Linear halogen bulb as a powerful light source for physics experiments

Zdeněk Bochníček
Department of Physical Electronics, Masaryk University, Brno, Czech Republic

E-mail: zboch@physics.muni.cz

Abstract
The paper describes the usage of a conventional lamp equipped with a linear halogen bulb for physics experiments. The irradiance gain and limitation of spectral resolution are treated in detail theoretically and verified experimentally. The analysis shows that, in comparison with a standard bulb and slit arrangement, the linear bulb can increase irradiance of the spectrum image in an order of magnitude without a significant loss of a spectral resolution in comparable experimental arrangements. Some concrete examples of experiments with a white light spectrum and diffraction are presented.

1. Introduction

In general, a point light source is ideal for further processing of an optical beam in most optic instruments and other optical experiments. But in some cases, namely when the problem is restricted to two dimensions, the linear shape of the light source is desirable. Spectral analysis is probably the best example. Here the linear source is mostly realized by a slit placed in front of the real source and it is the width of this slit that is the main parameter which influences the spectral resolution. The first person to use a slit in spectroscopy was William Wollaston in 1802 [1] and this invention improved spectrum images significantly. Another example could be diffraction experiments with linearly shaped diffraction objects such as single or double slits, linear grid etc. where a thin slit provides indispensable spatial coherence of the light.
It is obvious that the slit strongly decreases the radiation flux which is processed in a subsequent optical system. The slit has less a destructive effect on the flux or even the slit can be omitted in cases where the light source itself has a linear shape. The Geisler discharge tube, where the central part is narrowed into a thin capillary, is an example of the usage of this idea and in the past it enabled spectroscopic measurements with low pressure discharge.

The linear halogen bulb is a standard light source frequently used by the general public especially for the illumination of exteriors. They are supplied by a mains voltage, are high powered and they are not expensive. Professionally made for safe manipulation, they are mounted into a simple inexpensive housing. The filament is a narrow linear coil with a diameter of about 1mm, depending on the bulb power. Thus this light source can serve as an alternative to a standard set up with a bulb and slit.

In this paper the usage of a linear bulb in selected physics experiments is discussed in detail. Attention is paid to the gain of irradiance and spectral resolution in experiments with a white light spectrum. Theoretical calculations are compared with experimental data. Finally, a few demonstration experiments which employ this light source are described.

For experimental verification, the standard low voltage halogen lamp OSRAM Halostar 100W/24V with a filament length/diameter of 0.58cm/0.24cm respectively and the linear bulb OSRAM Haloline 120W/230V/78mm with an active filament length/diameter of 2.40cm/0.08cm were used .

2. The gain of radiation flux and irradiance in the spectrum image

In this part we will derive flux and irradiance gain when a standard bulb with a cylindrical filament (we will call it 2D (two dimensional) bulb or 2D filament) is replaced by a linear bulb without a slit being in front of the bulb. The theoretical model of the gain of flux and irradiance is based on a relatively simple geometrical consideration where the radiation flux which hits the lens of the spectroscope is compared for these two bulbs. The model is based on the following assumptions:

1) The filaments obey Lambert's emission law (cosine emission law), that means the brightness in the whole area of the filament is constant[1].
2) To make a direct comparison between 2D and line source, the width of the slit in front of the 2D source is supposed to be the same as the real width of the line source.
3) The effects connected with the vertical dimension of both filaments are neglected. This simplification causes a systematic error which overestimates the final gain. This error decreases as the focal length of the lens increases.
4) The distance from lens to screen is much larger than the focal length and thus the object to lens distance is supposed to be equal to the focal length.
5) The prism placed in front of the lens is large enough to refract the whole radiation flux coming through the lens.
6) The reflection losses within the optic elements are neglected, mainly because they should be almost the same in the case of both linear and 2D bulbs.

2.1 Linear filament bulb

The experimental setup of a linear bulb spectroscope is in FIG. 1(a). Within the approximation according to assumption 3 from the previous paragraph, the radiation flux through the lens can be expressed as

$$\Phi_{\mathrm{L}} = \frac{P_{\mathrm{L}}}{4\pi f^2}\pi\left(\frac{D}{2}\right)^2 = \frac{P_{\mathrm{L}} D^2}{16 f^2}, \qquad (1)$$

where P_{L} is power of the linear bulb, f the focal length and D the diameter of the lens. The expression $\frac{P_{\mathrm{L}}}{4\pi f^2}$ is the irradiance at the lens position.

[1] In fact the radiation from a tungsten filament does not obey Lambert's emission law and the radiance increases with an increase of the viewing angle [2]. But the increase is larger than 5% in only 15% of the apparent emitting area and larger than 10% in less than 8% of the same area. So, in this paper, this effect can be neglected.

