owing to that lowering of size and mass of the detection block is obtained as well as substantial reduction of production costs. Moreover, reliability of an analyser with no moving parts is higher.

A frequently used sources of infrared radiation in simple detection blocks [3,4], designed for measurement of carbon monoxide and dioxide and hydrocarbons concentration, are microbulbs [5]. They permit direct modulation of radiation within the frequency range up to several Hz. A certain disadvantage of the microbulbs is very high temperature of their operation (up to 2000 K) which causes significant power radiation being emitted in a short-wave range. This radiation may be a cause of generation of parasitic components of the detector signal.

Infrared sources with lower maximum temperature (1000–1200 K) designed for direct modulation are often made of thin foil [6,7]. In some cases, the surface of foil is subjected to special treatment ensuring increasing emissivity value [8]. Special modelling of the surface structure gives also strong dependency of emissivity upon the radiation wavelength. This permits to adjust radiation spectrum of source to the band of absorption of gas which concentration is being measured [9]. Similarly as in the case of microbulbs, direct modulation frequency for foil sources should not be too high (several Hz). Nevertheless, it is still sufficient for most of the applications.

In some NDIR analysers, modulation of radiation with significantly higher frequency is essential. Capnometric studies applied in medicine for measurement of carbon dioxide concentration in exhaled air are a particular case of such situation [10,11]. In these studies, 30–50 measurements of concentration per second are carried out. IR sources adapted for direct modulation with such frequency usually have dimensions in the fraction of millimeter range and very small thermal mass. Constructing of miniature

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sources is frequently carried into effect with the use of silicon micromachining technologies applied in production of electronic elements. Filament of such sources is made of polycrystalline silicon [12,13]. Operational temperature of silicon filament can reach 1500 K, and modulation frequency even 30 kHz [14]. For source heaters, platinum films applied to thin SiO<sub>2</sub> substrate are also used. Fast sources with higher power are made in the process of thin- and thick-layer technology [16,17]. A characteristic feature of these sources is their adaptation to pulse operation with low duty cycle.

Electroluminescent diodes emitting radiation in the mid-infrared (Mid-IR LEDs) have been used for a couple of years as radiation sources in NDIR analysers [18–20]. The diodes enable swift pulsed radiation modulation. Nonetheless, these sources are infrequently used nowadays because of low output power of the emitted radiation and strong dependency of power and spectrum characteristics on temperature. Moreover, current Mid-IR LED prices significantly exceed the prices of thermal sources.

The objective of the following work was to elaborate construction of a simple and reliable source adapted for direct modulation. The sources are assigned for application in various types of NDIR analysers.

## 2. Theoretical models

IR source designed for direct modulation should be characterised by low thermal inertia which means that the ratio of volume to the surface of the element heated by flowing current should be as small as possible. That is why metal filament or foils are used for such sources construction. Apart from suitable thermal properties, the elements should be characterised by good mechanical parameters since their vibration or deformation can cause interference of IR signal detector and influence measuring accuracy of concentration inconveniently. Thus, a compromise between mechanical stability and small thermal mass is indispensable. Hence, foil thickness the sources are made of is 10–50 μm [6,7].

Part of heat of every infrared source is given off by radiation. This way of lowering source temperature is called radiation self-cooling. For adequately constructed sources with high maximum temperature, radiation self-cooling can be a dominating way of heat transfer. It can be proved that

for 10-μm platinum foil with emissivity equal to 0.8 time of radiation self-cooling from temperature 1200 K to 685 K is app. 135 ms. Ten-times decreased radiation power for wavelength 4 μm corresponds to such a change of temperature. Thus it is apparent that in this case radiation self-cooling is sufficient to obtain deep modulation at 5 Hz frequency. Adapting source to higher modulation frequencies requires additionally other ways of heat transfer. Phenomena that can be used for this purpose are: heat conduction through insulator layer, convection cooling, and heat transfer through conduction in the heater material.

Two alternative IR-source models appropriated for direct modulation have been considered inhere. Their schemes are presented in Fig. 1. In the first one (A-type source), additional heat transfer from the source surface takes place through the insulator layer. Loss of heat for conduction through the insulator is proportional to the difference of source and substrate temperatures. Linear dependence of heat loss upon temperature difference can be assumed also for convection exchange [12,15].

In the second model, heat is transmitted through conduction in material which B-type source heater is made of. Transferred heat is received through supports or other construction elements the heater is fixed to.

