Visualization of infrared radiation using thermal sensitive foils

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Abstract
The paper describes a set of demonstration school experiments where infrared radiation is detected using thermal sensitive foils. The possibility of using standard glass lenses for infrared imaging is discussed in detail. It is shown that with optic components made from glass infrared radiation up to 2,5μm of wavelength can be detected. The effect of surface emissivity is studied qualitatively where in different experimental arrangements lower or higher detected irradiance from a low emissivity surface can be obtained.

Introduction

The visible part of the electromagnetic spectrum is surrounded with ultraviolet radiation (UV) at short wavelengths and infrared radiation (IR) at long wavelengths. The existence of both parts of invisible radiation is well known to the general public, especially in connection with two actual environmental problems: ozone hole and green house effect. The human body is somehow sensitive to these parts of the electromagnetic spectra – heat radiation (IR) and sunburn (UV) but human senses cannot detect these radiations directly.

There are two frequently used possibilities for the detection of infrared radiation in school demonstration experiments:

1) Photodiode. This is a semiconductor device where absorption of IR photon generates an electron-hole pair and this causes an electric voltage or current in the outer circuit. The spectral sensitivity of these devices is limited to near the IR region. The absorption edge (and at the same time the detection limit) depends on the semiconductor band gap. For the most common semiconductors the absorption edges wavelengths are the follows: Si – 1.1 μm, GaAs – 0,82 μm and Ge – 1.7 μm[1]. This is a very simple and cheap method and when the photodiode output is transferred, for instance, to an acoustic signal, it is suitable for experimentation in front of a large audience. Instead of a photodiode the phototransistor can be used which provides higher sensitivity [1].

2) Video camera. The photodiode is a point detector giving information about IR at one "point". Images in near IR region can be realized with a standard amateur video camera, especially when it is equipped with an IR night vision mode[2]. The CCD or CMOS chip in these cameras is made solely from silicon and thus the sensitivity limit is around 1μm in

[1] Silicon and Germanium are so called indirect band gap semiconductors for which the absorption from the absorption edge towards shorter wavelengths grows very slowly. In the following text Silicon will be considered to absorb radiation up to 1,0 μm which is more realistic.
[2] Contemporary video cameras available on the market are only rarely equipped with IR night vision mode. But most black and white cameras do not have an IR cut-off filter in front of CCD chip and thus they are sensitive up to 1μm in wavelength.

wavelength. There are many published papers which describe school experiments of an IR image with cameras [2-8].

In this paper another possibility for the detection and imaging in near IR which is very suitable for school demonstrations is described. This method exploits liquid crystal thermal sensitive foils (TSF) and the physical principle of IR detection is very simple: IR radiation is absorbed by the TSF, heat it up and the foil changes its colour.

TSF are widely used for rough temperature measurement of home aquariums or the human body for instance. They change their colour with the temperature over a relatively narrow temperature scale – only a few degrees centigrade, and that is why they can serve as quite sensitive and fast thermometers. Nowadays they are also commercially available in large sizes at a convenient price (approx 25 EUR per 12’’ times 12’’ sheet).

Using an ordinary glass lens for infrared imaging

In comparison with the semiconductor detectors there is no strict physical limit in spectral sensitivity in IR detection with TSF. But in most experiments additional optical components are necessary which can introduce a limitation in the spectral sensitivity. The main restriction is provided by absorption in glass optical elements.

The infrared thermal imaging cameras must be able to detect mid-infrared radiation even at wavelengths of about 10 μm. For this purpose special materials for optical elements are necessary, e.g. Germanium with an excellent transmittance from 2μm up to 14μm. But these components are very expensive even for a small lens diameter. Under certain conditions an ordinary glass lens can be used for this purpose.

Optical glass has a relatively good transmittance up to wavelength 2,5μm or even higher [9], depending on the particular type of glass. Absorption at higher wavelengths limits the possibility of infrared imaging only for quite hot objects. Spectral distribution of black body radiation is described by Planck’s law which is for selected temperatures depicted in Fig. 1.

