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# Efficiency measurements on electroluminescent devices

The measurements of the light power and efficiency of electroluminescence devices at different temperatures have been performed with the aim photomultiplier and integrating sphere. For the calibration of the arrangement the He—Ne laser and HP Radiant Flux Meter was used.

## 1. Introduction

In connection with a rapid development of optoelectronics a great interest in the measurements of the total power of light has been observed recently. An accurate measurement of the total radiant flux spectral distribution of the electroluminescent devices is important not only for the selection of possible electroluminescence mechanisms but also for the purposes of the devices design.

The method of the light power determination used in electroluminescence investigations should take into consideration the following conditions:

1. The spatial distribution of light.
2. The temperature difference between light sources and detector.
3. Spectrum of the emitted light.
4. The great spread of total light power.

Because of the first conditions an integrating Ulbricht sphere is used in the experiment. The fullfilment of the remaining conditions depends of the type of the detector used.

In most cases the radiant flux meters are thermal--type detectors. This allows to obtain flat spectral response from 0.2 μm up to 15 μm. Measurements made at one wavelength can be directly compared with measurements made at any other wavelength. The most sensitive thermal-type detectors are multijunction vacuum-deposited thermopiles. This type of detectors, if compared with photoelectric detectors, has a relatively high sensitivity in the infrared region of spectrum and low sensitivity in the visible one. This property is not advantageous in the case of electroluminescence investigations. The high sensitivity of the thermoelectric detectors in infrared region impedes the measurements of low level power of light emitted by the source at low temperature (e.g. 77 K). In this case the unstable negative signal is observed because of the energy flow from detector to the low temperature source of light in infrared region. Due to high level of temperature fluctuations near the low temperature source, zeroing of flux meter is practically impossible. Moreover, the low sensitivity of thermoelectrical detectors in visible region makes a fundamental difficulty in measurements, especially when integrating sphere is used. When source and thermoelectric detector are at room temperature the sensitivity is too low the lower limit for irradiance measurements being about 1 $\mu W/cm^2$.

The radiant sensitivity of photomultipliers in visible range of spectrum is very high. We can easily measure irradiance at about $10^{-10}$ $W/cm^2$ level. Moreover on the longwavelength side of spectrum the photoelectric effect has a sharp edge. In typical photoelectrodes it ranges between 700—900 nm. The abrupt decreasing of the sensitivity in the infrared region of spectrum allows to avoid difficulties with measuring power of light from sources in different temperatures, but when photomultipliers is used their more complicated spectral response characteristic must be taken into account.

## 2. Experimental details and procedure

In the present method, as outlined in the Introduction, Ulbricht sphere for "integrating" of light and photomultiplier as detector are used.

Inner surface of the sphere is coated with a special lacquer whose constant spectral diffuse reflectance coefficient is equal to 0.90 within a wide region of spectrum ranging from 420 nm to 850 nm. The diameter of sphere is 0.4 m. Provisions exist for low temperature investigations of sample held in a Dewar. The

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integrating sphere and photomultiplier are interconnected and fixed on an optical bench. Integrating sphere is equipped with an additional windows used to let in a laser beam. This comparative beam is diffused on shielding flag inside the sphere.

In this experiment He—Ne laser which emits the light at the wavelength 632.8 nm (Cobrabid—Poznań) and Radiant Flux Meter (HP 8333 A, 8330 A) are used for calibration. The Radiant Flux Meter is used only for measurements of the total power of light — $\Phi_{0l}$ emitted by laser (fig. 1a).

where $d$ is the sphere diameter, $\varrho_\lambda$ is the reflection coefficient, and $\Phi_{0\lambda}$ — spectral power density of light (in W/nm). The anodic current — $i_\lambda$ from photomultiplier is proportional to the spectral irradiance $E_\lambda$, photomultiplier sensitivity — $A_\lambda$ and effective surfaces of detector — $S$. Then, the photomultiplier current suitable for the monochromatic light diffused in sphere may be calculated from (2)

$$i_\lambda = \frac{1}{\pi d^2}\frac{\varrho_\lambda}{1-\varrho_\lambda} S A_\lambda \Phi_{0\lambda}. \tag{2}$$