Changes of temperature over a time for A-type infrared source are described with a simple heat balance equation

$$\frac{dT}{dt} = \frac{1}{c\rho} p_{el}(t) - \frac{1}{c\rho d} k(T - T_0) - \frac{1}{c\rho d} \varepsilon \sigma (T^4 - T_0^4), \quad (1)$$

where  $c$  is the specific heat of the material,  $\rho$  its the density,  $d$  is the foil thickness,  $k$  is the heat transfer coefficient,  $\varepsilon$  is the emissivity,  $\sigma$  is the Stefan-Boltzmann's constant. Electric power  $p_{el}(t)$ , dissipated in volume unit, is a function of the supplying voltage  $U(t)$  and the layer resistance changing with the temperature  $R(T)$

$$p_{el}(t) = \frac{P_{el}(t)}{Sd} = \frac{U^2(t)}{SdR(T)}, \quad (2)$$

where  $P_{el}$  is the total power, and  $S$  is the surface of one side of layer. Basic assumption taken for the above model is neglected heat capacity of the insulator. This assumption is

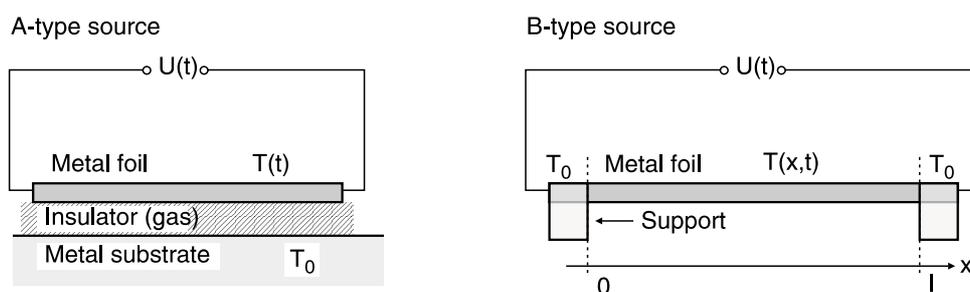


Fig. 1. IR source models for direct modulation with heat transfer through insulator (A-type source) and through conduction in the material of the heater (B-type source).

approximately valid for gas filled space between heater and substrate.

For B-type source the changes of temperature distribution over a time are described with thermal conductivity equation

$$\frac{\partial T}{\partial t} = \frac{1}{c\rho} p_{el}(x,t) + \frac{\omega}{c\rho} \frac{\partial^2 T}{\partial x^2} - \frac{2}{c\rho d} \varepsilon\sigma(T^4 - T_0^4), \quad (3)$$

$$T(0,t) = T(l,t) = T_0$$

where  $\omega$  is the heat conductivity. Dependence of electric power density upon the co-ordinate  $x$  results from dependence of resistivity on temperature

$$p_{el}(x,t) = \frac{P_{el}(t)}{Sd} \frac{r[T(x,t)]}{r_{av}(t)} = \frac{U^2(t)}{l^2} \frac{r[T(x,t)]}{r_{av}^2(t)}, \quad (4)$$

where  $r$  is the resistivity and  $r_{av}$  is its mean value along whole foil length.

Current flowing through the source heater heats it over a time of the supplying pulse  $t_i$ . Heater cooling occurs in  $t_r - t_i$  time, where  $t_r$  is the time of pulses repetition. If resistance of the heater material depends on temperature, two plausible ways of supplying the source should be considered:

- $P_{el}(t) = P_0$  for  $0 < t < t_i$ ;  $P_{el}(t) = 0$  for  $t_i < t < t_r$  – supplying with constant power pulses,
- $U(t) = U_0$  for  $0 < t < t_i$ ;  $U(t) = 0$  for  $t_i < t < t_r$  – supplying with constant voltage pulses.

Since temperature coefficient of resistivity for metals has positive value, then while supplying with constant voltage pulses, power dissipated in the source heater diminishes over a time of supplying pulse duration. In case of supplying with constant power pulses, voltage on the heater increases.