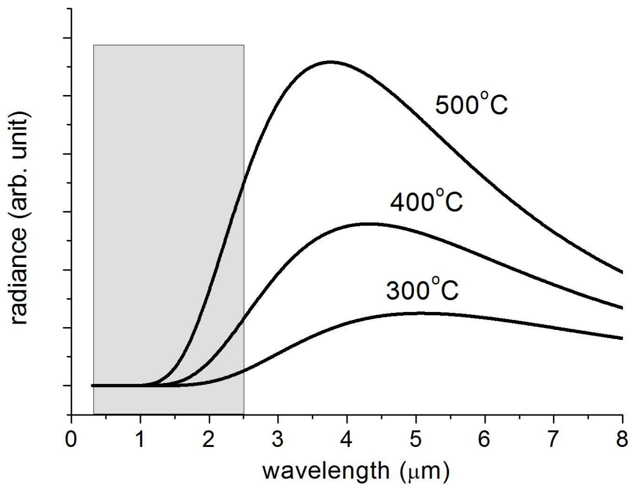


Fig. 1. Black body radiation for selected temperatures. The grey zone shows the spectral range transmitted through glass.

With increasing temperature, the total emitted radiant exitance increases by fourth power of thermodynamic temperature (Stefan–Boltzmann law) and simultaneously the wavelength of the peak of the emission is shifted towards shorter values (Wien's displacement law).

As a result of both these effects, the irradiance, which is transmitted through the glass, increases very rapidly with temperature. Figure 2 shows the relative irradiance in the wavelength region up to 2.5μm with respect to the total emitted irradiance. One can see that it growths rapidly from 0.2% to 20% in the temperature range from 200ºC to 800ºC. In this calculation a sharp absorption edge at wavelength 2,5μm of glass was supposed and reflections at air-glass interfaces were neglected. Because the transmission properties vary for different glasses there is no sense in doing a more precise calculation.

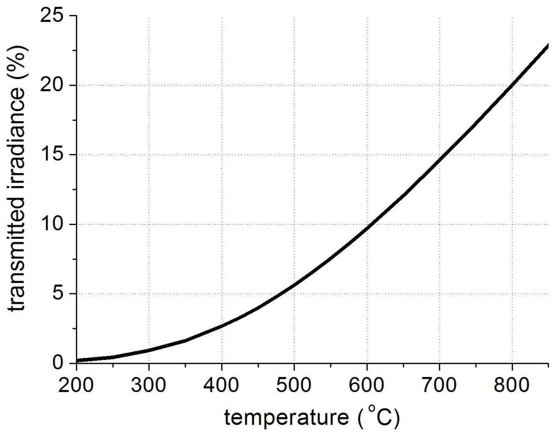


Fig. 2. The percentage of irradiance of black body radiation transmitted through the glass lens as a function of the surface temperature..

In Fig. 3 the total irradiance emitted by the hot surface (Fig. 3 (a)) is compared with the irradiance restricted by the glass transmission region (Fig. 3 (b)). The second one has a much steeper slope in the region of about 500ºC which shows a high sensitivity to surface temperature.

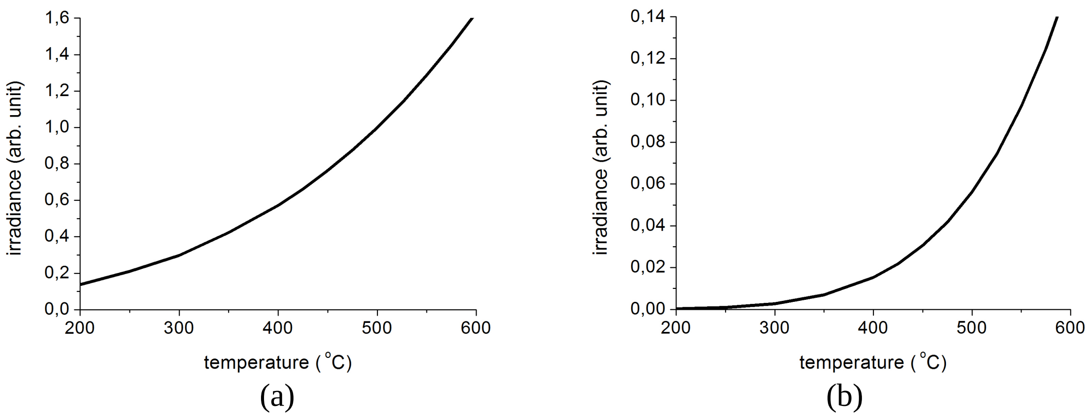


Fig. 3. Irradiance directly emitted by black body (a) compared with irradiance transmitted through the glass (b). Take note of the difference in scaling of the vertical axis.

