Calculation of the Quantum Efficiency of Phosphor Screens in CRTs and FL Tubes

Lyuji Ozawa and Yakui Tian

Abstract

The quantum efficiencies of CRT and FL tubes that use a phosphor screen as transducer of invisible particles to light in visible spectrum wavelengths were calculated in this study. The phosphor screens in CRT tubes have quantum efficiencies greater than 3,000, which give the luminance of comfortable images on phosphor devices for the observation by the eyes. The established FL tubes have the amazing quantum efficiency of $3x10^{10}$ photons per moving electron per FL tube, which allows the illumination of a 5x5 m^2 room by three FL tubes, with heating at 40°C. Thus, FL tubes, including for backlighting of LCD displays, have a superior over other illumination sources.

Keywords: Quantum efficiency, energy conversion efficiency, CRT, FL

1. Introduction

Living standards have markedly improved with illumination and communication. Illumination sources have evolved from wood fire to torch flames, the burning of oil, candles, gas flames, incandescent lamps, fluorescent lamp (FL) tubes, and light-emitting diodes (LED), combined with luminescence from phosphor screens. Lightings until gas flames use chemical reactions of heated materials. The chemical reactions at high temperatures release the energy as light and heat. Incandescent lamps use the heated tungsten (W) filament by the combination of the electric resistance and the electric current, which is the Joule heating. Lighting after with FL tubes uses phosphor screens that recombine the pairs of electrons and holes in luminescent center to generate the visible light. The volume of the luminescent center in a phosphor screen is 10^{-18} cm^3, which makes it invisible with the eyes. The developed illumination source is made by recombining the number of invisible pairs of electrons (diameter: 10^{-13} cm) and holes (diameter: 10^{-8} cm) from the phosphor screen in thickness (e.g., 10^{-3} cm = 10 μm). The developed illumination sources are a large area (1,000 cm^2) in visible sizes with an extremely small volume (e.g., 1,000cm^2 area x 10^{-3}cm thickness = 1cm^3 volume). By the developed illumination sources in small volumes, life's activities are significantly prolonged into dark night hours and extend to rooms in houses, offices, and shopping malls of big and tall buildings in cities. Phosphor screens in small volumes should emit an appropriate amount of photons of light in visible spectral wavelengths (e.g., 10^{21} photons cm^{-1} s^{-1}), which correspond to daytime sceneries under a slightly overcast sky. A large-area phosphor screen (> 1,000 cm^2), rather than a spot light source (< 1 cm^2), has an advantage as a lighting source for wide rooms (e.g., 4x5 m^2), with the illumination level of 10^{21} photons (cm^2, s^{-1}) on the surface of materials. Modern lightening sources are concrete materials (visible with the eyes) as a consequence of the abstraction of electrons and atoms (invisible with the eyes).

The communication of information has evolved from the faces of rock cliffs, to the walls of caves, to clay tablets, parchments, wood and bamboo plates, sheets of paper, magnetic tapes (and disks), and electronic chips (large-scale integrated circuits, LSIs) that are assembled into 10^{10} elements on 1cm^2 dais. Until the emergence of sheets of paper, the recording media were surfaces of visual materials (concrete materials). After the emergence of the magnetic tape, recordings start to use the invisible magnetic segments and electrons that allow recording sizes of submicron meters and further nano-meters, which can only be observed as magnified images on a screen of an electron microscope. Electronic devices have significantly increased the speed and contents of communication information. In-

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Corresponding author: Lyuji Ozawa
Building 69-2-403, 30 Litang Lu, Changping Qu, Beijing, China 102209
E-mail: rotsun4@hotmal.com **Tel:** +86-10-8176-3872 **Fax:** +86-10-8256-1887

formation stored on chips in electronic devices (e.g., cellular phones, computers, and TV sets) are invisible to the human eyes. Processed information should be visualized with the eyes. Display devices have been developed as interfaces between human and electronic devices for visualization of invisible information in electronic devices using a phosphor screen. The images on the phosphor screens are produced by 10^{21} photons $(cm^2\ s)^{-1}$ that are adjusted by the human eyes for 5 million years. Reading of images on phosphor screens in communication devices are concrete materials for the eyes, and recording media and light generation on phosphor screens are the abstractions in atomic sizes. In this paper, the quantum efficiencies (η_q) of phosphor screens were calculated to find the reason for the advantages of FL tubes as illumination devices and of CRTs as information devices.

