Advances in Image Pickup and Display

Supplement 1

Color Television Picture Tubes

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LANCASTER, PENNSYLVANIA

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Foreword

This supplement to *Advances in Image Pickup and Display* is concerned entirely with color television picture tubes. Color television picture tubes are already in such widespread use that no serious effort is needed to convince the reader of the importance of such devices to the field of imaging. Aside from the development of the black-and-white picture tube and the invention of electron-beam camera tubes such as the iconoscope, no other single device has contributed to the growth of television and so fully augmented its potential as the shadow-mask color tube.

A few words are, perhaps, in order explaining the reason for devoting an entire volume to color television picture tubes. As one can expect, in view of the extended history of research, development, and commercial production of present shadow-mask tubes, many publications exist covering individual phases of the subject. However, no comprehensive or cohesive treatment exists in the literature covering the entire subject. Included in this supplement are not only a broad discussion of the basic principles and operation of such tubes but also an extensive analysis of the electron-optical factors determining tube brightness as well as a detailed analysis of the interrelated factors involved in the design of the mask and screen and their influence on color purity. In addition, the book contains an unusual amount of important and, to a large extent, heretofore unpublished information on the details of construction and fabrication of shadow-mask tubes.

The reader should be reminded that a number of other types of color tubes have also been extensively studied over the years as possible contenders for use in commercial television. Here again, many publications exist but no comprehensive treatment exists covering this effort. A significant portion of this book has thus been devoted to reviewing and analyzing these other schemes, making clear their significant advantages and disadvantages compared to the shadow-mask tube. Finally, it should be noted that, although color tubes have been in commercial production for many years, continuous improvements have taken place and significant new developm nts have been occurring up to the present time. In keeping with the general intent of the series, it is thus felt that the book, aside from its other functions, will serve to bring the reader up to date on recent advances in the field.

All of the authors of this supplement have been so intimately connected with the development of color television picture tubes that they need no special introduction. As indicated in their preface, so many other individuals have played important and essential roles in the development of the color tube that acknowledgement of each one separately is hardly possible in a short introductory statement. One particular name, however, stands out above all others and must be mentioned—that of David Sarnoff—who was the guiding light of RCA from its inception and Chairman of the Board through the years during which color television was developed to a state of commercial reality. His unusual faith in the value of research in general and his unyielding conviction that color television tubes could be made a commercial reality in the face of seemingly insurmountable technical difficulties undoubtedly accelerated the development of this field by many years.

B. KAZAN

Preface

This volume is the first comprehensive review of the vast amount of scientific and technological information on color picture tubes that has accumulated over the past 25 years. Color television as we know it today was made possible only by the mass production of a picture tube that appeared to be a technical impossibility in 1949. It required the development of technology for manufacturing cathode-ray structures having specifications for precision, uniformity, and reliability that had not been achieved or even attempted with such large structures in forty prior years of electron tube production. In particular, the shadow-mask color tube ranks, along with the semiconductor device and its many offspring, as one of the most remarkable achievements of electronics in this century. The authors have been involved with color television picture tubes since their inception, but the work we describe is that of thousands of researchers, most of whom are unpublished and unsung contributors to this most exciting engineering adventure. We have included references to much published work, but the names are only a few of the many engineers engaged in this work. In addition, we must credit the managers, the production personnel, and the executives and financial entrepreneurs whose expertise, dedication to success, and willingness to take risk, made the shadow-mask tube a reality.

In our volume, we cover all types of color picture tubes, but greatest space has been allotted to the shadow-mask type because it is so predominant. We hope that those who wish a better understanding of either its basic principles or technology will find our text of value. Beyond this, our descriptions of nonshadow-mask tubes should help those readers who want to evaluate the future potential of these methods, as well as those who wish to approach the problem of picture reproduction afresh.

Parts of our book are purely descriptive, if only a word-picture is needed, but other parts are mathematical and analytical for persons who are deeply committed to a quantitative and detailed approach to tube design and performance.

In concluding this preface, we express our sincere appreciation to Dr. Benjamin Kazan, editor of this series, for his encouragement and his review of our manuscript. Others who were exceptionally helpful to us were our many colleagues at the RCA Corporation, particularly those at the David Sarnoff Research Center and the Engineering Department in Lancaster, Pennsylvania.