Equations (1) and (3) were solved with finite difference scheme for input function in form of square wave of voltage or power ( $t_i = 0.5 t_r$ ). Obtained solutions compose dependencies of temperature or temperature distribution upon time. On the basis of these solutions, using Planck's law, time dependence of radiation power emitted in defined

wavelength band were computed. Sample results of the computation of temperature and radiation power for A-type source made of 10  $\mu\text{m}$  platinum foil are presented in Fig. 2. The source is supplied with constant power pulses. Radiation power is calculated for 3.9  $\mu\text{m}$  wavelength and 100-nm bandwidth. These quantities correspond to typical parameters of interference filters for reference channel in NDIR analysers designed for measurement of CO, CO<sub>2</sub> and HC concentration.

Limit frequency  $f_{0.5}$  has been assumed as a suitability measure of direct modulation. For this frequency variable component of radiation power  $P_{rad}$  in the chosen band equals half of amplitude of radiation power obtained at mechanical modulation

$$P_{rad}(t_i) - P_{rad}(t_r) = 0.5(P_{rad,DC} - P_{rad,0}), \quad (5)$$

$$f_{0.5} = 1/t_r$$

$P_{rad,DC}$  value is radiation power of source supplied with constant potential difference, and  $P_{rad,0}$  is the power of background radiation. Temporal run of radiation power presented in Fig. 2 corresponds to fulfilling Eq. (5).

The ways of defining limit frequency can be various. RMS values of variable components of radiation power at mechanical and direct modulation could be compared, for instance. Analysis of solutions of Eqs. (1) and (3) showed that, independently from a source type and its parameters, diminishing RMS value of radiation power by half in relation to the value received for mechanical modulation is obtained for frequency almost two times lower than it is defined by Eq. (5).

$$f_{0.5(RMS)} = (0.5 - 0.6)f_{0.5(p-p)}. \quad (6)$$

In order to receive higher frequency limit it is necessary to increase the heat transfer. For A-type source it means increasing value of  $k$  coefficient of insulator. For B-type source shortening of the foil length  $l$  is indispensable. Additional heat loss accelerating cooling of film or foil causes higher electric energy necessary for source supplying in order to get given maximum work temperature. In relation to that, energetic efficiency of the source decreases. This

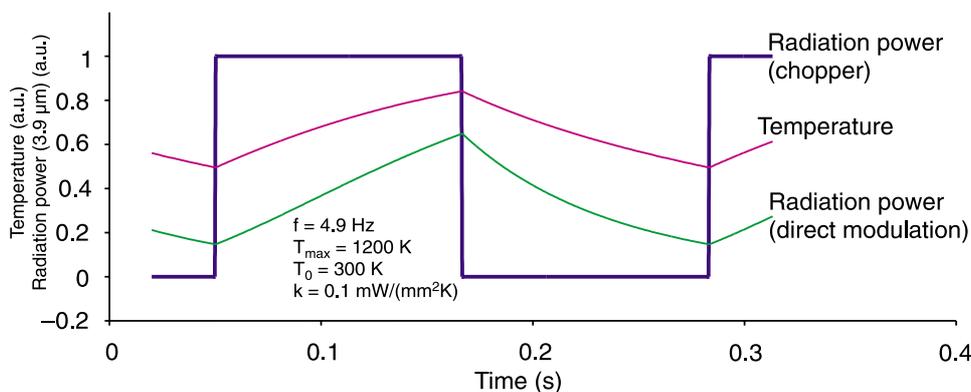


Fig. 2. Exemplary time dependence of temperature and radiation power for A-type source.

quantity can be defined as the ratio of RMS value of variable component of IR radiation power in the chosen band to RMS value of electric power dissipated on the source heater

$$\eta(f) = \frac{\text{RMS}[P_{\text{rad}}(t, f) - \overline{P_{\text{rad}}(t, f)}]}{\text{RMS}[P_{\text{el}}(t)]} \quad (7)$$

For a given source and constant RMS value of electric power, energetic efficiency reaches maximum value at frequency approaching zero. This value is equal to the ratio of radiation power at constant voltage to electric power

$$\eta_{\text{max}} = \eta(f \rightarrow 0) = \frac{P_{\text{rad}, \text{DC}} - P_{\text{rad}, 0}}{P_{\text{el}, \text{DC}}} \quad (8)$$

Maximum energetic efficiency and limit frequency defined by Eqs. (8) and (5) comprise a couple of parameters permitting comparison of various IR thermal sources. Both quantities depend on the source construction, maximum temperature reached at DC supply, and a way of supplying.

