# Efficiency of cathodoluminescent phosphors for a field-emission light source application

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(Received 16 December 2002; accepted 5 May 2003; published 31 July 2003)

The efficiency of major types of cathodoluminescent phosphors has been investigated at high-brightness (up to 30 000 cd/m$^2$) operational conditions using thermionic electron source. The accelerating voltage was varied from 4 to 14 kV and electron beam current density was independently varied from 2 to 50 $\mu$A/cm$^2$. Under those conditions both thermal quenching and current saturation of the phosphors were observed. Due to combined influence of those factors, it was found that the best way to characterize the phosphor is plotting the efficiency (in lm/W) versus the specific power density (in mW/cm$^2$) graph. The resulting plots show the integrated influence of current loading and elevated temperature on the phosphor efficiency. The best efficiencies at 200 mW/cm$^2$ and 10 kV were measured for a green color phosphor −55 lm/W, for a blue one—10 lm/W, and for a red—13 lm/W.  [DOI: 10.1116/1.1587134]

## I. INTRODUCTION

The use of field emission cathodes to illuminate cathodoluminescent phosphors until recently was restricted only to field-emission displays (FEDs).[1,2] Other prospective applications of field-emission cathodes include pixel-size cathode ray tubes (CRTs) for giant outdoors displays,[3] specialized, and general-purpose lighting applications.[4–6] The proposed light-source devices typically rely on usage of existing red–green–blue cathodoluminescent phosphors commercially available for television applications, or on mixes of color components resulting in white light emission. Due to practically 100% efficiency of a field-emission cathode, the general efficiency of the field-emission light sources will be determined by the phosphor efficiency, measured in lm/W.

Unfortunately, the fact that television phosphors have been commercially available for the last 4 decades does not assure that these phosphors are readily applicable to the field emission light sources. Most modern CRT phosphors are optimized to operate at very high acceleration voltages, typically in the range of 13–30 kV, which imposes significant challenges for design and geometry of field emission devices. Operation of field emitters can be achieved at considerably lower voltages, however the light efficiency of standard CRT phosphors reduces significantly at lower acceleration voltages. Another challenge for the practical usage of the cathodoluminescent phosphors in light source application is their relatively low brightness level. Typical CRTs as well as FEDs operate at brightness of 70 cd/m$^2$ (or ‘nit’), in use as a monitor, and at 100–300 cd/m$^2$,[2] if used for television applications, whereas lighting application requires brightness up to 30 000 cd/m$^2$.[3,6] Therefore, for the range of practically realistic accelerating voltages between 8 and 12 kV the required current densities for light sources will exceed corresponding CRT level of 1 $\mu$A/cm$^2$ by a factor of 100. At that combination of accelerating voltages and current densities a steady state temperature of a phosphor layer is expected to be far above the room temperature. As a result, the phenomenon of a thermal quenching will become a significant factor influencing the phosphor's efficiency. Recently, the thermal quenching was measured in a range of 25–150 °C for the P-55 phosphor at 10 kV and current density 0.5$\mu$A/cm$^2$,[6] however we were interested to know the phosphor's efficiency at up to 100 times higher current density.

Consequently, in this article we are reporting results of phosphor efficiency investigation for a viable selection of modern cathodoluminescent phosphors for field emission light source applications. Samples of commercial P-22 type CRT phosphors were obtained from manufacturers and are listed by manufacturers corporate name: *Kasei*-Kasei Optonix LTD, Japan; *Sylvania*-Osram Sylvania, USA; *Platan*-Platan Co, Russia; *Saratov*-Volga R&D Co, Russia.

## II. EXPERIMENT

The preparation of the phosphor screens included wet settling of the individual phosphors with a surface density of 4 mg/cm$^2$ on flat microscopic glass slides, followed by lacquering with an organic sacrificial film applied using the flotation method, and subsequent metallization with a thin aluminum layer deposited using electron beam evaporation. The aluminum layer is used as a reflecting mirror for unidirectional light emission as well as for collecting secondary electrons. After the deposition of the aluminum layer, the lacquer layer was pyrolized by 20 min baking at 400 °C. The specifications of the phosphor studied in this research are summarized in Table I.