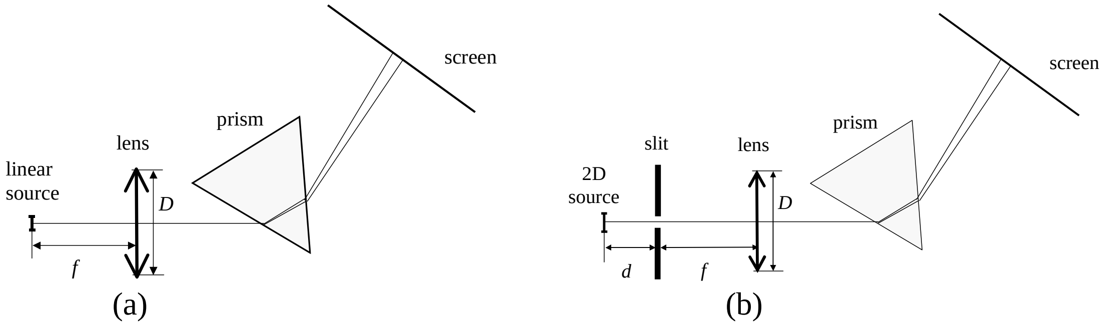


Figure. 1. The experimental arrangement of a prism spectrometer with linear bulb (a) and with a standard 2D filament bulb and slit (b). Top view.

2.2 2D filament bulb

The standard experimental arrangement of a prism spectroscope is depicted in figure 1(b). The light emitted from the filament is restricted by a slit which is placed at distance *d* from the filament. The slit is the object for the lens.
The presence of the slit limits the radiation flux coming through the lens; the lens is irradiated only in a vertical strip. Moreover, the irradiance in the lens position is not homogeneous in the horizontal direction because different points of the lens are irradiated by a different portion of the surface area of the filament. The situation is shown in figures 2 (a) and (b). From a simple geometrical consideration the width of the central strip of the maximum irradiance *w* is given by

$$w = \frac{f}{d}(u-b)-b \tag{3}$$

and the total width of irradiance area B can be expressed as

$$B = \frac{f}{d}(u+b)+b\,. \tag{4}$$

Here *b* is the width of the slit, *f* the focal length of the lens and *u* the width of the 2D source.

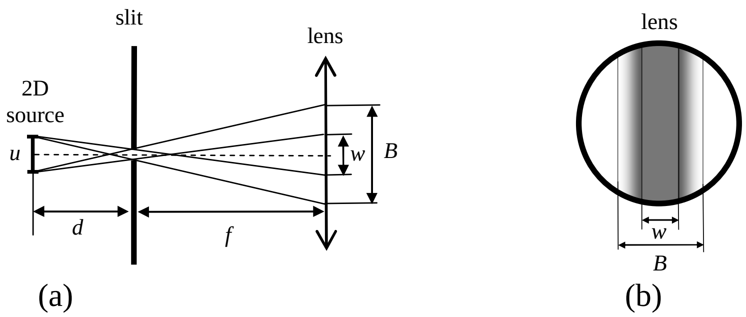


Figure. 2. The path of the selected rays for the calculation of the lens irradiation, top view (a). Illustration of lens irradiation, front view (b).

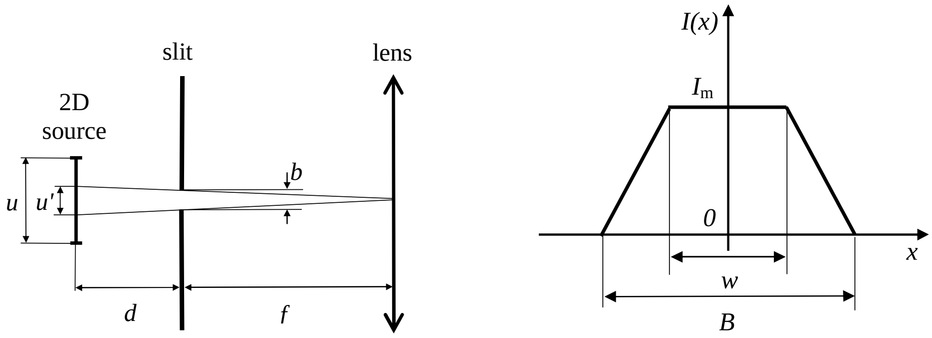
The maximum irradiance in the central strip is given by (see figure 3(a).)

$$I_m = \frac{P_{2D}}{4\pi(d+f)^2}\frac{u'}{u} = \frac{P_{2D}b}{4\pi u f(d+f)} \tag{5}$$

where the quantity P_{2D} is the power of the 2D source bulb and *u'* is part of the 2D source which irradiates the lens in the central strip. Irradiance decreases linearly from the central strip reaching zero at the point B/2, see figure 3(b). This linear decrease of the irradiance can be expressed as

$$I(x) = \frac{I_m}{B-w}(-2x+B), \tag{6}$$

where x is the distance from the centre of the lens.



(a) (b)

Figure 3. On the calculation of the irradiance of the lens.