Princeton, New Jersey

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CHAPTER 1

Introduction

Some of the earliest thoughts of television included the concept of pictures in full color. Inventions were made by the score and were almost universally confined to paper designs (*1*). The few demonstrations of the 1920's used scanning-disc techniques and showed only that the concepts of color, in terms of tristimulus phenomena, were applicable to electrical control. By 1940, however, black-and-white electronic television with camera tubes and a cathode-ray-tube reproducer was well advanced.

That year, an impressive demonstration was made (*2*) of color television using a synchronized rotating color wheel in front of a black-and-white picture tube. The picture was then modulated sequentially in accordance with the three color-component luminances. Unfortunately, mechanical limitations of size and rotational speed are sufficiently severe so that this type of field-sequential color picture reproduction has disappeared. (Rotating color filters, however, remain useful in small sizes, for use with TV cameras, such as those used in early television from the moon.)

The major challenge that faced inventors and promoters of color television was to find a picture reproduction method that compared in simplicity to that of the black-and-white cathode-ray tube.* Optical superposition of pictures from three tubes was tried and is still in use in projection systems. For direct viewing on a single picture tube, however, the first successful demonstration was made in early 1950 using an internal structure that is commonly known as the shadow mask (*3*, *4*). This type of tube employs three electron beams which pass through a common deflec-

* For a bibliography and description of important early work not otherwise referred to herein, see Herold (*1*).

tion yoke (*5*), with one beam for each primary phosphor color, i.e., red, green, and blue. The beams are "shadowed" by a perforated metal mask so that each beam can strike but one color of phosphor. The shadow-mask tube was intensively developed in the 1950–1957 period and many basic improvements were made. Of these, the most important were the use of a curved mask (*6*) (initially, it was flat), the use of photodeposited phosphor dots (*7*), better phosphors, and refinements of technology in manufacture that led to better uniformity and lower cost. However, two different single-beam tubes were also developed. In the one, then known as the Lawrence tube (*8*), vertical phosphor stripes were used to form a line screen that was spaced from a wire grill on which a high-frequency potential was impressed to deflect the beam from one phosphor color element to another. The other single-beam type also used vertical phosphor stripes and a single beam, but required no mask or grill (*9*). Instead, the phosphor screen supplied an index signal to switch the beam control to whichever color signal corresponded to the phosphor being struck. This early period also led to proposed variations of the three-beam shadow-mask tube, some using wire grills and line screens instead of perforated masks (*10–12*). Although the principles of other types of color tubes still survive in the laboratory, the three-beam shadow-mask method outdistanced its competitors and achieved commercial success (*13*, *14*).

From 1955 to 1967, about 15 million shadow-mask color picture tubes were made, and manufacture of a highly satisfactory product became routine. Round metal envelopes were replaced by glass ones (*15*); these were then changed to a rectangular shape, picture size was increased, and deflection angles (total swing across diagonal axis) were changed from 70° to 90° thereby improving picture sharpness and decreasing tube length (*16–18*). By 1973, color television was well established in most industrially sophisticated countries of the world, and of the order of 20 million color picture tubes were being made each year, worldwide. Improvements and innovations were added to the basic shadow-mask principle. Among the more important were a trend to even larger deflection angles of 110°, and use of a black matrix that surrounded each phosphor element so as to reduce reflected light and increase contrast (*19*, *20*). Coupled with new, highly efficient, color phosphors, some using rare-earth elements (*21*, *22*), these improvements permitted major increases in picture brightness. For the electron beam, there were modifications in the gun for both the most common triangular arrangement and also for the in-line arrangement of beams (*23*, *24*). Although the most common aperture shape in the shadow mask remained circular, several commercial types were introduced that used vertically elongated apertures (*24*, *25*). The phosphor screens in these types resembled the vertical line screen of the early single-beam tubes mentioned above, although the principles were those of the shadow mask.