We tested each phosphor screen in the metal vacuum chamber at accelerating voltages ranging from 4 to 14 kV. The lower accelerating voltage was determined by the electrons ability to penetrate through aluminum anode film, and the upper voltage was limited by the power source. The test

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TABLE I. Specifications of phosphor studied in this research.

| Type | Chemical base | Color | Efficiency at 2 $\mu$A/cm$^2$ and 10 kV (lm/W) | Efficiency at 20 $\mu$A/cm$^2$ and 10 kV (lm/w) |
|---|---|---|---|---|
| Platan CLR-1 | $Y_2O_2S$:Eu | Red | 15 | 5 |
| Platan CLR-2 | $Y_2O_2S$:Eu | Red | 22 | 6 |
| Platan CLR-3 | $Y_2O_3$ : Eu | Red | 25 | 13 |
| KASEI P-22 | $Y_2O_2S$:Eu | Red | 12 | 4 |
| KASEI LDP-R2 | (ZnCd)S:Ag +In2O3 | Red | 10 | 3 |
| Sylvania 9420 | $Y_2O_2S$:Eu | Red | 14 | 5 |
| Platan G-2 | $Gd_2O_2S$:Tb | Green | 46 | 20 |
| Platan G-3 | $La_2O_2S$:Tb | Green | 44 | 19 |
| KASEI P-15 | ZnO:Zn | Green | 20 | 5 |
| KASEI P-22 | ZnS:Cu, Au, Al | Green | 69 | 48 |
| Sylvania 9520 | ZnS:Ag, Al | Blue | 12 | 8 |
| Saratov VFD | ZnS:Ag | Blue | 17 | 9 |
| KASEI LDP-B3 | ZnS:Zn | Blue | 23 | 11 |
| KASEI P-22 | ZnS:Ag, Al | Blue | 13 | 9 |

chamber setup is shown in Fig. 1. An electron flux formed by thermionic filament cathode and rectangular diaphragm illuminated a $2\times2$ cm$^2$ area on the aluminized screen surface. The Hugner-S3 photometer was used to measure local brightness of the phosphor screen through a 3 mm thick glass window. The light spectrum was recorded by the Ocean Optics S1000 spectrometer. The screen temperature during operation was measured with *J*-type 25 $\mu$m thermocouple attached to the OMEGA CN9000 digital thermometer. The efficiencies were measured at low (2 $\mu$A/cm$^2$) and high (10–50 $\mu$A/cm$^2$) levels of the current density. For each combination of the current density level and acceleration voltage a waiting time of 10–20 min was used prior to each measurement of the light output to achieve a steady state temperature of the phosphor screen.

To achieve brightness from 10 000 to 30 000 cd/m$^2$ as required for lighting applications,[3,6] we had to excite the phosphor screens with an electron beam having a power density from 50 to 400 mW/cm$^2$. As a result, the thermal loading for phosphors was considerably more demanding in comparison to the conventional CRT level. An equilibrium temperature directly measured on the phosphor layer was found to be up to 100–150 °C. An experimental relationship between power density and screen temperature is shown in Fig. 2.

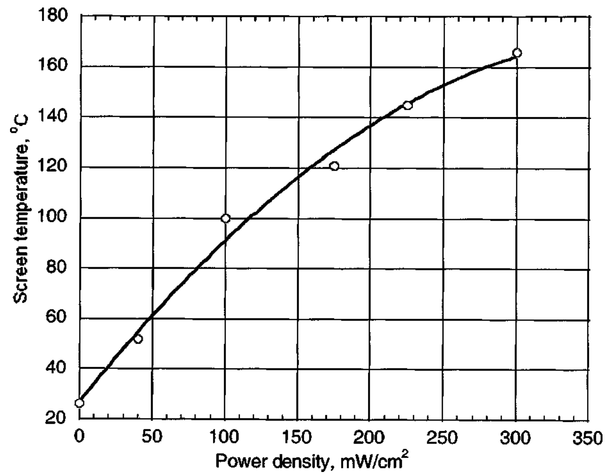


FIG. 2. Experimental relationship between the phosphor screen temperature vs the power density.