The phosphor screen has a large screen area (e.g., 10^3 cm^2) with a thickness of 10^{-3} cm (= 10 μm). The optimal thickness of phosphor screens is determined by the optical transmission of the emitted lights in the 10^{-3}cm (= 10μm) phosphor screens. The total volume of the phosphor screen is calculated as only 1 cm^3 for a $10^3 cm^2$ screen size.

Phosphor screens in 1cm^3 volumes become an important role in illumination sources and communication devices. Images on display devices are illustrated on the phosphor screen by cathodoluminescence (CL) in a CRT. CL is generated in phosphor particles arranged in the phosphor screen under irradiation of electrons. The luminance of the phosphor screen in FL tubes as illumination sources is given by the photoluminescence (PL) in FL tubes. PL is generated in phosphor particles under irradiation of the 254nm ultraviolet (UV) light, which is emitted from vaporized Hg atoms in FL tubes. The vaporized Hg atoms are excited by sampling the Hg atoms with the moving electrons in the FL tubes. CL in CRTs and PL in FL tubes are observable with the eyes. CL generation is restricted, however, in tiny phosphor particles (average size of 4 μm) that incident electrons have penetrated. The PL intensity of the phosphor screen is proportionate to the UV intensities from excited Hg atoms, which are sampled by the moving electrons in the positive column in FL tubes. Thus, CL and PL are primarily controlled by the incident electrons, which are invisible to the eyes. The preparation of the phosphor screen in CRTs and FL tubes requires good comprehension of the intrinsic and induced charges of the tiny phosphor particles in operation.

The technologies involved in the production of phosphor screens are important in the development of both illumination sources and communication display devices. In practice, the most important feature of CRTs and FL tubes is their high quantum efficiency, η_q. The value of η_q is given by the ratio of the number of the photons generated from the phosphor screens by an incident electron to the phosphor screens in the CRT, and the ratio of the Hg atoms excited by the moving electron in FL tubes, under the assumption that the phosphor screens have a quantum efficiency of 1.0 (η_q = 1.0). The η_q values of CRTs and FL tubes may thus be calculated to verify their advantages.

2. Quantum efficiency (η_q value) of CRTs

In a CRT, one electron from the cathode is taken out from the heated Ba on BaO layers on metal cathode into vacuum [1]. The electron taken from the cathode is accelerated by the anode potential (25 keV). The accelerated electron penetrates a phosphor particle to generate CL light. The incident electron that has penetrated in to the phosphor particle collides (Coulomb's repulsion) with lattice sites (atoms or ions) in the phosphor particle. Each collision with the lattice atoms (and ions) generates one secondary electron in the space between lattice atoms, leaving a hole in the orbital shell of the atoms. The incident electron in the phosphor particle collides with lattice sites more than 3,000 times before the energy of the incident electron attenuates to the phonons that disappear in the phosphor particle by heat. Consequently, 3,000 pairs of free electrons and holes in the phosphor particle are generated by one incident electron in the phosphor particle. The creation energy of a pair of electron and hole is 3 Eg, where Eg is the band gap of the phosphor crystal (particle) [2]. The generated pairs of free electrons and holes in the phosphor particle are called "electron-hole pairs." In the phosphor particle, one electron-hole pair recombines at only luminescent center and disappear from the phosphor particle. The recombination of the electron-hole pair at the luminescent center releases a photon in the visible light without heat. Consequently, the quantum efficiency, which is the number of photons to the number of incident electrons, becomes $\eta_q > 3{,}000$ [3].

The current of the electron beam that generates the comfortable images on the phosphor screen in a CRT can be calculated. The maximum number of electrons extracted from the cathode for the generation of an appropriate number of photons (10^{21} cm^2 s^{-1}) from the unit phosphor screen is calculated as 10^{18} electrons (cm^2 s)$^{-1}$ (= 10^{21-3}). The 10^{18} electrons (cm^2 s)$^{-1}$ correspond to the electron density of 0.16 A (cm^2 s)$^{-1}$ [= 10^{18} x $1.6x10^{-19}$ Coulomb (cm^2 s)$^{-1}$]. The diameter of the electron beam in a CRT is around 1 mm. The practical current of the electron beam in a CRT was calculated as 1.6 mA (mm^2 s)$^{-1}$ (= $0.16x10^{-2}$ A mm^{-2}) maximum. The calculated electron current from the cathode of CRT accords with the practical electric current from a single cathode (1.0- 1.5 mA).