In practice, one can get an infrared image onto a thermal sensitive foil using an ordinary glass lens only when the surface temperature is close to 500ºC. And every increase by a few tens of degrees makes the experiment faster and easier to provide. On the other hand it is almost hopeless to try to get any image with a surface temperature of about 450ºC when, in comparison with 500ºC, only half of the radiation power impacts onto the thermal foil (see Fig. 3).

Experiment No. 1: Infrared shadow

Infrared radiation propagates in a straight line just like visible light (neglecting diffraction). When we put any object into an IR beam, it casts a shadow. This can be simply demonstrated using thermal foils.
A powerful source of IR radiation, for instance, a vertically mounted electrical cooker or high powered IR lamp is necessary. (Though the installation of an electrical cooker is more complicated, its usage has some advantages from the didactic point of view. Everybody expects that an IR lamp emits IR radiation but it can be surprising for somebody that a hot cooker plate does the same thing.).
The thermal foil is placed at an appropriate horizontal distance and our hand put somewhere between the IR source and foil. After a short time a shadow of the hand can be observed see Fig. 4. Because the IR source has a relatively large area, the shadow sharpness is dependent on the distance between hand and foil and this effect can be discussed. It is obvious that the sharpness decrease with an increasing hand to foil distance.

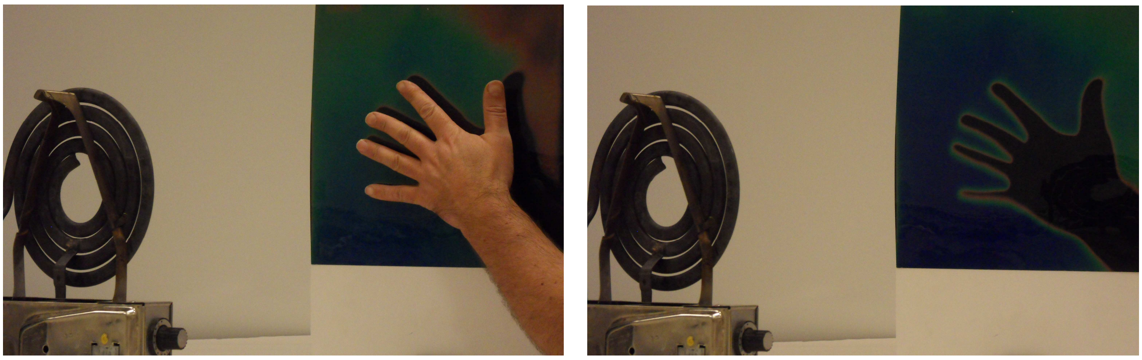


Fig. 4. Infrared shadow o human hand.

Experiment No. 2: Spectrum in IR

Using thermal foils, the infrared part of the electromagnetic spectrum can be visualized. This experiment requires a high power light source. A linear halogen bulb with a power of 500W was used in a simple spectroscope made on the optical bench and equipped with a glass lens and prism. The results are depicted in Fig. 5. Within a few seconds after switching on the bulb the TSF starts to change its colour in the infrared region Fig 5 (a). When the bulb is switched off, there is no heat detection in the visible area Fig 5 (b). This is unquestionable proof that the maximum power emitted by the bulb is in the infrared part of the electromagnetic spectrum.

In Fig 5 (c) the bulb spectrum taken with a video camera is depicted. In comparison with TSF the detection limit of the camera is restricted to the lower wavelengths as was expected. The silicon chip in the video camera loses its sensitivity at about 1,0 μm but TSF with glass optics is able to detect IR radiation at least up to 2,5 µm. Both these values coincide well with the estimation calculated from glass dispersion of IR.