## III. RESULTS AND DISCUSSION

### A. Green phosphor

Green phosphors are most efficient due to their highest value of so-called Lumen equivalent—up to 580 lm/W. The efficiencies of the green phosphors, determined at low power density of exciting electron flux—20 mW/cm$^2$ and accelerating voltage from 4 to 14 kV, are shown on the graph in Fig. 3(a). The best efficiency—up to 90 lm/W—was measured for the green phosphors of the well-known P-22 family (ZnS:Cu,Al). A minor variation depends on grain size or conductive additives (for the low-voltage version). The phosphors on the base of gadolinium or lanthanum oxy-sulfides doped with terbium (G-2 and G-3) have lower efficiency, which does not exceed 50 lm/W even at 14 kV. The lowest efficiency was observed for the P-15 of ZnO:Zn composition, used in old monochrome CRTs for oscilloscopes. In Fig. 3(b) the efficiency of green phosphors is shown to depend on power density at 10 kV. At that condition it is possible to

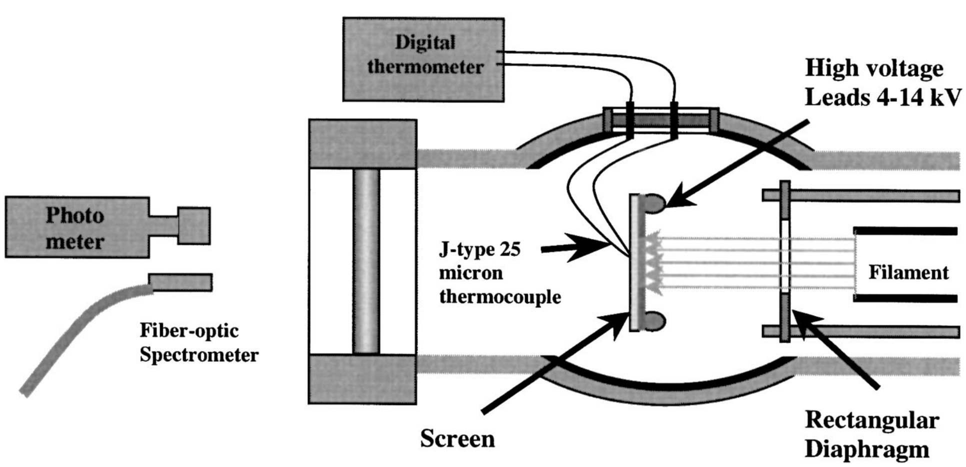


FIG. 1. Test setup for the phosphor efficiency measurements.

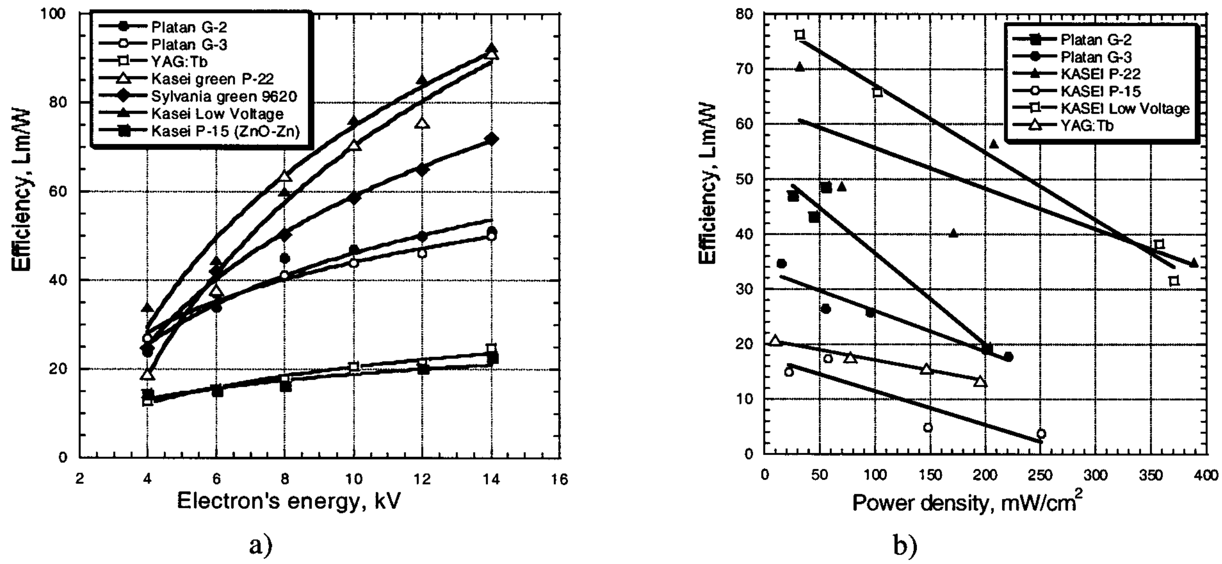


FIG. 3. Efficiency of green phosphors: (a) vs electron energy at 20 mW/cm$^2$ and (b) vs power density at 10 kV.