In this discussion, we shall first review the fundamental principles that underlie any color picture tube and classify the several methods that make such a tube possible. Because of its predominance, greatest attention will thereafter be given to the shadow-mask method and its principles of design and manufacture. Some of the other methods. particularly those that do not appear to have been entirely abandoned, will also be described, but in less detail. The emphasis, throughout, will be on tubes for full color display, i.e., tubes providing the three primary colors and a luminance range (gray scale) sufficient for good contrast and satisfactory picture rendition. It is evident that there are applications that are considerably less demanding; for example, two-color systems or systems for alpha-numerics or line drawings in which color is used but no "gray scale" requirement is imposed. Such displays can be made with the cathode-ray tube methods herein covered, but permit employment of many other methods not included in the present volume.

CHAPTER 2

Requirements of a Color Picture Reproducer

The variables in a reproduced picture may be briefly listed as size and shape, sharpness and resolution, brightness (luminance), contrast, and color hue and saturation. Some of these are related in that one can be traded off for another in the design of a reproducer. Also of importance are such matters as white balance and uniformity, the "gamma" or degree of nonlinearity of light output vs. electrical input, and spatial coincidence when separate color images are superimposed. Each of these factors will be discussed in turn.

The size of a reproduced color picture is one of the most flexible of the requirements. Direct-view picture tubes, as of 1973, range in size from 266 mm (9V) diagonal to as much as 667 mm (25 V). Projected pictures can be much larger. Because of the well-known psychological principle of "size constancy" with distance (*26*), large pictures are more pleasing than small ones, even when the latter are viewed at shorter distances and subtend the same angle at the eye. Since present television systems transmit a rectangular picture with a 4:3 aspect ratio, the reproduced picture should conform to this aspect ratio to avoid picture distortion or loss of information. It is common practice to overscan or use a raster that exceeds the phosphor screen size which, especially for circuits employing tubes, may be needed to provide for possible raster shrinkage with use of the receiver. Overscanning, of course, causes a loss of picture information and brightness, but makes objects appear slightly larger.

Sharpness and resolution of a color picture reproducer are best discussed in terms of the modulation transfer function (MTF), i.e., the sine-wave luminance response curve plotted against spatial frequency (*27*, *28*).

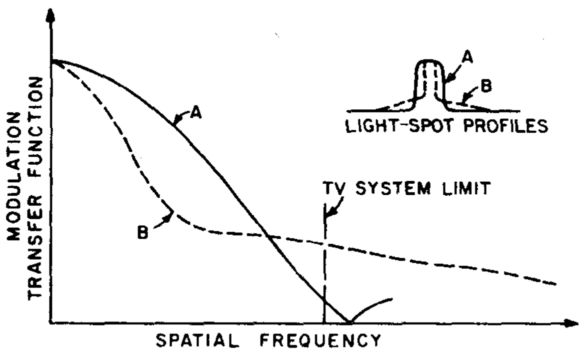

Fig. 2.1. Response curves for two hypothetical picture tubes. Tube A will have a much sharper picture even though it will not show scanning lines as well and will have only half the resolution of Tube B.

Sharpness is the subjective effect on the viewer of step-function changes in scene luminance, and resolution is the ability to distinguish detail. In terms of the MTF, limiting resolution is determined by the highest spatial frequency that is discernible, and sharpness is determined by the shape of the MTF response at frequencies below the resolution limit. In television, there is a resolution limit imposed by the system itself. In addition, the eye has its own MTF and resolution limit that depends on the viewing distance and the pupil diameter. A picture reproducer need not have resolution beyond the limit of the television system and the eye. Below this limit, however, the reproducer should have a luminance MTF as close as possible to 100%. For most existing color TV systems, the upper limit for the resolution of the system is between 350 and 600 TV line numbers (equivalent to 175 to 300 line pairs per picture height). The smaller numbers are in the horizontal direction and the larger are the extreme imposed by the scanning lines, neglecting the "Kell" factor reduction in vertical resolution (*29*) by 0.7. With bright pictures and close viewing distance, the luminance MTF of the eye is not limiting and can be disregarded. Because the eye is relatively insensitive to color in small detail, the MTF for color is of even less importance. However, known reproducers tend to have equal MTF responses for the three primary colors, i.e., they exceed the perceptual requirements substantially.