The heat of the spot of the phosphor screen can be calculated. The electron beam was calculated as 25 W (= $2.5x10^4$ V x $1x10^{-3}$ A). The spot diameter of the electron beam is 1 mm under a scanning electron beam with the NTSC (National Television System Committee) system, which has 525 vertical lines at 50 Hz. With a screen size of 20 inches diagonal, the duration of one scanning line is $3.8x10^{-5}$ s. The length of one horizontal line is 375 mm. The scanning speed of the electron beam is $1x10^5$ cm s^{-1} [= 375 cm ($3.8x10^{-5}$ s)$^{-1}$]. The irradiation duration of a 1mm phosphor screen is calculated as 10^{-7} s [= $3.8x10^{-5}$ s x (375)$^{-1}$]. The irradiated energy of the electron beam on one phosphor pixel is $2.5x10^{-6}$ W, with $2x10^{-2}$s intervals (50 Hz). The irradiated phosphor screen does not heat up. It is nearly always at room temperature. No heat from the phosphor screen via the scanning electron beam is confirmed with the touch of the fingers on the front face of the operating CRT. The emitted photon number per 1mm phosphor screen for 10^{-7} s is 10^{12} photons. Assuming that the average photons from the phosphor screen is 2.5 eV, the energy of the emitted photons from the phosphor pixel is $4x10^{-7}$ W. The energy conversion efficiency was calculated as 16% [= $4x10^{-7}$ W ($2.5x10^{-6}$)$^{-1}$ x 100]. The calculated η value is close enough to the reported η value of CL (e.g., 20%) [3]. The high η_q (> 3,000) allows the high η value without heat.

The electrons are taken out from the heated Ba on the BaO layers on the metal electrode (cathode). The details of the BaO thermoelectron source will be separately published elsewhere.

3. Quantum efficiency (η_q value) of FL tubes

Following calculations are made from the published data on the FL tubes produced before 1965. The optimized FL tubes were found to have a diameter of 30 mm from the lead sodium lime glass (PbO-NaO-CaO-SiO_2) and to contain 5Torr Ar gas pressure. The phosphor screens were made with the white-emitting calcium halophosphate [$(Ca_5(PO_4)_3(F,Cl):Sb^{3+}:Mn^{2+}$] PL phosphor powder. The FL tubes were produced via heating at 400°C, and the produced FL tubes were sealed off from the pumping facilities by melting down the pumping glass tip with a gas burner. The produced FL tubes have a great advantage as illumination sources with their high quantum efficiency.

There is a difficult to start (ignite) the lightening of Ar atoms. The following description is made after the start of the lightening of Ar atoms in the FL tubes. The injected electrons from the cathode into the FL tubes did not directly recombine with holes to generate light in the Ar space. The electrons reached the anode electrode that collects the electrons from the vacuum to close the electron flow inside of the FL tubes (the internal electron circuit in the FL tube). The injected electrons moved on in the vacuum between the Ar atoms, according to the longitudinal electric field between electrodes with the direction of cathode to anode, i.e., the vector for moving electrons in FL tubes. Thus, the moving electrons in the vacuum have a chance to meet the Ar atoms.

The electron trajectories of the injected electrons will be discussed next. The injected electrons in the vacuum in the FL tube have a kinetic energy below a few hundred eV. As the moving electrons meet the Ar atoms, the moving electrons receive a strong Coulomb's repulsion from the electrons in the orbital shells of the Ar atoms, so the moving electrons never get into any orbital electron shell of the Ar atoms. The moving electrons sharply change their movement direction to the vacuum, which scatters the moving electrons in the longitudinal electric field. A moment after the change in the direction (scattering), the scattered electrons again take the direction of the longitudinal electric field. The electrons will thus have a chance to meet other Ar atoms. The moving electrons will repeat their scattering by colliding with Ar atoms in the direction of the longitudinal electric field. Finally, the electrons will reach the anode that collects the electrons in the FL tubes.