Theoretical values of limit frequency and energetic efficiency were computed on the basis of solutions of Eqs. (1) and (3) for different maximum temperatures and different values of parameters characterising additional heat transfer ( $k$  for A-type source and  $l$  for B-type source). The computation results for heating with constant power pulses are presented in Fig. 3. Dependencies between  $\eta_{\text{max}}$  and  $f_{0.5}$  are presented in form of two families of the curves corresponding to the defined structure ( $k = \text{const}$ ,  $l = \text{const}$ ) or defined maximum temperature at DC supply ( $T_{\text{DC}} = \text{const}$ ,  $T_{\text{DC}, \text{max}} = \text{const}$ ).

Energetic efficiency of A-type sources is slightly better. For instance, for A-type source reaching temperature 1200 K at DC supply, maximal energetic efficiency equals 0.0014 and corresponds to 20 Hz frequency limit. For B-type source which maximum temperature is also 1200 K,

this value is 0.0010. Furthermore, it can be observed that for A-type sources, the maximum work temperature influences on the limit frequency to a smaller degree than for B-type sources.

The presented results have been obtained using very simple theoretical models neglecting numerous effects occurring in real IR sources. In particular, constant value of emissivity has been assumed. In reality, this quantity depends on wavelength and temperature. Emissivity value impacts the frequency limit and maximum energetic efficiency. For the sources with radiation self-cooling, increase in emissivity causes faster energy giving off in the wide range of wavelength. Thanks to that limit frequency increases. Energetic efficiency remains constant. In case of the sources the radiation cooling of which is neglected in comparison with other ways of heat transfer, emissivity has an impact on energetic efficiency to a greater degree than on the limit frequency. Dependencies of limit frequency and energetic efficiency upon emissivity for a source with radiative self-cooling and A-type source characterised by high value of  $k$  coefficient are presented in Fig. 4.

Dependencies of maximum energetic efficiency on frequency limit for A-type source and B-type source are similar (Fig. 3). In that case, choice of structure type should be based on other premise. A-type source advantage is possibility to construct a heater with relatively high resistance. It is beneficial as it permits to avoid interference of detector signal which results from too high currents flowing in electronic circuit of the analyser. Fundamental technical problem while constructing A-type source is to ensure strictly defined and stable heat flow between foil the heater is made of and a substrate. If gas layer comprises the insulator, the distance of foil from the substrate should be constant on overall surface and should not be subject to change as a result of foil deformation. Air layer indispensable for obtaining the high heat transfer coefficient  $k$  is very small. For instance, 200  $\mu\text{m}$  air layer corresponds to the value  $k = 0.3 \text{ mW}/(\text{mm}^2 \text{ K})$ . Ful-

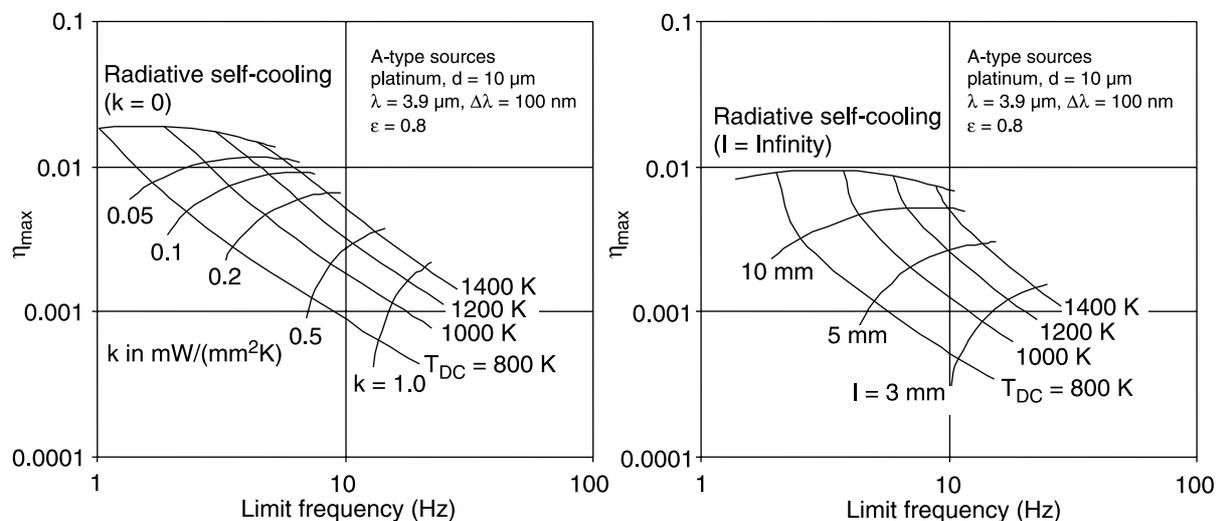


Fig. 3. Dependence between maximum energetic efficiency and limit frequency for A- and B-type sources.