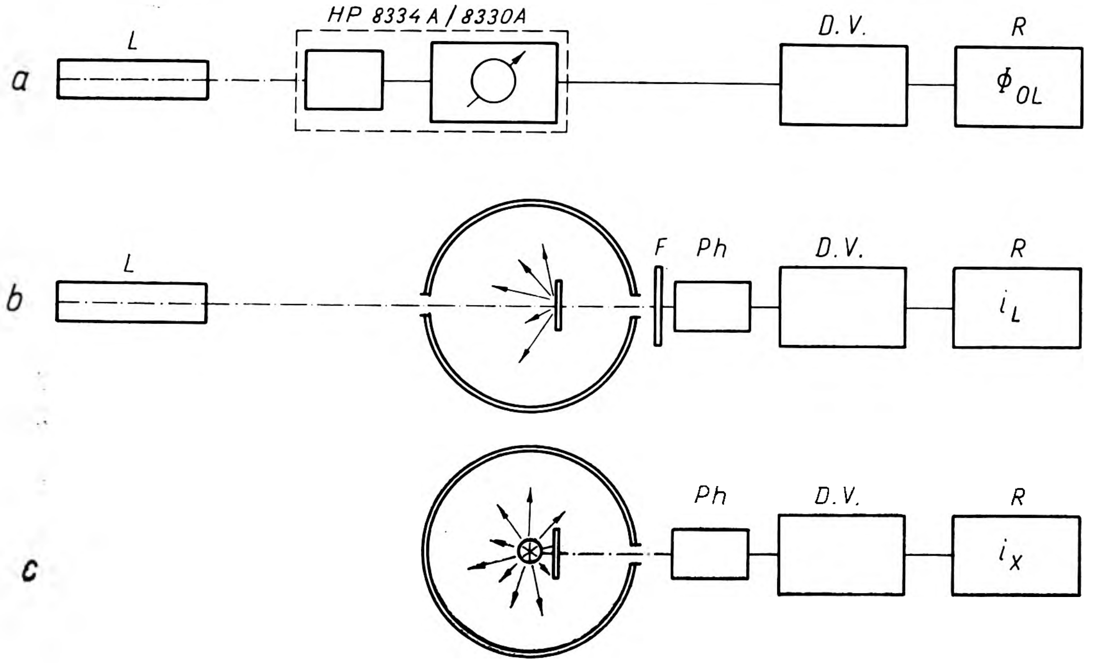


Fig. 1. Block diagram of measuring system for light power determination: a) arrangement for determination of laser power — $\Phi_{0l}$; b) calibration of the integrating sphere and photomultiplier set by measurement of $i_l$ current; c) determination of light power for the source investigated by measurement of current $i_x$. $L$ — He—Ne laser, $D.V.$ — digital voltometer, $R$ — recorder, $F$ — non-selective filter, $Ph$ — photomultiplier

For this purpose He—Ne laser is much convenient because of small area of cross-section (about 0.02 cm$^2$) of the emitted monochromatic light and sufficient power stability. Small area of cross-section is important for an accurate determining of the total light power with HP Radiant Flux Meter whose active absorbing area is 0.1 cm$^2$.

The method is based on the comparison of two photomultiplier currents: $i_l$ which flows when the sphere is illuminated by laser (fig. 1b), and $i_x$ suitable for the source under investigation (fig. 1 c). In this method we assume that the relative spectral power distribution $\Phi_{\lambda x}$ of the sample investigated is known.

The spectral irradiance $E_\lambda$ on sphere surface can be at any given wavelength calculated from the following formula [1, 2]:

$$E_\lambda = \frac{1}{\pi d^2}\frac{\varrho_\lambda}{1-\varrho_\lambda}\Phi_{0\lambda}, \tag{1}$$

If the spectral diffuse reflectance — $\varrho_\lambda$ is independent of the light wavelength in the wavelength interval ranging between $\lambda_1$ and $\lambda_2$, then eq. (2) may be rewritten in the form

$$i_\lambda = K A_\lambda \Phi_{0\lambda}, \tag{3}$$

where factor $K$ is independent of the wavelength. According to this assumption the ratio of two photomultiplier currents $i_x$ to $i_l$ suitable for the investigated source (index $x$), and laser (index $l$) respectively is given by

$$\frac{i_x}{i_l} = \frac{\int_{\lambda_1}^{\lambda_2} A_\lambda \Phi_{0\lambda x} d\lambda}{A_\lambda \Phi_{0l}}, \tag{4}$$

where $\Phi_{0\lambda x}$ is the spectral power density of the source.