To illustrate the significance of the above, Fig. 2.1 shows modulation transfer functions for two hypothetical color TV picture tubes. Tube A has a nearly ideal flat-topped light-spot profile, while Tube B has a much smaller central spot but wide flaring skirts similar to a halo. The light-spot profile and the MTF response curves are Fourier transforms of each other. Although reproducer B has much higher limiting resolution than A, and

A has poorer responses at the scanning line frequency, A will nevertheless have a much sharper picture and would be preferred over B for the TV system limit shown in Fig. 2.1, and possibly for any other system as well (*30*).

A projected still color picture continues to give greater satisfaction as highlight brightness is increased up to some few thousands of candela per square meter.* In television systems employing 50 fields/sec, flicker begins to be annoying as brightness is increased above approximately 200 cd/m^2 when using the exponentially decaying phosphors commonly used in direct-view picture tubes. Somewhat brighter pictures would be tolerable if the "on" time for a picture element were more nearly square-topped. With 60-field/sec systems using phosphors, flicker becomes annoying with peripheral vision at something over 350 cd/m^2 but can be tolerated with on-center viewing up to considerably more than that (*31*). Such high luminance values are readily obtained on direct-view tubes but are much more difficult to achieve in projection systems. The eye is so adaptive, however, that pictures of only a few candela per square meter are pleasing if viewed in sufficient darkness. On the other hand, in home television the ambient illumination is often appreciable and high brightness is decidedly advantageous. Under such conditions, brightness and contrast are closely related, because the ambient light is often reflected and diffused from the face of the picture tube and raises the black level.

Contrast is one of the most perceptible factors in a reproduced picture, particularly when the picture is in color. If the ratio of the highest luminance to the lowest is reduced because of ambient light, color saturation also is reduced and the picture appears "washed out" in both color and in contrast (*22*). To improve contrast under ambient light, brightness has often been sacrificed, as with direct-view picture tubes in which a neutral-density absorbing glass is used to reduce the effect of the ambient illumination. Such glass is effective because the ambient light is diffused by the white phosphor and passes through the faceplate twice, while light emitted from the phosphor passes through only once. In more recent designs of shadow-mask tubes, a black matrix surrounds the phosphor dots (*20*), thereby reducing the need for absorption in the glass and permitting greater brightness. In darkness, the contrast ratio of direct-view picture tubes is limited by electron and optical scattering to the order of 50:1, but this contrast ratio can give an excellent picture. Projected pictures usually have a lower contrast ratio than this. Many home direct-view picture tubes are viewed with about 250 lux ambient illumination and have a contrast ratio of under 10:1; yet this condition is accepted.

* 1 footlambert (fL) = 3.43 cd/m^2 = 3.43 nits.

Human perception of absolute color hue and saturation is extremely diverse, both because of individual variations and because the eye is primarily conscious of color differences and not of absolute color. On the other hand, a color television system must be designed to permit a relatively high degree of color fidelity. Fortunately, only three primary colors are sufficient; if there is a match between the primaries at the camera end and those used for the picture reproduction, accurate colors will result and perceived color differences will be equally correct. Using the International Commission of Illumination chromaticity diagram shown in Fig. 2.2 (known as the CIE diagram), the entire range of colors observed by the normal eye is found within the horseshoe-shaped figure (*32*). Any color may be represented by the x, y coordinates in this diagram, with the hue angularly displaced around the central "white" region and the saturation increasing from the center out to the curved border. Combinations of two colors lie on the line joining their two coordinate points. The three primary points specified for most color television systems throughout the world are indicated on the diagram by open circles and, except for a region in the green-cyan range, cover enough of the area to produce very satisfactory color accuracy. The "white" point for the system is also indicated and corresponds closely to the radiated color of a blackbody at 6500°K, an approximation to daylight.

For the reproducer to do maximum justice to the system, its primary colors should correspond with the system primaries. Phosphors available for color picture tubes permit this, but not always under highest efficiency, i.e., maximum brightness. For this reason, compromises are usually made, particularly for the red and the green phosphors. The adaptability of the viewer and the propensity of most viewers to trade off some color fidelity for brightness have led to acceptance of picture-tube colors displaced from the specified system, as indicated in Fig. 2.2 by the crosses and the dashed triangle joining them. The greatest loss of saturated color is in the cyan-to-green region, but a brighter picture is obtained with excellent color fidelity in the red-to-yellow-green region. Fortunately, it has been shown that few objects and scenes require the missing region of color (*22*). In the United States, because there has been a consumer preference for a very bluish "white" for monochrome television, color receivers are normally adjusted for a white point close to the 9300°K blackbody point, another expedient deviation from the system. It is likely that, as color becomes predominant in television and improvements are made in phosphors, the white point and the three primary colors will eventually match those for which the system was designed.