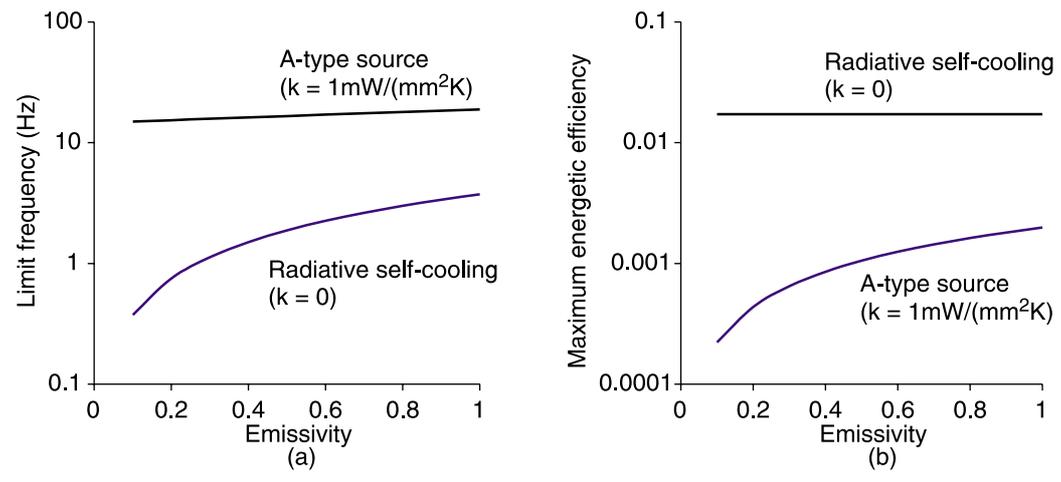


Fig. 4. Influence of emissivity on frequency limit (a) and maximum energetic efficiency (b).

filling this condition is difficult if a length of foil strap the heater is made of is 20 mm.

Receiving high frequency limit value for B-type source which heater is made of 10 μm platinum foil requires about 5-mm foil length (see Fig. 3). If foil strap width is 1 mm, then resistance of cool heater (T = 300 K) is only app. 0.5 Ω. In order to avoid the necessity of supplying the heater with too high current, filaments with smaller width should be applied.

### 3. Technology

Crucial problem occurring while constructing infrared sources is the choice of material for the heater. In the discussed study, solely sources made of platinum were examined because it is a material enabling work with relatively high temperatures and it does not oxidise when it is exposed to the air. Moreover, platinum is suitable for making both thick layers and foil of 10 μm thickness. The major disadvantage of platinum is its small emissivity, which amounts from 0.08 in low temperatures to 0.18 for 1000 K for smooth surface. Modification of the surface, however, permits significant enlargement of emissivity.

Two IR source models designed for direct modulation have been worked up (Fig. 5). Heater of the first source (model of A-type source) is made of 10 μm foil placed 200 μm from the substrate. Total length of the heater is

about 20 mm and its resistance was approximately 1.3 Ω in temperature 300 K.

Type B source model is made according to thick-layer technology. The thickness of the platinum layer is 8 μm. A part of the 4-mm long path was torn from the alumina substrate and raised to about 500 μm. Due to the fact that resistivity of thick platinum layers containing glaze is significantly higher than for pure metal, “cold” resistance of the heater amounted to 3 Ω in this case.

Shape of both sources is similar but size of the heater and its distance from the substrate varies. It can be proved that dominating way of heat transfer in model of A-type source is conduction through the air layer between heater and substrate. For the model of B-type source, heat conduction within the material of the heater itself is relevant.

### 4. Measurements

Testing of the elaborated infrared source was conducted in a set-up which scheme is presented in Fig. 6.

