A Developmental Tricolor Vidicon Having a Multiple-Electrode Target*

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Summary—Color television cameras which are now widely used require three separate camera tubes to supply the simultaneous primary color information transmitted by the compatible system. This paper describes a developmental tricolor camera tube of the vidicon type for use in a single-tube color camera. The ability to generate the three simultaneous signals is achieved in the tricolor vidicon by means of a multiple-electrode target structure having three interlocking groups of color-sensitive strips connected to separate output terminals for each primary color. A single low-velocity electron beam scans the photoconductive target. No special requirements are made on the beam with respect to focus or scanning accuracy. Registry of the three signals is inherent in the design of the target.

The performance of the developmental cameras which have been constructed to date does not equal the three-tube image orthicon camera from the standpoint of sensitivity, color fidelity, and uniformity. In its present state, the tube is potentially useful for industrial and scientific purposes where sufficient light is available and structural defects do not obscure the information desired. To extend its range of application, the development of more sensitive photoconductors and improved methods of fabrication are required.

Introduction

The signal transmitted in the compatible color television system used in this country is formed by encoding three simultaneous independent video signals. In a widely used camera[1] the simultaneous information is derived from three separate camera tubes. The light from the scene is split by means of dichroic mirrors, as shown in Fig. 1, to form separate red, green and blue images on the sensitive surfaces of the three tubes. Optical and electrical registry of the three images is maintained in order to preserve the required resolution.

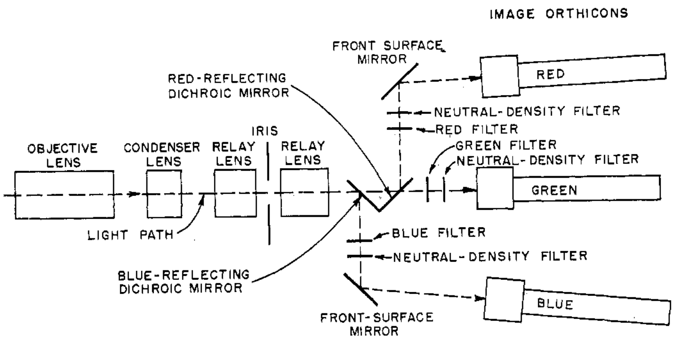

Fig. 1—Optical lens system of a color television camera using three image orthicon camera tubes.

During the past several years, research has been carried out at the RCA Laboratories on a tricolor camera tube having a multiple-electrode target which directly provides the three simultaneous signals. The resulting single-tube camera uses conventional lenses and can be made to resemble a black-and-white camera in size.

This paper will describe the basic principles and operating characteristics of the new tube which is a form of tricolor vidicon. The present research models of the tube have been found to offer many attractive features but have not equaled the performance of a carefully adjusted three-tube camera.

General Description of the Tricolor Tube

The ability to generate three independent simultaneous video signals is achieved in the tricolor vidicon described here by means of a multiple-electrode target structure having three interlocking groups of color-sensitive strips connected to a separate output terminal for each primary color.[2] Fig. 2 shows two sizes of tricolor vidicon which have been tested. A standard black-and-white image orthicon can be seen in the background. The two-inch vidicon[3] has a picture diagonal of 1.5 inches and can be

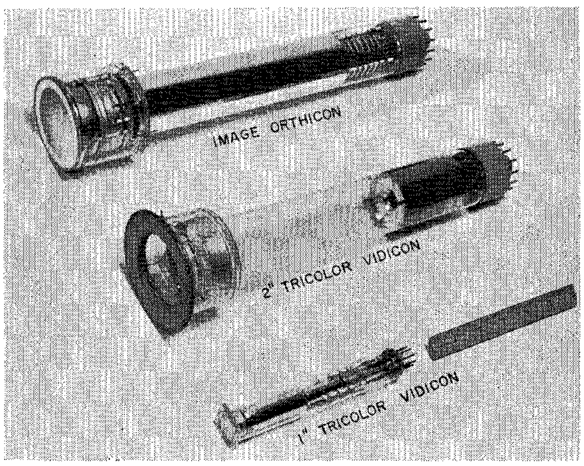

Fig. 2—A photograph of the one-inch and two-inch versions of the tricolor vidicon with a black-and-white image orthicon in the background.