The moving electrons give the some energy to the Ar atoms with each collision. As the moving electrons have kinetic energies greater than the ionization energy of the Ar atom (15.7 eV), the collisions will result in the ionization of the Ar atoms (Ar^+). As the kinetic energies are between 11.5 eV and 15.6 eV, the collisions of the moving electrons will excite the Ar atoms (Ar^*). As for kinetic energies below 15.5 eV, the moving electrons will be scattered among the Ar atoms, and the scattered electrons will recombine with Ar^+ to return to the Ar atoms. Fig. 1 illustrates this phenomenon.

If there is no deceleration factor to the moving electrons in the vacuum, a given electron multitudinously collides with the Ar (and Hg) atoms (hereinafter called "Ar atoms") in the FL tubes. As the moving electrons have kinetic energies greater than 15.7 eV, each collision of a moving electron with Ar atoms gives some energy to the orbital electrons that rise to the vacuum, leaving a hole in the orbital shell (i.e., ionization). Ionization is invisible with the eyes. As the moving electrons have kinetic energies between 11.5 eV and 15.6 eV, the moving electrons excite the Ar atoms. The excited Ar atoms generate light without heat. As the moving electrons have kinetic energies smaller than 15.5 eV, the moving electrons combine with Ar^+ to return to the Ar atoms. Fig. 2 illustrates the multitudinously collided electron. The multitudinous collisions with Ar atoms by a single electron injected from a cathode give FL tubes that contain Hg droplets a remarkable feature.

As illustrated in Fig. 2, the major collisions of the moving electrons in FL tubes result in the ionization of Ar atoms. The moving electrons lose some kinetic energy with each collision. As the kinetic energy of the moving electrons attenuates to the excitation energy of the Ar atoms (between 11 eV and 15 eV), the collision of the attenuated moving electrons results in the excitation of the Ar atoms. For the attenuation of the moving electrons to the excitation energy of the Ar atoms, the moving electrons collide with the Ar atoms more than 10 times to ionize the Ar atoms. The ionization of the Ar atoms has two roles in the operation of FL tubes. One is the attenuation of the kinetic energy of the moving electrons, and the other is as a heat source for Hg droplets. The Hg atoms are excited only by the electrons with kinetic energies that attenuated the excitation energy of the Hg atom (between 6.7 eV and 10.4 eV). The luminance of FL tubes is related merely to the number of the excited Hg atoms in the FL tubes. For the excitation of the Hg atoms by the moving electrons, the Hg atoms must evaporate in the Ar space. The number of evaporated Hg atoms is determined by the temperature of the Ar space in the FL tube. Using the term "discharge of gas" draws attention only to the excitation of Hg atoms, and never to find the role of the ionization of the Ar atoms, which are invisible with the eyes.

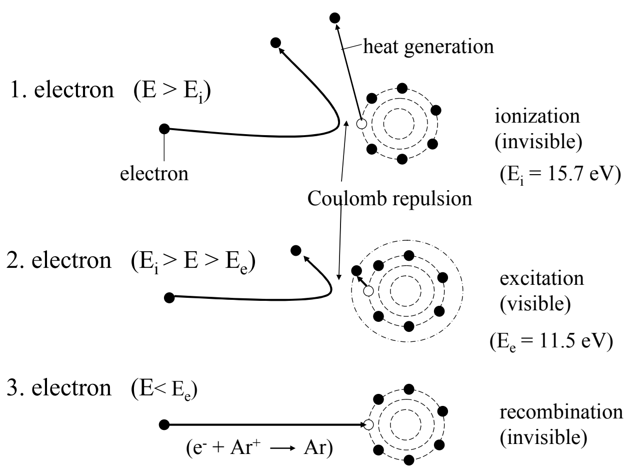

Fig. 1. Schematic illustrations of three different collisions of moving electrons with Ar atoms. The collisions are (1) ionization (2) excitation and (3) recombination, depending on the kinetic energies of the moving electrons.