The total radiation flux through the circular lens is then calculated via the integration of the irradiance

$$\Phi_{2D} = 2 \cdot \int_0^{\frac{D}{2}} I(x) \cdot 2\sqrt{\frac{D^2}{4} - x^2}\, dx \tag{7}$$

where

$$I(x) = \begin{cases} = I_m, & \text{for } x \in \left\langle 0, \frac{w}{2} \right\rangle \\ = \frac{I_m}{B-w}(-2x+B), & \text{for } x \in \left\langle \frac{w}{2}, \frac{B}{2} \right\rangle \\ = 0, & \text{otherwise} \end{cases} \tag{8}$$

and the expression

$$2\sqrt{\frac{D^2}{4} - x^2}\, dx \tag{9}$$

is the vertical infinitesimal area of the lens. Due to the symmetry, integration is provided through only half of the lens area and multiplied by two. The integral can be solved analytically.

2.3 Gain of flux and irradiance

The gain of the flux that we obtain by substituting the 2D light source with the linear filament bulb can be calculated as

$$Z_\Phi = \frac{\Phi_{\mathrm{L}}}{\Phi_{\mathrm{2D}}} \tag{10}$$

where we have to put $P_{\mathrm{L}} = P_{\mathrm{2D}}$.

The gain of the irradiance is a more interesting parameter for the user. Because the vertical size of the linear bulb spectrum projected on the screen is different, in general the irradiance gain differs from the flux gain.
The irradiance gain can be calculated by multiplying the flux gain with the ratio of spectrum areas projected on the screen. The spatial width of the spectrum is dominantly given by the dispersion of the prism and that is why only the vertical dimensions of the spectrum from the linear and 2D light sources are different. Because the geometry of the lens imaging is the same for both cases, the ratio of spectrum height is the same as the ratio of the height of the objects.
For the linear bulb the object is the filament itself; for the 2D bulb the object is a part of the slit from which light hits the lens. But from a simple geometrical consideration this virtual object from the 2D source does not have the homogeneous radiance, see figure 4. Only in the B-B part of the slit does all the radiation emitting from the 2D source hit the lens. From B to A it decreases approximately linearly reaching zero at point A. The corresponding distances are

$$h = \frac{(D-v)d}{f+d} + v \quad \text{and} \quad g = \frac{(D+v)d}{f+d} - v \tag{11}$$

where v is the vertical dimension of the 2D bulb filament[2]. The spectrum from the 2D source has an inhomogeneous irradiance in the vertical direction. Contrary to the above, the spectrum of the linear bulb is vertically homogeneous because the radiance of the tungsten filament is homogeneous.
In the experimental verification (section 4 of this paper) the irradiance was measured in the middle of the spectrum (in vertically direction). To compare theoretical and experimental data the effective height of the virtual object of the 2D bulb h_{ef} was used for the calculation of the irradiance gain, where

$$h_{ef} = \frac{h+g}{2} = \frac{d\,D}{f+d}. \tag{12}$$

This is the height of a virtual radiation source located within the slit which provides a vertically homogeneous irradiance of the spectrum with the radiation flux coming through the lens as it was calculated in section 2.2. The effective height is a simple mean value of h and g because between B and A in figure 4 the radiation from the 2D filament which hits the lens drops approximately linearly.

The irradiance gain Z_I is then given by

$$Z_I = Z_\Phi \frac{h_{ef}}{H} = \frac{\Phi_{\mathrm{L}}}{\Phi_{\mathrm{2D}}} \frac{1}{H} \left(\frac{Dd}{f+d} \right), \tag{13}$$

where H is the sum of the heights of the active parts of the linear bulb filament, see figure 8.

[2] The quantity g is negative for the large focal length of the lens. This means that the crossing C in figure 4 is located between the slit and the lens and the approximation used in this calculation is no longer valid.. For the experimental arrangement used in section 4 of this paper (diameter of the lens is 5cm) the limiting focal length is about 30cm. But in this situation the irradiance gain is so small that there is no reason to use the linear bulb instead of the standard 2D bulb.

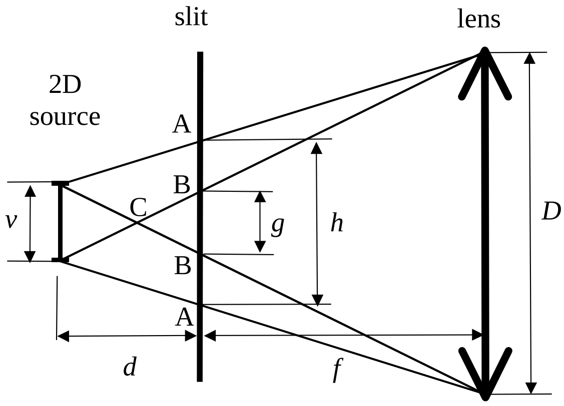


Figure 4. On the calculation of the active part of the slit. Side view.

Examples of the results of the theoretical calculations are in figure 5. Both flux and irradiance gains strongly depend on the lens diameter and focal length. Obviously the larger the diameter and smaller the focal length, then the bigger both gains are. An ordinary lens with a 5cm diameter and 10cm focal length provides gain of 11 times (irradiance) and 21 times (flux). Using the same diameter lens with a focal length of 5cm we can even reach gains of 44 and 56 respectively. But using a lens with a higher optical power can spoil the quality of the spectrum (see experimental part).