In static examination the sources were supplied with constant voltage with maximum value which enabled obtaining heater temperature equal to app. 1300 K. Radiation emitted from the source was modulated at 280 Hz frequency with the use of mechanical chopper. Measurement of the radiation power was performed with the use of cooled photovoltaic MCT detector. In front of the detector,

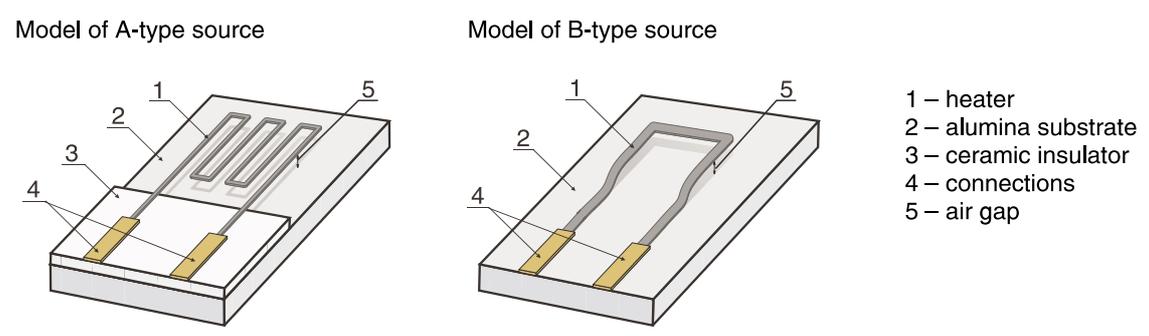


Fig. 5. Structure of tested infrared source models.

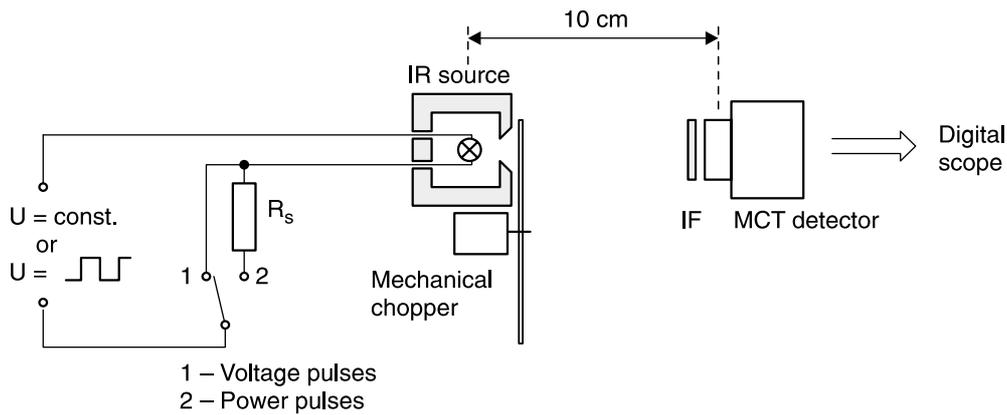


Fig. 6. Scheme of the system for static and dynamic examination of the IR sources.

there was placed an interference filter with the central wavelength  $3.89 \mu\text{m}$  and  $100\text{-nm}$  wide transmission band. In all of the measurements distance between the detector and source was  $10 \text{ cm}$ . Because of fixed distance relative signal of the detector equal to the ratio of the signal to the electric power dissipated on the heater, can be treated as a value proportional to the maximum energetic efficiency of the source.

Mechanical chopper was not used in the system during dynamic testing. The sources were supplied with alternating voltage in a shape of a square wave. Voltage was fed directly into the source or via the serial resistor  $R_s$ . Application of this resistor aimed at fulfilling the condition of supplying the source with constant power pulses. A value of the resistance  $R_s$  was selected in such a way as it would equal mean resistance of the source heater in the full range of operation temperatures. It can be shown that if the heater resistance changes twice (from  $R_0$  to  $2R_0$ ) and serial resistance value is  $1.5R_0$ , then power dissipated in the source changes only by  $4\%$ .

In dynamic tests dependence of amplitude of detector signal on frequency was set which allowed defining frequency limit.

Dependence of relative detector signal on limit frequency for various sources is presented in Fig. 7. The results for models of A-type and B-type source are compared

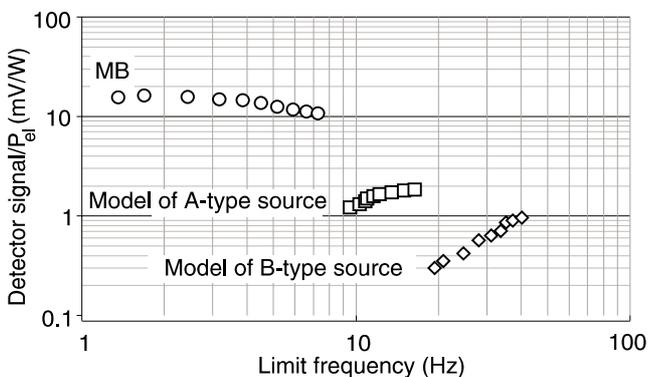


Fig. 7. Dependence of relative detector signal on limit frequency for models of A- and B-type sources and microbulb.