With all systems of color television, the reproducer with its associated circuits must be controllable independently for each color primary. The

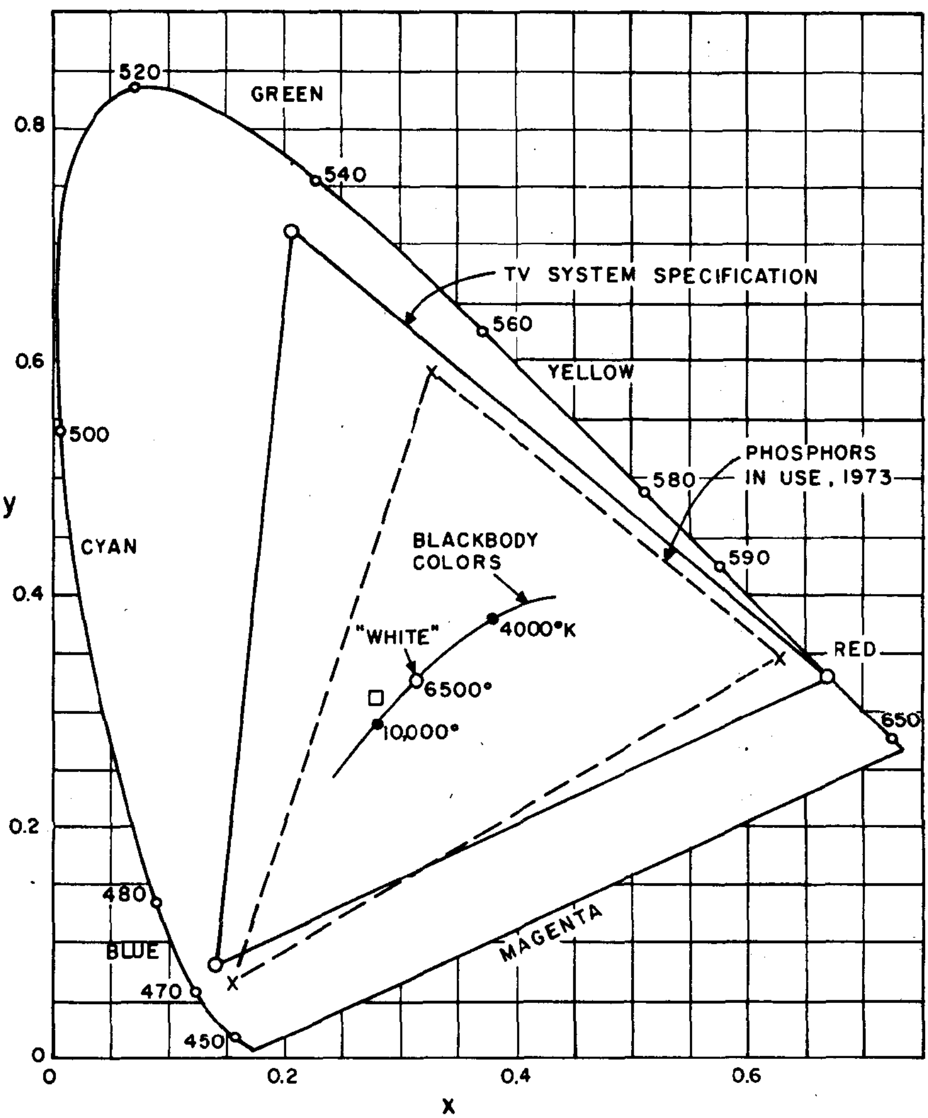

Fig. 2.2. The CIE color diagram. The specified color system primaries and white point are shown by the open circles. Typical United States color picture tube phosphors are shown by crosses and the frequently used white by the square.

color produced with any one or any fixed arbitrary combination of the three primaries must be uniform over the entire picture area. The white balance, i.e., the combination of the three primaries to produce white, must be either controllable or fixed at a point in the CIE diagram suitable for the system. In addition to these requirements, the white balance and