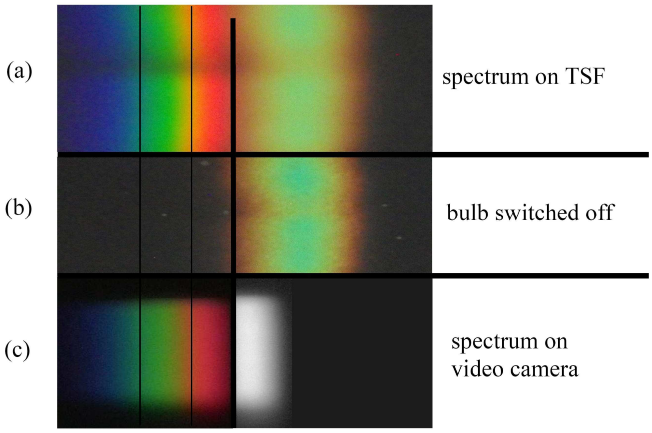


Fig.5. Spectrum of halogen bulb where the IR part is visualized by a thermal sensitive foil (a) and (b). The same spectrum as seen by a video camera in IR night vision mode (c). Visible part of Fig. (c) is presented here in colours using an ordinary photograph for better comparison with Fig. (a). Original IR night vision picture was fully black and white.

Experiment No. 3: Infrared image of bulb filament

The tungsten filament of any standard light bulb is a convenient and very safe source of radiation with very high brightness. Due to the high temperature, more than 80% of the emitted power is transmitted through the glass lens. But for the experiment with pure IR imaging the visible light should be filtered out. There are a few possibilities of how to do this (see appendix B). In our experiment a silicon wafer polished on both surfaces was used. A combination of Silicon wafer with a glass lens transmits radiation in the range 1,0 – 2,5 µm. For the filament temperature of 2500ºC, about 50% of the radiation power is lost due to absorption in the glass and Silicon. The index of refraction of Silicon is very large in the near infrared region (about 3.5) and that is why the reflections at the interfaces cannot be ignored. As a result of both absorption and reflection, only about 20% of the energy is transmitted to the thermal foil. But it is almost a four times bigger relative value in comparison with an object with a surface temperature of 500ºC as discussed previously. Moreover the tungsten filament has more than 50 times larger radiant exitance than a surface at 500ºC, even if the relatively small emissivity of tungsten (0.2 - 0.4 [10]) is taken into account. Thus this experiment is easy, fast and reliable.

The experiment should be done in the following way: Firstly the bulb filament is projected onto a white screen in the usual way, see Fig. 6 left. It is good to use the highest power bulb available (approx. 150W) and lens with a focal length of about 10 cm and a diameter of at least 50mm. The dimension of the image should be about 10 cm. A small image is difficult for the whole class to observe. A large image on the other hand does not provide enough IR irradiance to warm the thermal foil.

Then place the IR filter (e. g. Si wafer) between the bulb and lens. The filament image disappears, of course, but the invisible IR image is still present. It is subsequently made visible by placing the thermal foil on the screen see Fig. 6 right.
The sharpness of the IR image is much worse than it was in the visible range. There are two reasons for this. Firstly due to dispersion, the refractive index of the glass lens is different for visible light and IR. It is possible to focus the image only with visible light and therefore it is defocused in IR. Secondly, the image is blurred by the thermal conductivity of the foil. It has been proved experimentally that the second effect is more dominant and any effort to get a better focus of IR using dispersion correction has negligible gain.

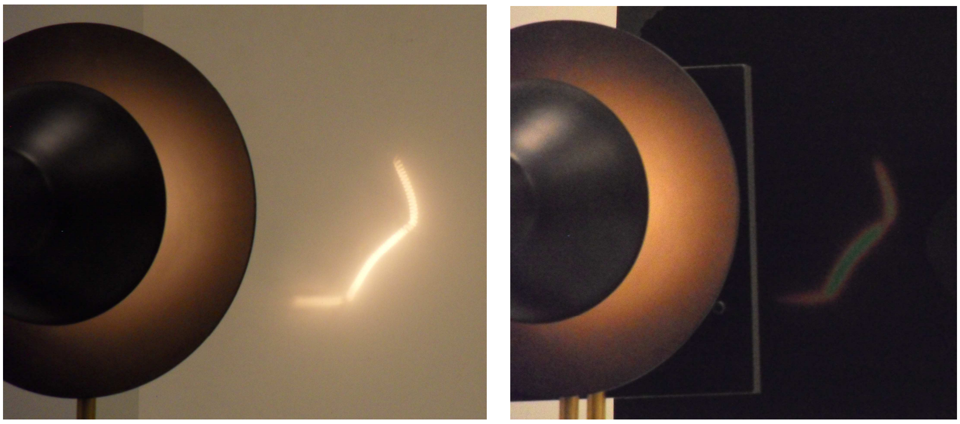


Fig. 6. The image of 150 W bulb filament with visible light (left) and with IR (right). The visible part in the IR image is filtered out by both sides of the polished silicon wafer.