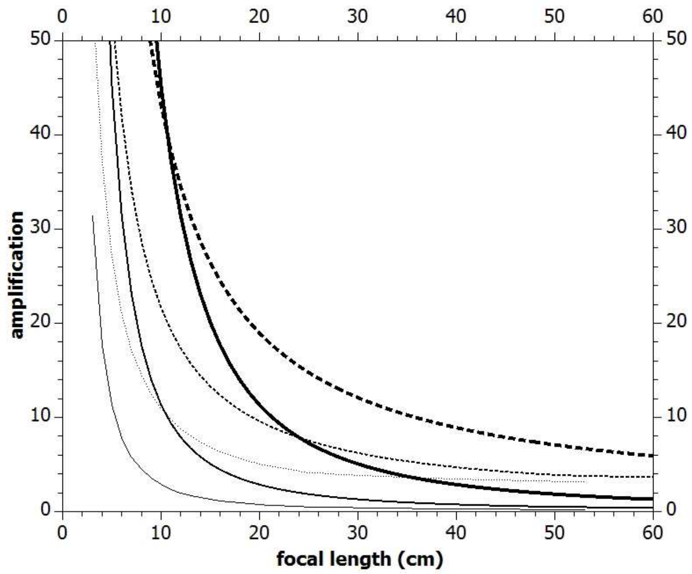


Figure 5. Theoretical calculations of gain of irradiance (solid line) and flux (dashed line). Thin lines hold for lens diameter 2,5cm, middle lines 5cm and thick lines 10cm.

3. Spectral resolution

Spectral resolution is a key parameter for any spectrometer. In the case of demonstration experiments the resolution is not as critical as in scientific measurement but trying to evaluate the gain from using the linear bulb, the spectral resolution must be taken into account.
The spectrum is in fact a superposition of images of the object at different wavelengths. The spectral resolution is then determined by the width of the image of the object. In a standard experimental arrangement with the 2D light source and a slit, the spectral resolution can be controlled by the width of the slit. There is no such possibility in the case of the linear bulb.

But the dimension of the image decreases with increasing focal length and this can be used to control the spectral resolution. From the results of the previous paragraph it is clear that the increase in the focal length (and the resolution) leads to a decrease of the intensity but this is a general problem of any spectrograph.

The situation is described in figure 6. A simple geometrical consideration leads to the relationship

$$\frac{b'}{a'} = \Delta\delta_{\min}\,, \tag{14}$$

where b' is the image size, a' the image distance and $\delta_{\min}$ is a minimal deviation of the light after refraction at the prism which can be calculated according to a well known formula [3]

$$\delta_{\min} = 2\arcsin(n\sin\frac{\varphi}{2}) - \varphi\,, \tag{15}$$

where φ denotes the apex angle of the prism and n the refractive index. By differentiation of this equation we get the relationship

$$d\delta_{\min} = 2\frac{\sin\frac{\varphi}{2}}{\sqrt{1-\left(n\sin\frac{\varphi}{2}\right)^2}}dn\,, \tag{16}$$

which also holds approximately for finite changes of $\Delta\delta_{\min}$ and Δn.

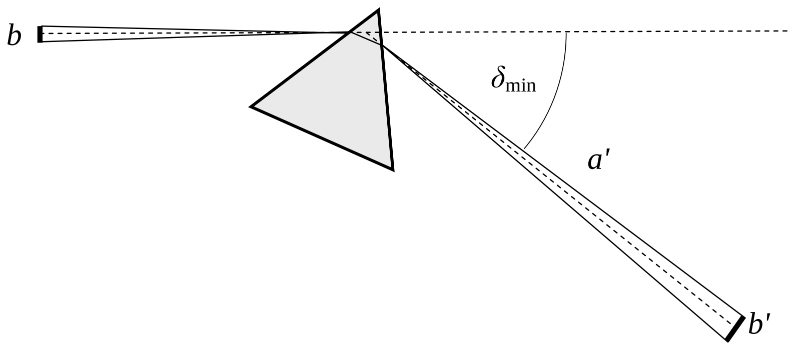


Figure 6. On the calculation spectral resolution.

The relationship between deviation angle and wavelength is incorporated via the dispersion relation $n(\lambda)$

$$\Delta n \approx \frac{dn(\lambda)}{d\lambda}\Delta\lambda\,. \tag{17}$$

From the equations (16) and (17) we get

$$\Delta\delta_{\min} = 2\frac{\sin\frac{\varphi}{2}}{\sqrt{1-\left(n\sin\frac{\varphi}{2}\right)^2}}\frac{dn}{d\lambda}\Delta\lambda\,, \tag{18}$$

To find a relationship between the light source size and the spectral resolution we use the following equation for the optical magnification

$$M = -\frac{b'}{b} = -\frac{a' - f}{f} \tag{19}$$

From the equations (14), (18) and (19) we get

$$\Delta\lambda = \frac{b(a' - f)\sqrt{1 - \left(n \sin\frac{\varphi}{2}\right)^2}}{2 f a' \sin\frac{\varphi}{2}} \left(\frac{dn}{d\lambda}\right)^{-1}, \tag{20}$$