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[1] J. D. Spradlin, "The RCA color television camera chain," *RCA Rev.*, vol. 13, pp. 11–26; March, 1952.

[2] Early proposals for tricolor camera tubes employing multiple signal electrodes have been made by A. C. Schroeder, U. S. Patten No. 2,446,249, August 3, 1948; and by E. D. Goodale and G. K. Graham, U. S. Patent No. 2,634,328, April 7, 1953. The multiple electrode structure may be applied to both photoemissive and photoconductive tubes.

[3] The earlier two-inch vidicon was described by P. K. Weimer, S. Gray, H. Borkan, S. A. Ochs and H. C. Thompson, "The tricolor vidicon—an experimental camera tube for color television," 1955 IRE Convention Record, pt. 3, p. 74.

operated in a modified black-and-white image orthicon camera using standard lenses. The smaller tube, with a picture diagonal of 0.75 inches, was designed for use in a modified one-inch vidicon camera.

A cross-sectional diagram of the two-inch tricolor vidicon is shown in Fig. 3. A low-velocity electron beam from a single gun scans the light-sensitive color target which is formed on the inside face of the tube. No special requirements are made on the electron beam, either in terms of focus or scanning accuracy. Registry of the three signals is inherent in the design of the target.

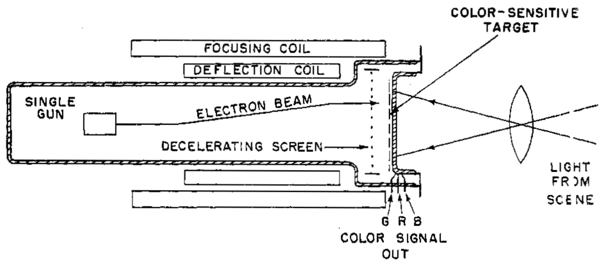

Fig. 3—Cross-sectional diagram of the two-inch tricolor vidicon. Three separate output terminals near the target provide simultaneous color signals.

Description of the Multiple-Electrode Color-Sensitive Target

An enlarged view of an experimental tricolor vidicon target is shown in Fig. 4. Color filters are built into the target in a repeated sequence of very fine vertical strips of red, green, and blue transmission. Covering the filter strips are three sets of interlocking semitransparent conducting signal strips. The signal strips corresponding to a given color are insulated from their neighbors, but are interconnected by means of "bus bars" to a common output terminal for that color. The one-inch target is similar in construction to the two-inch target except for having strips twice as fine. Each has approximately 290 strips of each primary color, making a total of 870 strips.

Fig. 5 shows in greater detail the method of connecting the signal strips to the bus bars, which extend along the top and bottom of the picture area. The signal strips consist of a film of metal, so thin as to be semitransparent, laid down in strips approximately 0.001 inch wide. In the one-inch target the signal strips are 0.5 mil wide with a 0.2-mil space in between. The bus bars are relatively thick metallic strips deposited on the glass. Crossover insulation for the signal strips is provided by the filters themselves which extend over the inner bus bars as shown. By connecting the signal strips to the bus bars at both the top and bottom of the target, the possibility of open strips arising from defects is greatly reduced. Many experimental targets in both sizes have been made which were entirely free of either open lines or shorts between adjacent strips.

A uniform layer of photoconductive material is deposited over the signal strips as shown in the sectional view of the target of Fig. 6. The thickness of the various layers is greatly exaggerated in this drawing.