For the same light source the spectral power density $\Phi_{0\lambda x}$ and the relative spectral density $\Phi_{\lambda x}$

are connected by a simple relation:

$$\Phi_{0\lambda x} = n\Phi_{\lambda x}. \quad (5)$$

The coefficient $n$ can be then calculated from the formula

$$n = \frac{i_x}{i_l} \frac{\Phi_{0l}}{\int_{\lambda_1}^{\lambda_2} a_{\lambda_l}\Phi_{\lambda x} d\lambda}, \quad (6)$$

where $a_{\lambda_l}$ is defined as

$$a_{\lambda_l} = \frac{A_\lambda}{A_l}. \quad (7)$$

The value of $a_{\lambda_l}$ is the relative photomultiplier sensitivity normalized for the laser wavelength. Finally, from eqs. (5) and (6) we obtain the spectral energy density $\Phi_{0\lambda x}$ as

$$\Phi_{0\lambda x} = i_x \frac{\Phi_{0l}}{i_l} \frac{\Phi_{\lambda x}}{\int_{\lambda_1}^{\lambda_2} a_{\lambda_l}\Phi_{\lambda x} d\lambda}. \quad (8)$$

It is easy to see that the basic assumption for this method is valid if $a_{\lambda_l}\Phi_{\lambda x}$ is different from zero only in a spectrum region for which the reflection coefficient $\varrho$ is constant.

Generally, for these calculations (eq. (8)) the numerical values of $\Phi_{\lambda x}(\lambda)$ and $a_{\lambda_l}(\lambda)$ with a constant step $\Delta\lambda$ are used. For this reason the integral in the formula (8) is replaced by the sum, according to the relation:

$$\Phi_{0\lambda x} \cong i_x \frac{\Phi_{0l}}{i_l} \frac{\Phi_{\lambda x}}{\sum_\lambda a_{\lambda_l}\Phi_{\lambda x}\Delta\lambda}. \quad (9)$$

The spectral power density $\Phi_{0\lambda x}$ calculated with a constant step $\Delta\lambda$ allows to estimate many interesting parameters which characterise different properties of the source.

When the spectral power density is integrated from $\lambda_3$ to $\lambda_4$ lying inside spectral region limited by $\lambda_1$ and $\lambda_2$, then the light power $\Phi_{0x}$ emitted in part of the spectrum is obtained. In such a case we get the following expression

$$\Phi_{0x} = \int_{\lambda_3}^{\lambda_4} \Phi_{0\lambda x} d\lambda \cong i_x \frac{\Phi_{0l} \sum_\lambda \Phi_{\lambda x}}{i_l \sum_\lambda a_{\lambda_l}\Phi_{\lambda x}}. \quad (10)$$

When the spectrum under investigation has only one band a useful approximation of $\Phi_{0x}$ is given by the formula

$$\Phi_{0x} \cong \frac{i_x}{i_l} \frac{\Phi_{0l}}{a_{l\lambda \max}}, \quad (11)$$

where $a_{l\lambda \max}$ is the value of relative photomultiplier sensitivity for the maximum of emission.

From the practical point of view the electroluminescence sources are specified better in terms of a luminous spectrum which describes visual sensation. With the help of a tabular Standard Luminosity Coefficient — $V_\lambda$ for the eye (C.J.E.) [3] the power spectrum can be easily converted into a luminous spectrum by using the following formula

$$\Phi_{f0\lambda x} = KV_\lambda \Phi_{0\lambda x}, \quad (12)$$

where $K$ is the photometric equivalent of radiant power. Here we have assumed [1]:

$$K = 673 \frac{lm}{W}. \quad (13)$$

The total luminous flux $\Phi_{f0x}$ emitted from the source and measured in lumens can be determined by integrating (13)

$$\Phi_{f0x} = K \int_{\lambda_1}^{\lambda_2} V_\lambda \Phi_{0\lambda x} d\lambda. \quad (14)$$

In sêlection of possible electroluminescent mechanisms important role is played by distribution of photons. At first we can define photon density — $n_\lambda$ versus wavelength

$$n_\lambda(\lambda) = \frac{dN}{d\lambda}, \quad (15)$$

where $dN$ is a number of photons emitted in unit of time in spectrum range between $\lambda$ and $\lambda+d\lambda$. Using eq. (15) we obtain the following relation between photon density — $n_\lambda$ and power density — $\Phi_{0\lambda x}$

$$n_\lambda(\lambda) = \frac{\lambda}{hc} \Phi_{0\lambda x}(\lambda). \quad (16)$$

Eq. (16) can be integrated in the interesting region of spectrum in order to obtain the total number $N_q$ of the emitted photons

$$N_q = \frac{1}{hc} \int_{\lambda_3}^{\lambda_4} \lambda \Phi_{0\lambda x} d\lambda. \quad (17)$$

This last result allows to calculate electroluminescence quantum efficiency, which is the most important parameter of the electroluminescence phenomenon. The electroluminescence quantum efficiency — $\eta_q$ is defined as:

$$\eta_q = \frac{N_q}{N_e}, \quad (18)$$

where $N_q$ is the number of photons emitted in unit of time in the interesting region of spectrum (e.g. in one emission band), $N_e$ is the number of electrons suitable for exciting current — $J$.