In most practical cases the image distance far exceeds the focal length $a' >> f$ thus we can neglect f in numerator of equation (18) and we get the final form of the equation for the spectral resolution

$$\Delta\lambda = \frac{b\sqrt{1 - \left(n \sin\frac{\varphi}{2}\right)^2}}{2 f \sin\frac{\varphi}{2}} \left(\frac{dn}{d\lambda}\right)^{-1}, \tag{21}$$

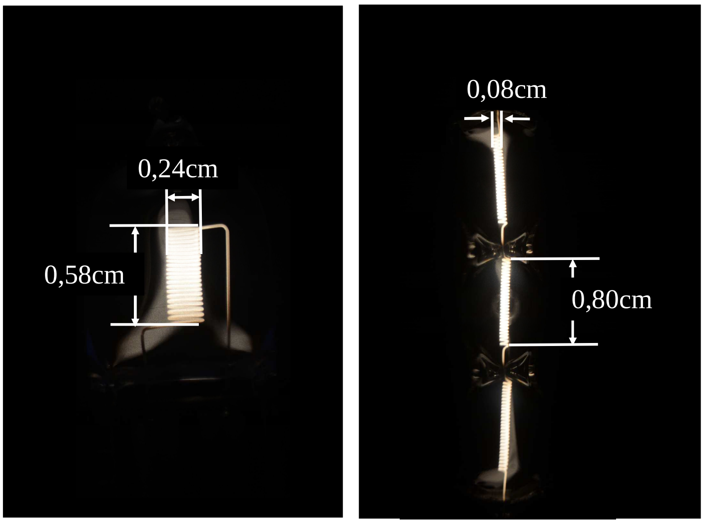
It is worth noting that for large image distances the spectral resolution depends only on the properties of the prism, width of the light source and the focal length of the lens and does not depend on the particular geometry of the experiment such as object image distance.

4. Experimental verification

Standard commercially available lamps were used, one equipped with 120W/78mm and the other with 500W/118mm linear bulbs both supplied with a voltage of 230V. The reflective metal mirror was removed and the interior of the metal housing was painted with black heat resistant spray. The front glass cover could be removed so as to allow better cooling, but if used by students the glass cover should be kept fixed for the sake of safety. Both lamps were adapted for an easy fixing on an optical bench, see figure 7.

Figure 7. The lamp with linear halogen bulb fixed to an optical bench.

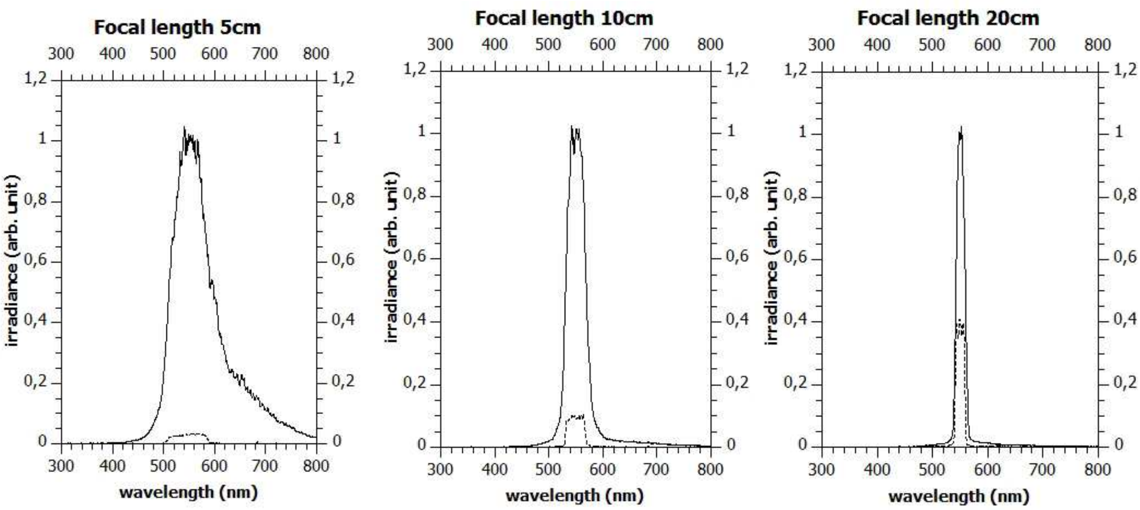
As a 2D light source a lamp with a 24V/100W bulb and axial filament was used . The dimensions of the filaments of all bulbs were determined by measurement of the dimensions of a highly magnified filament image and calculated using the equation (19), see figure 8. The light spectrum was measured by USB fiber optic spectrometer AvaSpec; the entrance aperture of the fiber was about 1.5mm, which was less than 0.5% of the actual spatial width of the spectrum. To verify the theoretical calculation the spectral composition in a selected point of the spectrum was measured at a wavelength of about 550nm.



(a) (b)

Figure 8. Dimensions of the filament of 2D (a) and linear (b) bulbs.