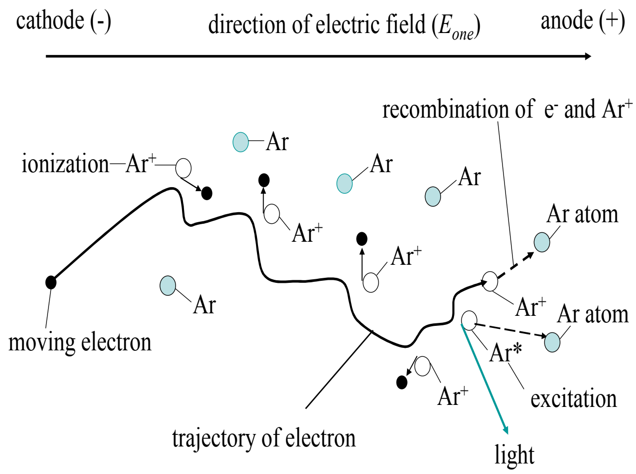

Fig. 2. Electron trajectory in the vacuum of an FL tube.

The electron in the excited Ar atom returns to the ground state after staying in the excited state for a while (10^{-8} s), releasing a photon with an energy that corresponds to the energy difference between the excited state and the ground state. Assuming that Hg atoms are excited by the moving electrons, the number of excitations of the Hg atoms determines the quantum efficiency of the injected electrons in the FL tube. It should be noted that the moving electrons never disappear in FL tubes, for as long as there is no deceleration factor, which will be reported elsewhere.

The number of excited Ar atoms in a unit volume of an FL tube can be calculated. The number of Ar atoms in a given FL tube can be calculated based on the Boyle-Charles law and Avogadro's number. It is $1x10^{12}$ atoms cm^{-3}, much small than the number of atoms in solids (10^{24} atoms cm^{-3}). The separation distance of the atoms is 1 μm [$(= 10^{12})^{-1/3}$ = 10^{-4} cm], which is much longer than the atomic diameter (Å= 10^{-8} cm). Fig. 3 shows a schematic illustration of a localized Ar space in an FL tube under 5Torr Ar pressure. The Ar atoms in the FL tube have no overlapping wave function with the neighboring Ar atoms, which indicates isolated atoms. Isolated atoms give a line-like emission from excited atoms. The orbital electron shells split in the electric field (the Stark effect) from the electrons of the neighboring Ar atoms. The split sublevels emit a line-like light and the absorption lines of the Ar atoms in the FL tube.

The reported mean free path of Ar, which has been experimentally determined, is 2 μm (= $2x10^{-4}$ cm) [4], that is close enough to the calculated distance between Ar atoms (1 μm). Assuming that the electrons are randomly scattered by the Coulomb repulsion of the orbital electrons (10^6 eV cm^{-1}) in the unit volume (cm^3) under a weak electric field from the electrodes (≈ 100 eV), the number of collisions of the moving electron in one side of the unit volume was calculated as $5x10^3$ [= $(2x10^{-4})^{-1}$ cm], which gives the number $1.2x10^{11}$ collisions cm^{-3} [= $(5x10^3)^3$]. In reality, the scattered electrons take the direction of the longitudinal electric field soon after the collision (scattering). The estimated number of scatterings may be in the range of 10^9 under the conditions of the ordinary FL tube operation. If it is so, we may calculate followings. The electrons should attenuate the kinetic energy to 11.5 eV from 100 eV by scattering.

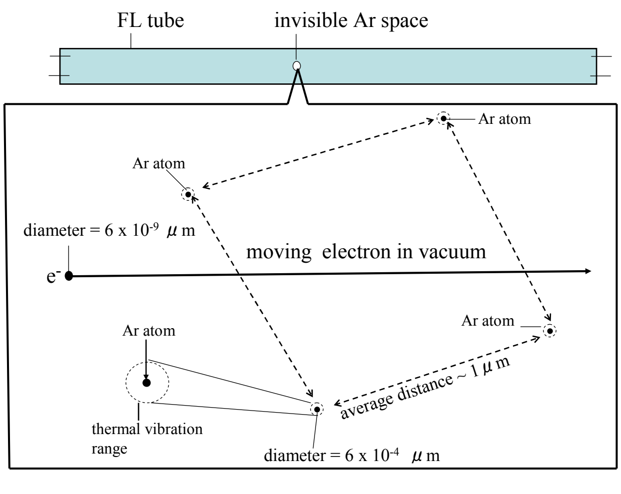

Fig. 3. Schematic illustration of a localized Ar space in an FL tube under 5Torr pressure.