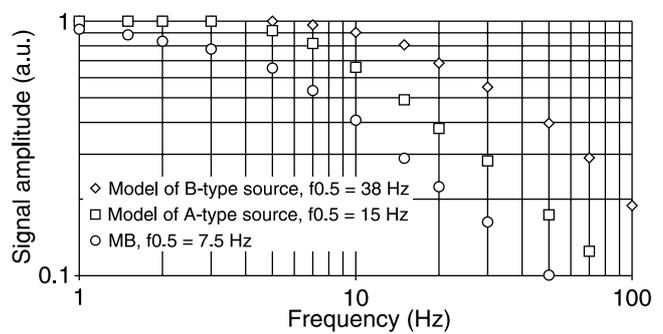


Fig. 8. Frequency characteristics of radiation power for direct modulation.

with data for microbulb (MB) which is a commonly applied IR source in simple NDIR detective modules [5]. Character of the received dependencies corresponds to theoretical anticipation (see Fig. 3).

Results of measurement of frequency characteristic of radiation power emitted by examined infrared sources are presented in Fig. 8. Amplitude of detector signal was related to amplitude obtained with DC supply and radiation modulation with the use of mechanical chopper. Course of characteristic is similar to course for low-pass RC filter. For high frequency, amplitude of power of radiation changes like  $1/f$ .

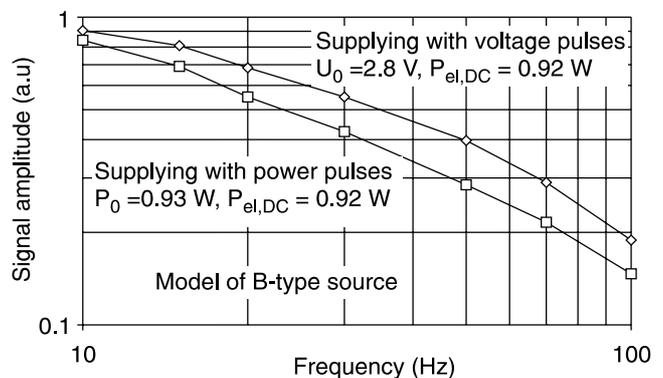


Fig. 9. Comparison of frequency characteristics for various ways of supplying.

Results presented in Figs. 7 and 8 were received for a case of supplying with constant voltage pulses. If a source is supplied with constant power pulses, then the energy dissipated on the heater over a pulse is lower, which causes lowering of limit frequency value. Outcome of comparing both ways of supplying received for model of B-source is presented in Fig. 9. Voltage and  $R_s$  resistor value were selected in such a way so electric power dissipated in the heater with DC supply would be the same.

## 5. Conclusions

Comparing various infrared sources assigned for direct modulation both possibility of obtaining high modulation frequency and energetic efficiency should be taken into consideration. With constant thickness of foil the source heater is made of, limit frequency can be enhanced by decreasing length of the source or diminishing its distance from the substrate. Dependencies of energetic efficiency on frequency limit for both methods of accelerating the process of cooling are similar. Due to easiness of construction, heat transfer by conduction in the material of the heater (B-type source) seems to be justified. Transmitting heat through the air layer (A-type source) is effective only when the distance of the foil from the substrate is very small. Practical accomplishment of such sources with several millimeters heater dimensions is thus very problematical.

Applying thick platinum film as the heater material has two basic advantages. Resistance of the heaters is relatively high thanks to which not too high currents flow in the electronic circuits of the source. Furthermore, emissivity of thick layer is significantly greater than for rolled foil. Nevertheless, elaborating a simple and reproducible technology for constructing thick-layer non-adhesive heaters is crucial.

Frequency limit obtained for model of B-type source is approximately 5 times higher than for microbulb, but energetic efficiency is 10 times lower. It should be noted that this source operates in lower temperatures and radiation spectrum is better "adjusted" for NDIR analyser requirements.

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**Rudolf Hartmann**

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