Lenses with focal lengths 5cm, 6cm, 10cm, 15cm, 20cm, 30cm and 50cm were used in an optical bench spectroscope; all lenses had a diameter D = 4.8 ± 0.1cm; image distance was about 6m in all cases which satisfies the condition $a' >> f$. The width of the slit located in front of the 2D bulb was the same as the width of the linear filament (0.08cm). The distance between the 2D filament and the slit was as small as it was technically possible (3cm). The experiments were provided with a linear 120W bulb and a 100W 2D bulb. Data were normalized with respect to bulb power.



(a) (b) (c)

Figure 9. A comparison of the spectral composition in λ = 550nm for three different focal lengths. The line bulb is drawn with solid line and the 2D bulb with dashed line.

Three examples of the results are depicted in figure 9. Here the spectra around λ = 550nm of linear and 2D light sources are compared for three different focal lengths. When the lens with a focal length of 5cm is used, the irradiance gain is almost 50 times, see figure 9 (a) and figure 10. But the spectral resolution is notably worse for the linear filament, though full width at half maximum (FWHM) is comparable for both curves. The broadening of measured spectrum is caused mainly by the optical aberration of the lens because in this case most of the optical rays are far away from paraxial approximation. When the spectrum is projected by a lens with a focal length of 10cm, see figure 9 (b), the spectral resolutions from linear and 2D sources are almost the same and the irradiance gain is about eleven. The usage of a 20cm lens also guarantees comparable spectral resolution for the linear bulb as is provided by the 2D bulb but the irradiance gain is about three times only, see figure 9 (c).

In figures 10 and figure 11 the theoretical results of gain and spectral resolution for λ = 550nm are compared with all the measured data. The total irradiances were calculated from the experiment by the integration of the spectral curves (examples in figure 9). The spectral resolution was determined by numerically fitting the measured spectral curves with the rectangular-shaped function.

In most cases the experimental results are in good accordance with the theoretical data. It was proved experimentally that the usage of a linear bulb instead of 2D bulb in a convenient experimental arrangement can increase the spectrum irradiance significantly without a relevant loss of the spectral resolution.

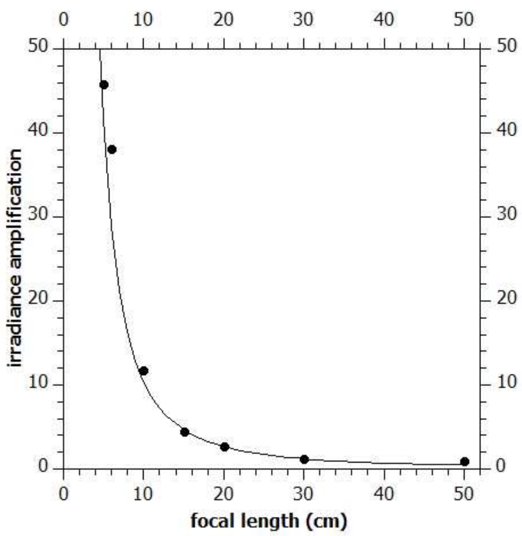


Figure 10. Experimental data of irradiance gain compared with the theoretical calculation from equation (13).

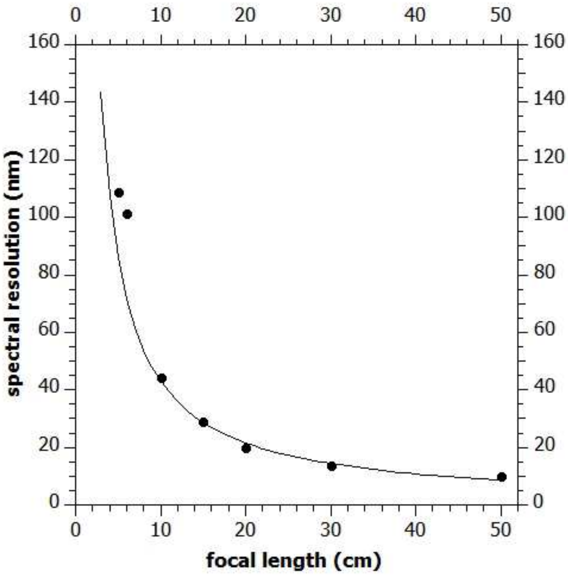


Figure 11. Experimental data of spectral resolution compared with the theoretical calculation from equation (21).

5 Demonstration experiments with linear bulb

5.1 Highly intensive spectrum image

As it has been shown in previous theoretical and experimental chapters the usage of a linear filament bulb can provide a highly intensive spectrum. The example of this spectrum is in figure 12. The spectrum was realized with a 500W linear halogen bulb and lens with focal length 15cm. The image distance was about 12m. In a dark room we can obtain the image of an intensive spectrum several meters high which is really spectacular. A smaller spectrum image with a height about a few tens of centimetres can be clearly visible on a sunny day even without any darkening of the classroom.

FIG. 12. Author of this paper with a huge and highly intensive spectrum.