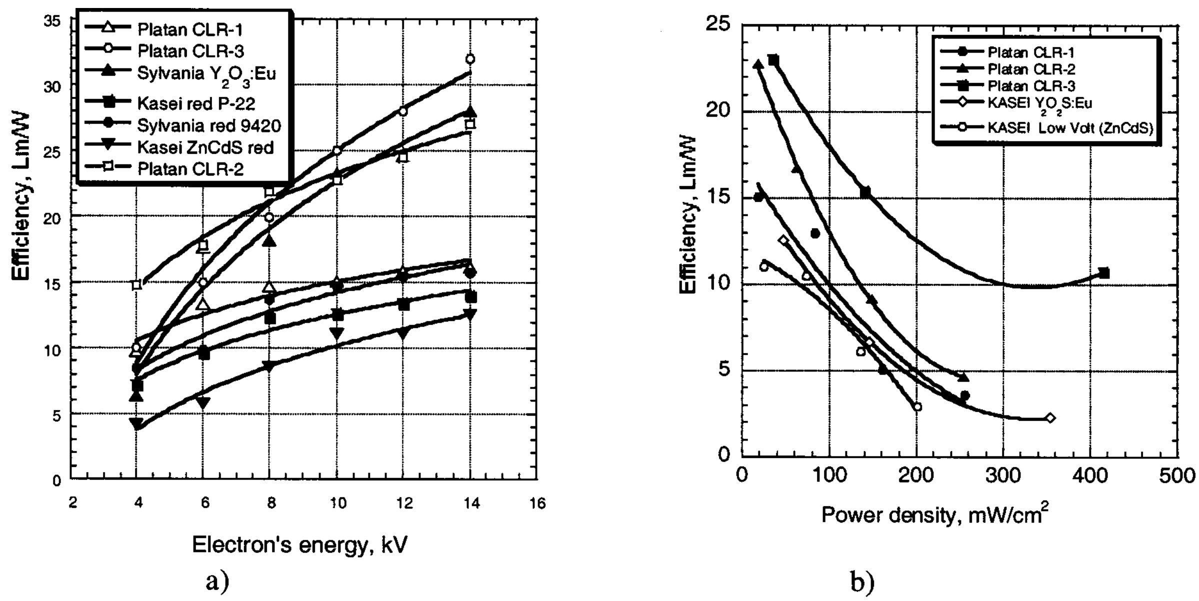


FIG. 4. Efficiency of red phosphors: (a) vs electron energy at 20 mW/cm$^2$ and (b) vs power density at 10 kV.