Experiment No. 4: Infrared image of a hot object

The installation of this experiment is more time consuming and its performance brings about some risk due to the manipulation of a very hot object. But this experiment does not require any special components, such as the IR filter in the previous experiment and its result is really spectacular.
The possible source of IR can be a single spiral electric cooker plate. The flat plate cooker is less convenient - its surface temperature is significantly lower. To avoid heating by convection, the optical axis must be horizontal with the cooker plate mounted vertically. Experimental arrangement is shown in Fig. 7.
A lens with a large diameter and short focal length should be used (in this experiment a lens with a diameter 12 cm and focal length 25 cm was used). It is best to have the object and image approximately equidistant from the lens. In this arrangement the image has roughly the same dimensions as the object which is sufficient for observation and at the same time the irradiance is high enough to warm the foil. Correct positioning of the object, lens and screen must be set up using a visible light source e. g. a torch. The difference in focal length of the glass lens due to dispersion is negligible in this case.
The cooker plate has a flat symmetrical shape and it is better when the object has a finer structure. A small piece of metal plate (shield in Fig. 7) brings the desired asymmetry which can be identified in the image.
Before placing the thermal foil on the screen the cooker should be heated to maximum temperature. After installing the foil the image should appear in twenty to sixty seconds depending on room temperature and the actual temperature range of the thermal foil.

It is clearly seen that the image is reversed in the same way as a usual optical image in contrast to the IR shadow presented in the first experiment. This experiment shows that optical imaging is possible also in different parts of the electromagnetic spectrum.