Using eqs (17) and (18) we obtain:

$$\eta_q = \frac{e}{hcJ} \int_{\lambda_3}^{\lambda_4} \lambda \Phi_{0\lambda x} d\lambda. \qquad (19)$$

In the case when the spectrum under investigation has only one narrow band a good approximation can be obtained in the form

$$\eta_q \cong \frac{e}{hcJ} \Phi_{0x} \cdot \lambda_{max}, \qquad (20)$$

where $\Phi_{0x}$ is the total power emitted in the investigated range of spectrum, and $\lambda_{max}$ is the wavelength corresponding to the maximum of emission.

The parameter more important for applications is energetic efficiency — $\eta_e$ defined for examined region of spectrum as:

$$\eta_e = \frac{1}{UJ} \int_{\lambda_3}^{\lambda_4} \Phi_{0\lambda x} d\lambda, \qquad (21)$$

where $U$ is the drop of voltage electroluminescence structure. Like in former calculations the energetic efficiency in all investigated spectrum can be obtained by using the formula

$$\eta_e = \frac{\Phi_{0x}}{UJ}. \qquad (22)$$

Finally it should be noted that for the interpretation of the electroluminescence phenomenon the dependence of the photon density spectrum upon the photon energy [4] appears to be the most helpful. In this case we define photon density $n_\varepsilon$ as:

$$n_\varepsilon(\varepsilon) = \frac{dN}{d\varepsilon}, \qquad (23)$$

where $dN$ is the number of photons emitted in a unit of time in spectrum interval $\varepsilon$ and $\varepsilon + d\varepsilon$. Since in the present paper we have assumed that wavelength — $\lambda$, and power density — $\Phi_{0\lambda x}$ are fundamental quantities (see (9)) then in order to obtain the spectrum of photon density — $n_\varepsilon$ ($\varepsilon$) relations, are required

$$\varepsilon(\lambda) = \frac{hc}{\lambda}, \qquad (24)$$

and

$$n_\varepsilon(\lambda) = \frac{\lambda^3}{h^2 c^2} \Phi_{0\lambda x}(\lambda). \qquad (25)$$

## 3. Results and discussion

In this method the fundamental condition which must be fulfilled to avoid incorrect light power measurements is the constant spectral reflection coefficient. It is easy to see that the 1% difference in spectral reflection coefficient with average value 0.90 leads to about 10% inequality for spectral irradiance in Ulbricht sphere (eq. (1)).

The selectivity of integrating sphere in the spectrum range from 420 nm to 850 nm is lower than 5%. In practice this region of spectrum is narrower because of 1 P 22 photomultiplier which was used as a detector. In this case the sensitivity of our arrangement enables the measurement of the total light power $10^{-8}$ W for the source spectrum of which is emitted between 420–650 nm.

The construction of photomultiplier housing allows to use the diaphragm shield with many small holes. This shield acts as a non-selective filter which attenuates hundred times photocatode irradiance and is used when light power is higher than $10^{-4}$ W. It is especially used to determine the detector current $i_l$ when integrating sphere is illuminated by laser. When 1 P 22 photomultiplier is supplied with 900 V then the calibration coefficient — $\Phi_{0l}/i_l$ is equal to about 40 W/A.

Let us now turn to the assumption of the independence of reflection coefficient — $\varrho_\lambda$ of the wavelength in the investigated spectrum range. It is easy to see that when the number factor $K$ in eq. (3) depends on the wavelength instaed of $a_{\lambda_l}$ (eq. (9)) the new values $b_{\lambda_l}$ which take into account the spectral selectivity of the sphere can be used. The coefficient $b_{\lambda_l}$ describing the spectral sensitivity of the photomultiplier and the integrating sphere can be obtained experimentally by using the monochromator and the light source where relative spectrum is known. Analogically, the selectivity of the sphere and photomultiplier was taken into account in the method described by Ralston and Bachrach [5].

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### Измерение производительности в электролюминесцентных приборах

Разработан метод измерения полной мощности излучения и к.п.д. электролюминесцентных структур при разных температурах на основе фотоумножителя в качестве детектора и с применением шара Ульбрихта. Калибровка прибора выполняется при помощи лазера He-Ne и абсолютного измерителя мощности излучения HP Radiant Flux Meter.

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