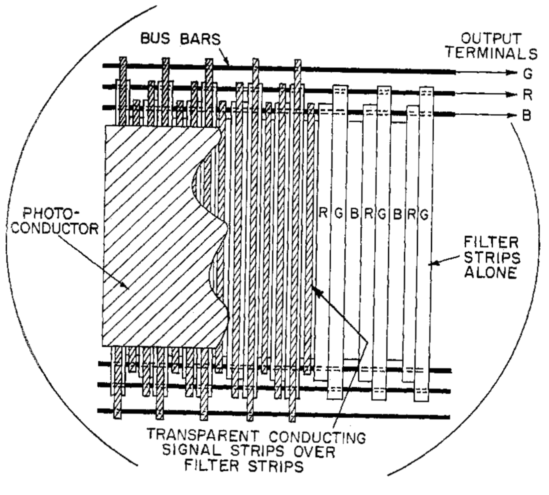

Fig. 4—Cutaway diagram of the tricolor vidicon target as viewed from the electron gun of the tube.

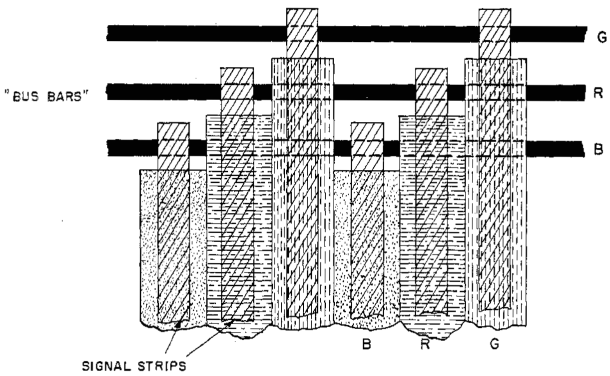

Fig. 5—Detail of the tricolor vidicon target showing signal-strip bus-bar connections. The insulating filter strips permit the signal strips to cross over the inner bus bars as shown.

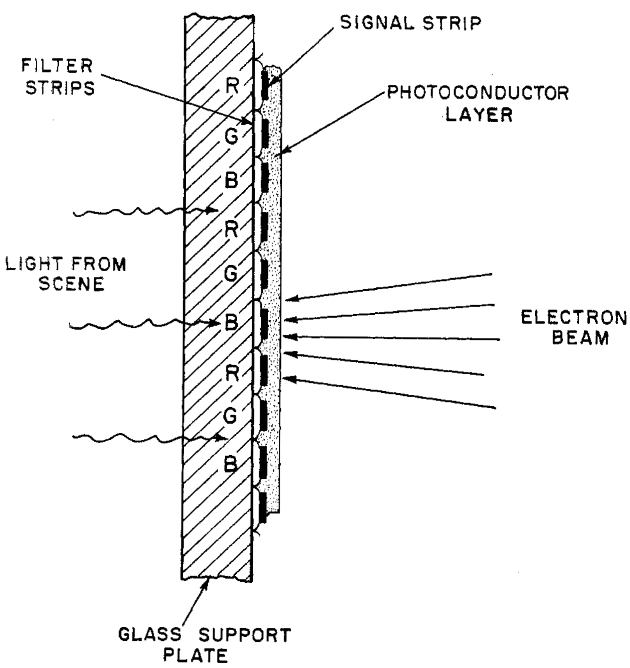

Fig. 6—Cross section of the tricolor vidicon target with the signal strips viewed end-wise.

Fabrication of the Tricolor Target

Several widely different techniques for producing the tricolor target structure are possible. The choice of method is considerably narrowed by the rigid specifications on fineness and precision and by the requirement that the target withstand tube processing.

The targets described above were formed by evaporation of the filter and signal strip materials through fine grills. Precision jigs were developed which have the necessary controls to permit many operations to be carried out in sequence with one evacuation. This technique has many advantages for making experimental targets. Some problems encountered in the evaporation of fine patterns through masks are discussed in a separate paper.[4] The construction of grill masks having adequate uniformity and freedom from striations is a particularly severe problem. A jig suitable for making color targets in the one-inch size is shown in Fig. 7.