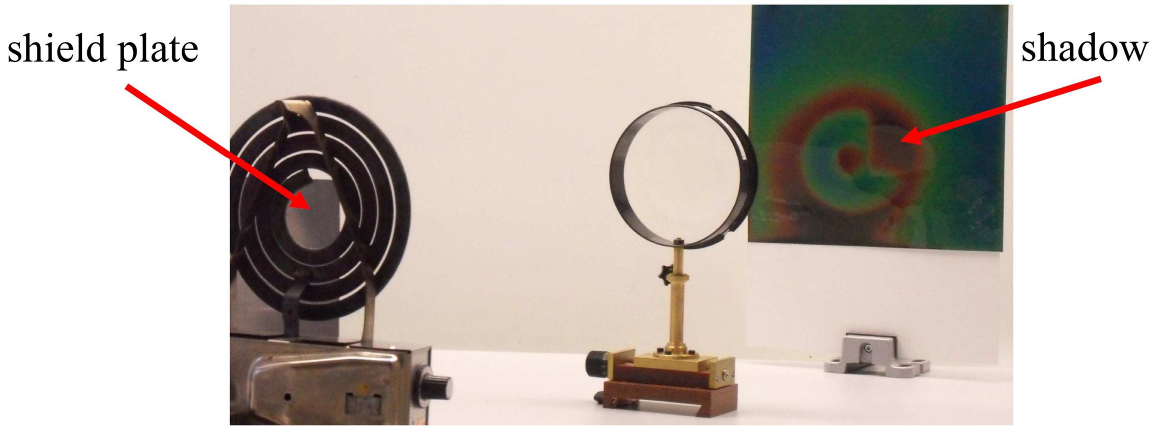


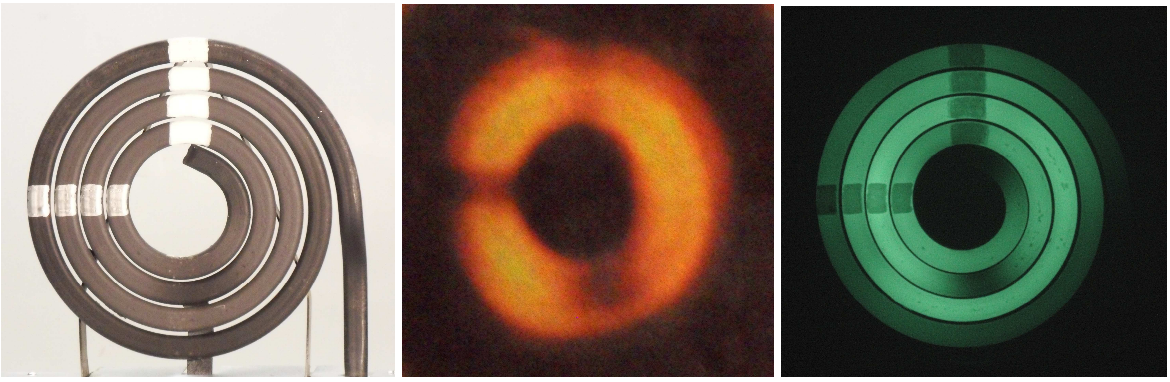
Fig. 7. An experimental arrangement of an IR image of a hot cooker plate. The temperature of the cooker was about 500 ºC. The metal shield plate provides a desired asymmetry of the object and the image.

Experiment No. 5: An effect of emissivity 1: low emissivity, low radiation

For this experiment the cooker plate was painted with heat resistant black paint. The emissivity of this surface varies between 0.9 and 0.95 or so and plates can be treated with a good approximation as perfect black bodies. Interesting results can be obtained when part of the emitting surface is painted in different colours to change its emissivity.

The emissivity is spectrally dependent. Most non-metals have a high emissivity in wavelength 3-15μm no matter which colour they have in visible light [11]. This means that they are close to black body parameters. This can be experimentally verified using an infrared thermometer which gives relatively good values of temperatures for the majority of non-metals without any correction of emissivity. The TSF detection range up to 2.5 μm (restricted by glass optics) is located in the intermediate area where "white turns to black". This will be shown in the following experiment.

Two stripes were painted on the spiral cooker: left horizontal with aluminium paint and top vertical with white heat resistant paint, see Fig. 8 (a). In the TSF infrared image the aluminium stripe shows contrasting black (darker region as a result of low emissivity surface) but the image of the white colour stripe is almost indistinguishable, Fig. 8 (b). This means that, in IR, the spectral range up to 2.5 μm white paint has a significantly larger average emissivity than aluminium paint and this emissivity is close to that of the neighbouring black painted surface. In an image taken with a video camera in IR night vision mode, see Fig. 8 (c) (sensitivity up to 1 μm) both aluminium and white paints are dark which justify low emissivity of these surfaces in this spectral range, similar to that in visible light.



(a) (b) (c)

Fig. 8. The spiral electric cooker (a) with aluminium (left) and white paint (up) stripes. Image on TSF (b) and by video camera using IR night vision mode (c). The reciprocal TSF image has been transformed to the same orientation as other pictures for the sake of clarity. Dark area at the bottom of Fig. (b) and (c) corresponds to a colder part of the cooker in the vicinity of the thermal gauge contact which is seen in Fig (a)..

Experiment No. 6: An effect of emissivity 2: low emissivity, high radiation

A surface with lower emissivity at a given temperature always emits lower integral radiant exitance. But in some cases, covering the surface with low emissivity paint can lead to increasing detected irradiance.

Supposing there is a heated body with constant heating power. When a significant part of the energy lost is through radiation, the decreasing of surface emissivity increases the equilibrium temperature of the body to keep the energy balance unchanged. Due to the higher temperature, the emission spectrum is shifted to lower wavelengths so, in the short wave spectral range, the total emitted power can be higher for a low emissivity surface in comparison with one of high emissivity at a lower temperature.

For the experimental demonstration of this effect the commercially available charcoal burner was used. This is an electrically heated meandering shaped rod. The free standing vertical burner reaches a maximal surface temperature of about 500 ºC after a few minutes. This is an ideal value for IR imaging on TSF - the object is hot enough to get an image reliably but not too hot to emit visible light which is important from the didactic point of view. The heated rod can be supposed to have constant linear electric power density and a relatively small thermal transfer along the rod due to thermal conductivity[3]. Part of heater was painted with aluminium paint see Fig. 10 (a).