5.2 Thermometer detection of infrared radiation

Infrared radiation was discovered by a German - British astronomer William Herschel, who detected unexpected warming of the thermometer outside the visible light of the solar spectrum in 1800 [4]. This experiment can be easily reproduced with a linear bulb light source. In a previous paper [5] the warming in the infrared region was detected using thermal sensitive foils but the same can be done with an ordinary thermometer.
A linear 120W bulb and lens with a focal length of 7.5cm were used in a spectroscope. Image distance was about 50cm. In this experimental arrangement, the irradiance gain is expected to be about twenty times in comparison with a common 2D light source of the same power. The irradiance was detected with a standard digital thermometer with thermocouple type K gauge. The gauge was painted black to get higher emissivity. The thermometer was located in different positions of the spectrum and temperature was read 5 minutes after switching on the bulb. Then the bulb was switched off and thermometer was moved to another position of the spectrum. The next measurement started after the thermometer had been cooled down to room temperature. In the visible light area the corresponding wavelength was measured using an AvaSpec spectrometer; during the measurement an optic fiber of the spectrometer was placed at the same position of the spectrum as the temperature gauge had been. The wavelengths in the infrared region were determined using the procedure described in the appendix.
The results of the measurement are described in figure 13. The theoretical calculation of the radiance of the black body with a temperature of 3000K is added to the experimental points. Supposing the heat loss being described by Newton’s law of cooling the temperature increment should be proportional to the heating power, i. e. radiance in this case. But the detailed interpretation of results from figure 13 is more complicated. The radiation heat loss, absorption of infrared radiation in the optical glass components and the nonlinearity of the dispersion curve must be taken into account for any quantitative comparison of the data plotted in figure 13. Without this detailed analysis the experiment can only serve as a qualitative demonstration of the existence of the infrared radiation.
A fast demonstration experiment can be simply arranged by putting the thermometer near to the red side of the spectrum. The response of the thermometer is fast and persuasive.

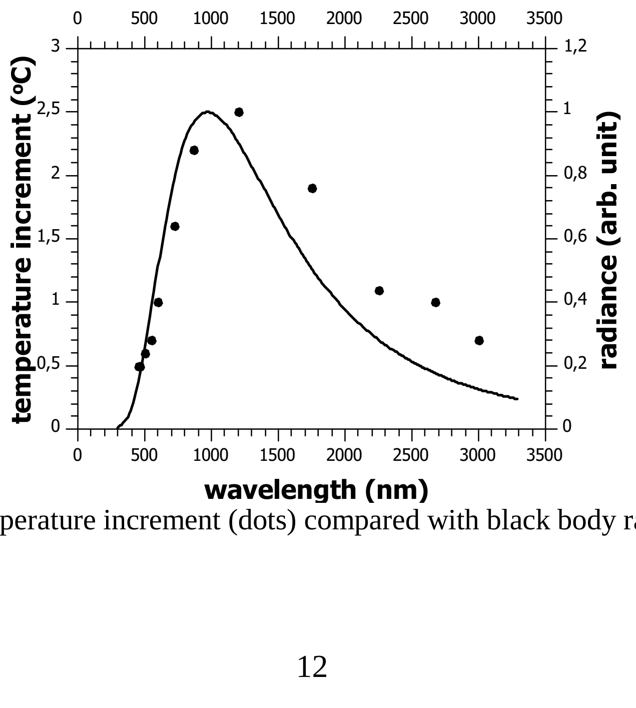


Figure 13. Temperature increment (dots) compared with black body radiation (line).

5.3 Scattering of light

The light scattering in air causes the blue colour of the clear sky and yellow or even red colour of the sunset. In air the light is scattered mostly on the density fluctuation dimensions which are much smaller than the wavelength of the light. In this case the scattering is described by so called Rayleigh approximation and scattering cross section grows with the fourth power of the wavenumber (inverse wavelength). Thus blue light is scattered much more than red light and this effect leads to the optical phenomena in the atmosphere.
This effect can be easily demonstrated with an aquarium filled with water which is slightly cloudy with milk or coffee cream. About one millilitre of cream in 10 litres of water is sufficient for the observation of light scattering.

The experimental arrangement is pictured in figure 14. The light spectrum goes through the aquarium which is half filled with cloudy water. As expected the scattering in water removes blue part of the light spectrum. This experiment is clearly visible even in the case when the lecture room is not in total darkness.

Figure 14. Light scattering.

5.4 The Young experiment with white light.

The Young diffraction experiment with white light is a delicate task. Due to necessity of spatial coherence the narrow slit must be placed in front of a light source and the diffraction double-slit must be at distance *a* from this slit which obeys the following condition

$$a > \frac{l \cdot b}{\lambda} \tag{22}$$

where *b* is the width of the slit and *l* the width of the diffraction object (double-slit in this case). For example when b = 0,08cm, l = 0,1cm and λ = 550nm This makes a > 1,5m. In these limiting conditions the intensity of the diffraction image is very small and the visibility of this experiment for a large audience is poor.
Also in this case the linear bulb can increase irradiance of the screen but the gain is significantly smaller than in spectrum imaging. Let us compare two situations: a) linear bulb

without the slit, b) 2D bulb with the slit with the same width as the width of the linear filament. The height of the diffraction image is bigger for the linear bulb because the height is in fact a geometrical projection of the filament's vertical dimension through the double-slit. From a simple view the irradiance gain is given by the ratio

$$Z_I = \frac{u_{2D}}{u_{\mathrm{linear}}} \tag{23}$$

where u_{2D} and u_{linear} are the widths of the 2D and linear filaments respectively. In this case the width of the 2D filament is three times larger than the width of the linear filament and thus the gain is about three times.