The moving electrons should attenuate to the excitation energy of the Ar atoms (11.5 eV) to lighten the Ar atoms.

In the case of an FL tube, only the excited Hg atoms generate UV light. The number of the Hg atoms at 60°C was calculated as 10^{10} cm^{-3}, which is one-hundredth that of the Ar atoms (10^{12} cm^{-3}). The injected electron in the vacuum in the FL tube may excite more than 10^7 Hg atoms cm^{-3} s^{-1} (= 10^9 x 10^{-2}). Assuming that the η_q of the phosphor screen is η_q = 1.0, the number of visible photons on the phosphor screen is 10^7 photons cm^{-3} s^{-1}. The calculated η_q of the electrons to the visible light in the FL tube is surprisingly 10^7 cm^{-3} s^{-1}. The total number of photons from an FL tube was calculated. The volume of a 100cm-long FL tube with a 3.0cm diameter was calculated as $3x10^3$ cm^3 (= π x d^2 x l = 9π cm^2 x 10^2 cm). The quantum efficiency of the electrons in an FL tube is $3x10^{10}$ per tube (= 10^7 photons x $3x10^3$ cm^3). The high η_q value (η_q = $3x10^{10}$) of the injected electrons in the practical FL tube causes the reported high η value (30%) of the FL tube with a heating temperature of 42°C (5). Although the reported η value of regular FL tubes is around 25%, FL tubes have the highest energy conversion efficiency among the proposed illumination sources, without the problem of heat (45°C). This feature of the FL tube is due to its amazing η_q ($3x10^{10}$).

The required number of FL tubes for a 5x5 m^2 ($2.5x10^5 cm^2$) room with a daytime scenery (10^{21} photons cm^{-2} s^{-1}) can be calculated. The required number of photons for the room is $2.5x10^{26}$ photons s^{-1} (= 10^{21} x $2.5x10^5$). The η_q of the electron in the FL tube has been calculated as η_q = $3x10^{10}$ per tube. The electron current inside of the FL tube is 0.2 mA [6]. The number of electrons in the FL tube was calculated as $1x10^{15}$ electrons [= 0.2 mA x $(1.6x10^{-19}$ Coulomb$)^{-1}$]. The number of the emitted photons in the visible lights was calculated as $3x10^{25}$ photons per FL tube (= $1x10^{15}$ x $3x10^{10}$). Three FL tubes (e.g., 10^{26} photons) may comfortably illuminate the surface of the materials in a $5x5m^2$ room with a daytime scenery. The calculation is close enough to the practical number of FL tubes needed to illuminate a $5x5m^2$ room. It should be noted that this calculation was made for FL tubes that were produced with production technologies established before 1970.

Table 1 shows the calculated quantum efficiencies and energy conversion efficiencies of LEDs, OLEDs, CRTs, and FL tubes.

Table 1. Summary of the quantum efficiencies of injected single electrons (η_q), the energy conversion efficiencies (η), and the usage limitations of LEDs, OLEDs, CRTs, and FL tubes.

Light source	LED	OLED	CRT	FL tube
Quantum efficiency (η_q)	< 0.5	< 1.0	10^3	10^{10} per tube
Energy conversion efficiency (η, %)	< 20	< 20	20*	30* per tube
Use limitation	Heat > 200°C	Heat and electric breakdown	None	None

* Reported energy conversion efficiencies.

4. Conclusion

To conclude the calculations of the quantum efficiency (η_q) value, FL tubes are superior ($\eta_q = 3x10^{10}$ per injected electron) to the proposed light sources, such as LED, OLED, and others. The FL tubes produced before 1965 have not yet been optimized with the technologies that are now established in the semiconductor industry. Therefore, there is a great possibility of improving the features of FL tubes, to respond to social demand. The results are directly applicable to emissive devices such as plasma display devices (PDPs) and flat fluorescent devices (FFDs), which use the vacuum ultraviolet lights (172 nm and 142 nm) from Xe atoms.

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