Let us denote T_a and T_b temperature of the aluminium and black part of the rod respectively and T_o the ambient temperature. Assuming a constant linear power density the Stefan Boltzmann law gives the following relationship

[3] Both these assumptions are verified in Fig. 10 (c) where radiance of the black and aluminium parts are quite homogeneous and the intermediate region between the hotter aluminium and colder black part is relatively narrow.

$$\varepsilon_a (T_a^4 - T_o^4) = \varepsilon_b (T_b^4 - T_o^4)$$

where ε_a and ε_a are emissivities of the aluminium and black part respectively. By measuring the surface temperatures of the black and aluminium surface, the ratio of emissivities can be calculated

$$\mathrm{E} = \frac{\varepsilon_a}{\varepsilon_b} = \frac{T_b^4 - T_o^4}{T_a^4 - T_o^4}$$

The temperature was measured with a surface thermocouple gauge with results T_a = 630 ºC and T_b = 480 ºC from which $\mathrm{E} = 0.48$ [4]. The calculated spectrum of emitted radiation of the black and aluminium parts of the heating rod is in Fig. 9. The lower emissivity and higher temperature of the aluminium painted surface shift the spectrum towards the shorter wavelengths though the total emitted intensities of both surfaces should be the same. When this radiation is detected by a detector with a spectral sensitivity limited to short wavelengths, the low emissivity surface gives a higher measured irradiance than the black body.

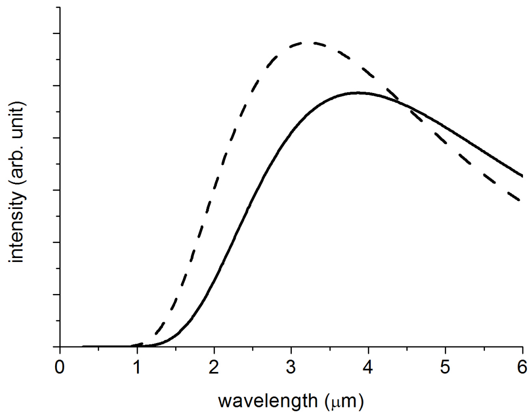


Fig. 9. Calculated emission spectrum for black part (solid line) and aluminium part (broken line) of heating rod respectively. For a detailed description see text.

As stated above, imaging using a glass lens and TSF is limited to approximately wavelengths up to 2,5 μm. There are at least two other readily available detectors with a sensitivity restricted to short wavelengths. Firstly it is human eye with a capability to see from 390 nm to 780 nm and secondly the previously mentioned video camera in IR night vision mode with a detection limit about 1 μm. The more restricted to shorter wavelengths the detector is, the higher is the dominance of the low emissivity surface in detected irradiance. This can be clearly seen from Tab. 1 where an irradiance ratio $R = \frac{I_a}{I_b}$ is calculated. Here I_a and I_b denote the total irradiance irradiance detected from aluminium and black surfaces respectively. The data were calculated for T_a = 630 ºC, T_b = 480 C and emissivity ratio $\mathrm{E} = 0.48$.

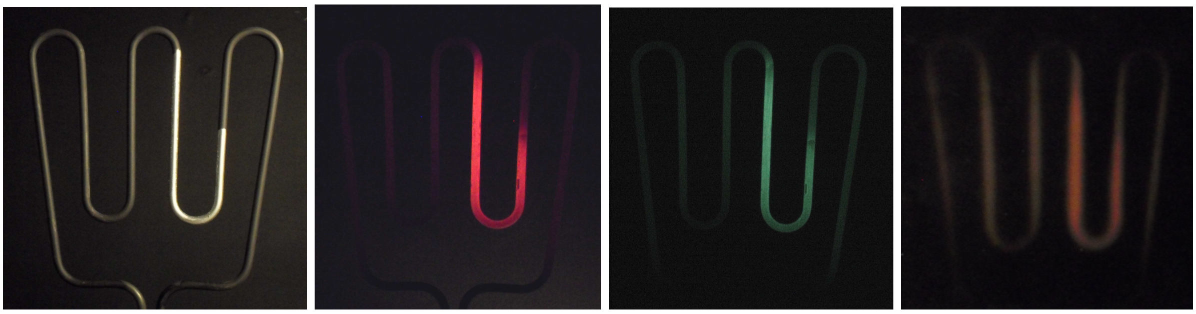
detector	**detection limit**	**irradiance ratio *R***
TSF with glass lens	2,5 μm	1,7

[4] It cannot be considered as a generally valid value. The emissivity of aluminium paint depends on the sort of paint, actual temperature and thermal history of the paint anealing.

video camera in IR mode	1,0 µm	12
human eye	0,78µm	30

Tab. 1. Irradiance ratio R for three detectors of radiation.