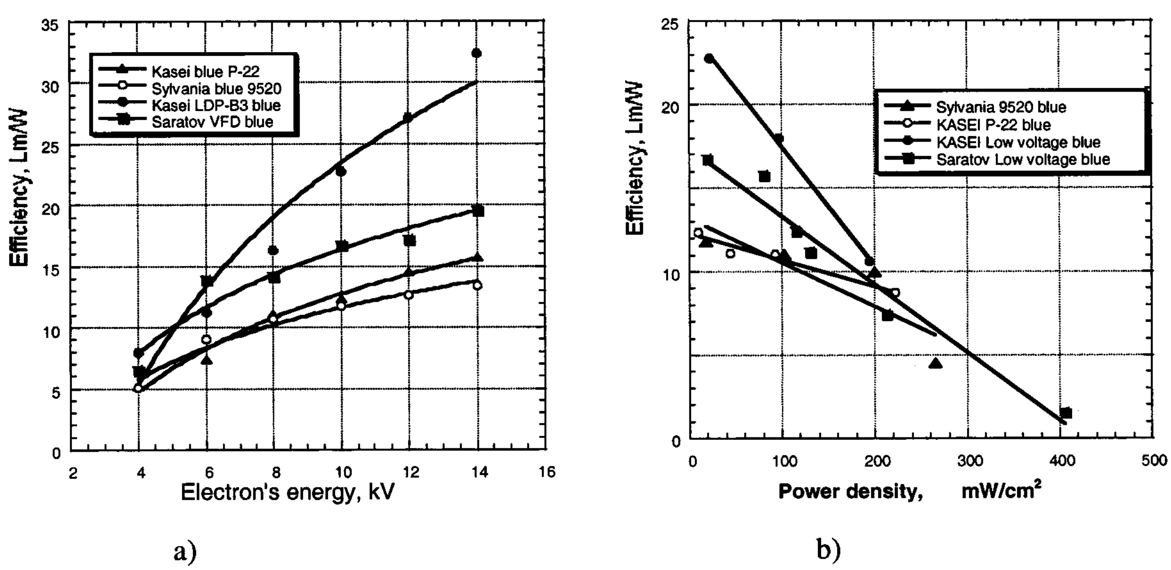


FIG. 5. Efficiency of blue phosphors: (a) vs electron energy at 20 mW/cm$^2$ and (b) vs power density at 10 kV.

observe a stronger difference in efficiency between individual phosphors. For example, the G-2 phosphor ($Gd_2O_2S$:Tb) at low current density is more efficient than the G-3 ($La_2O_2S$:Tb), but at a power density of 200 $mW/cm^2$ the G-3 has better efficiency due to low thermal quenching and/or good linearity. Similarly, the KASEI low voltage green phosphor has some advantage in comparison with the KASEI P-22 green at a power density lower than 320 $mW/cm^2$, and vice versa at a higher current density.

Therefore, a modern version of the P-22 green phosphor (ZnS:Cu,Al) still would be a better choice for a high brightness cathodoluminescent device for lighting applications.

### B. Red phosphor

Practically, the only modern red phosphor currently used in high-voltage field-emission flat-panel displays is P-22 red on the base of yttrium oxy-sulfide ($Y_2O_2S$:Eu).[6] However, as it clear from Fig. 4(a), at low power density the CLR-3 red phosphor and other phosphors, based on yttrium oxide ($Y_2O_3$:Eu), have compatible and even better efficiency, when accelerating voltage exceed 10 kV. This advantage dominated at high power density, as it shown in Fig. 4(b). At 200 $mW/cm^2$ the $Y_2O_3$:Eu phosphor has efficiency of 13 lm/W in comparison with 6 lm/W for the best representative of the P-22 red phosphor family. The FED application of a P-22 red phosphor seems to be reasonable due to better C.I.E color coordinates, but for a lighting application efficiency is more important and the usage of an $Y_2O_2S$:Eu phosphor is expected to be of reasonable interest.

### C. Blue phosphor

The results of low power density tests of most efficient blue phosphors are in Fig. 5(a). It is evident, that so-called "low-voltage" blue phosphors, designed for vacuum fluorescent devises (VFDs), demonstrated significantly better efficiency in comparison with regular TV phosphors. Moreover, at high power density the low-voltage phosphors also kept better efficiency and demonstrated good thermal quenching tolerance and good linearity. Finally, though rarely used the ZnS:Zn phosphor demonstrated the highest efficiency at power density below 200 $mW/cm^2$. The low-voltage version of ZnS:Ag,Al phosphor (Saratov VFD blue) was excellent over 200 $mW/cm^2$ and 10 kV with efficiency 10 lm/W as it plotted in Fig. 5(b).

## IV. CONCLUSION

The efficiency of the color phosphors was experimentally compared in the range up to 90 lm/W for green, up to 30 lm/W for blue, and up to 35 lm/W for red color at 14 kV at various current density levels. At 10 kV accelerating voltage and 200 $mW/cm^2$ of power density the measured efficiencies for green color phosphor was 55 lm/W, for blue 10 lm/W, and for red 13 lm/W, which is a reasonable figure in comparison to the efficiency of modern compact fluorescent light sources. The selection of appropriate CRT phosphors will impact the future success of the field emission light sources.[7]

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