Using the linear bulb the experimental arrangement of Young diffraction is very simple. Most of the front glass of the lamp should be covered by a black or aluminum sticky tape leaving only a small slit with the dimensions slightly larger than the dimensions of the linear filament. The double-slit is placed at a convenient distance (see equation (22)) and irradiated with the lamp. The experiment must be undertaken in darkness. If light from the bulb spoils the visibility of the diffraction image, a small mirror placed in front of the double-slit can reflect the diffracted light to a darker part of the lecture room.

Figure 15 compares the diffraction images made with linear and 2D bulbs. Just one double-slit was simultaneously irradiated with both bulbs slightly horizontally separated from each other. The picture of the screen was taken by a single shot to avoid brightness and contrast distortion caused by the uncontrolled digital processing of the image.

Figure 15. Young diffraction experiment with a single double slit irradiated with linear bulb (left) and 2D bulb (right).

6 Conclusion

The linear halogen bulb is a valuable light source for a variety of physics experiments. It is simple, high powered, very cheap and professionally shielded. It does not require any special power source but is easily supplied by mains voltage. It is especially suitable for experiments with white light spectrum when higher spectral resolution is not demanded. In comparison with standard light sources it can enlarge the brightness of the spectrum in an order of magnitude. With this source many experiments which utilize the white light spectrum can be realized easily without the need for room darkening.

In general this source can serve well in most cases when the light beam must be restricted by a vertical slit.

Acknowledgement
Author thanks to Pavel Konečný for his help with photographs.

Appendix: Estimation of dispersion of the prism in infrared region

In visible light the dispersion relation of a given prism can be relatively simply measured using a discharge tube or set of LEDs as light sources of known wavelengths or with a convenient spectroscope if available. But the task is much more complicated in the IR region up to 3μm in wavelength unless we have an infrared spectrometer which is not a common apparatus. Using the following procedure the dispersion relation can be estimated throughout the whole range of glass transmission.
The idea is based on the fact that the dispersion relations in the infrared region for different optical glasses are quite similar apart from the vertical shift, see figure 16. The dispersion relation of the prism used in this paper was measured using an AvaSpec spectrometer in the range 400nm - 1100nm and this data were fitted to selected tabulated dispersion relation which was properly vertically shifted. This estimation procedure was used for an evaluation of thermometer detection of the infrared radiation, figure 13.

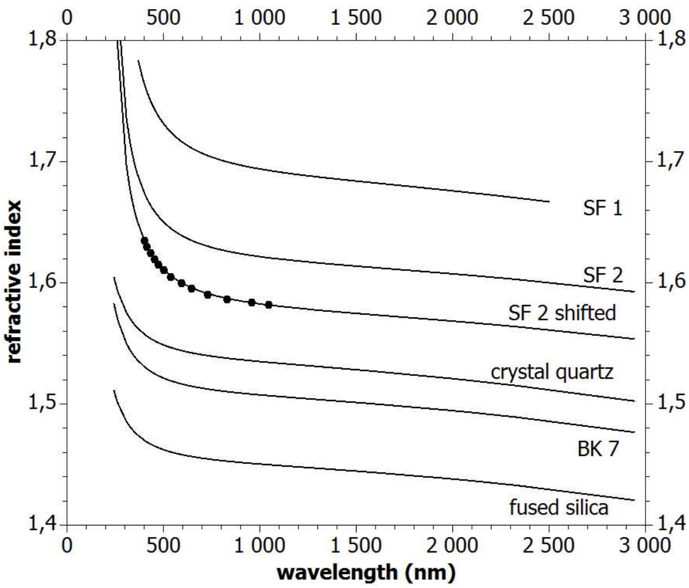


Figure 16. Dispersion relation for selected types of optic glasses (lines) [6]. Dots correspond to experimental data and they were fitted with vertically shifted curve of SF 2 glass.

References

[1] W. H. Wollaston, *A Method of Examining Refractive and Dispersive Powers, by Prismatic Reflection*, Phil. Trans. Roy. Soc. London **92**, 365-380 (1802).
[2] W. E. Forsythe and A. G. Worthing, *The Properties of Tungsten and the Characteristics of Tungsten Lamps,* Astrophysical Journal **61**, 146-185 (1925).
[3] See for instance M. Born and E. Wolf, *Principles of Optics*, (7th edition Cambridge University Press 1999), p. 192.

[4] W. Herschel, *Experiments on the Refrangibility of the Invisible Rays of the Sun*, Phil. Trans. Roy. Soc. London **90**, 284-292 (1800).
[5] Z. Bochníček, *The visualization of infrared radiation using thermal sensitive foils*, Physics Education **48**, 607-615 (2013)
[6] Newport Company Web Site http://www.newport.com/Optical-Materials/144943/1033/content.aspx.