The experimental demonstration of this effect is in Fig. 10. In all three cases the detected brightness of the aluminium painted part of the heating rod is larger than that of the black part.



(a) (b) (c) (d)

Fig. 10. Meandering heating rod of a charcoal burner with a part covered with aluminium paint. Photographed in daylight (a). Hot burner as seen in darkness by the human eye (b) (here represented by an ordinary photograph), the image taken with a video camera using IR night vision mode (c) and the image on TSF (d) (The reciprocal TSF image has been transformed to the same orientation as the other pictures for the sake of clarity.)

Conclusion

TSF brings a good possibility for the detection of infrared radiation and imaging in the IR spectral range in school physics demonstrations. The great advantage from the didactic point of view is that there is no need to use any "black box" equipment and background physics of the detection is quite clear. Using TSF, the existence of IR radiation can be simply proved (Exp. 2) and the fundamental physical laws of spreading radiation demonstrated (Exp. 1, 3 and 4). In more sophisticated experiments, the effect of surface emissivity and its spectral changes can be qualitatively studied (Exp. 5 and 6).

The infrared shadow and IR image of a bulb filament through any VIS cut filter is a demonstration which is easy to prepare and provide without any problems. The IR image of a hot object and the effects of emissivity are more complicated and, at particular room temperature, can be a little bit difficult and time consuming to get convincing results for the audience.

Appendix A: A few practical notes to experiments with thermal foils

Thermal foils have a particular temperature interval where they change their colour with temperature with a relatively high sensitivity. Below and above this interval, colour doesn’t

change with temperature and so TSF cannot be used for qualitative measurement of temperature.
This temperature range is quite narrow, mostly 5ºC. This is advantageous due to a high sensitivity to small temperature changes. But it complicates their usage in class demonstrations. The average temperature in class changes during the year or even during the day or lesson. To guarantee a successful presentation, a set of foils with different temperature ranges is necessary. Three foils 20-25ºC, 25-30ºC, and 30-35ºC are probably the minimum which should be available.
Nevertheless even when a set of foils covers the thermal range which is obvious in classrooms, the actual room temperature can be, in some cases, crucial for the successful presentation. For instance when foils 20-25ºC, 25-30ºC are available and the room temperature is 24ºC, the infrared image of a hot object (experiment No 4) is problematic. The "colder" foil is on the edge of the usable scale and the "hotter" one is difficult to warm enough to get a convincing contrast image.

Appendix B: IR filters

The elimination of visible light from tungsten bulb radiation can be realized by different commercial filters. An excellent result is achieved by a so called Si window, which employs a silicon plate having an absorption edge at wavelength 1100 nm. Other IR bandpass or VIS cut filters are available. But they all are rather expansive and it is possible to satisfactorily replace them with cheap impromptu elements.
In Fig. 11 the transmission spectra of different materials are presented. In comparison with professional IR bandpass filters best result were attained with a black alcohol felt-tip pen filter which was made by pouring the contents of the pen onto a thin glass plate.

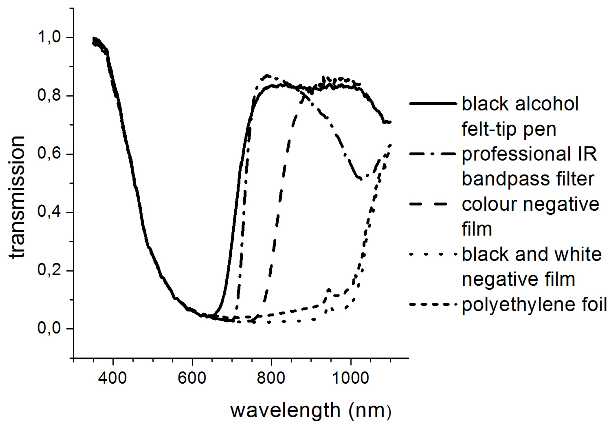


Fig. 11. The transmission spectra of some IR filters.

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