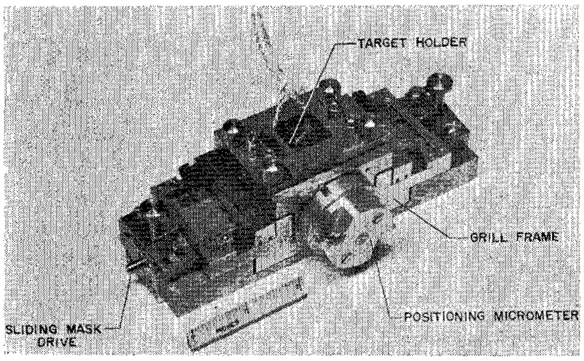

Fig. 7—View of a precision jig used in evaporation of filters and signal strips for the one-inch tricolor vidicon target.

The filters used most successfully were of the multilayer interference type consisting of alternate layers of high- and low-index materials. In the optical design of these filters, it is necessary to take into account the reflectance of the thin metal signal strip as well as the optical characteristics of the photoconductor. Fig. 8 shows a typical set of transmission curves for each of the primary filters in combination with its conducting signal strip. The curves show a peak transmission relative to air of about 30 to 60 per cent, with rejection bands in which transmission falls to less than one per cent of the peak. Although the efficiency of the filter strip combination plotted in Fig. 8 is not as high as can be obtained in large-area filters, they were considered entirely adequate for experimental tubes.

Other types of filters have also been tested. These include absorption filters and interference filters of the Fabry-Perot type using layers of thin metal separated by a dielectric spacer. In the latter type, the filter and signal strips are one integral unit.

[4] S. Gray and P. K. Weimer, "Production of fine patterns by evaporation," *RCA Rev.*, vol. 20, pp. 413–425; September, 1959.

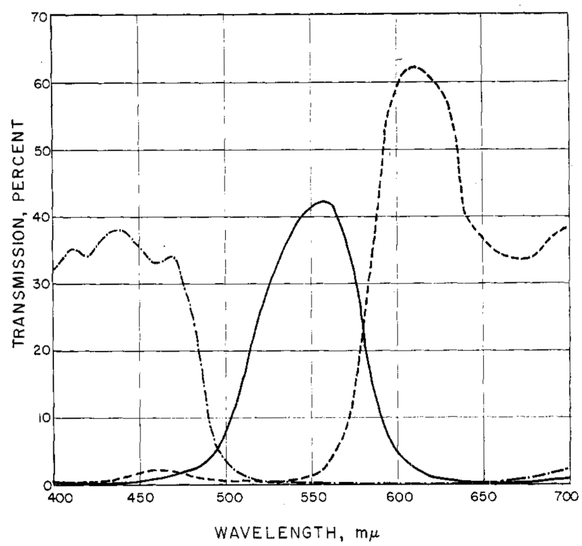

Fig. 8—Transmission characteristics of a set of multilayer interference filter strips overlaid with conducting signal strips as used in the tricolor vidicon.

Operation of the Tricolor Vidicon

The light from the scene to be transmitted is imaged by means of a standard turret-mounted lens onto the color-sensitive target. The charge-discharge cycle of each elemental area of the photoconductor is similar to that of the monochrome vidicon.[5] The signal strips may be operated at a common potential, some thirty or forty volts positive with respect to the thermionic cathode of the gun. In the absence of light, the scanned surface of the photoconductor is charged to gun cathode potential. Light from the scene passes through the filters and is absorbed in the photoconductor, causing its conductivity over each strip to be increased in accordance with the intensity of that primary color component. Three substantially independent but interlocking charge patterns build up on the surface of the photoconductor during the interval between scans, the brightest areas becoming several volts positive with respect to the gun cathode. The simultaneous discharge of the three charge patterns by the scanning beam causes separate video signal currents to be induced in each set of signal strips. By connecting each of the three output leads to an amplifier of proper design,[6] color signals are obtained for each primary color.

Camera Circuit Considerations for Operation of Multiple-Electrode Targets

The large capacitance existing within the target between the three sets of strips would cause severe mixing of the colors if it were used with conventional camera preamplifiers. An equivalent circuit of the target is represented in Fig. 9 by a delta in which the vertices are the signal strips and the arms are the cross-coupling capacitances

[5] P. K. Weimer, S. V. Forgue, and R. R. Goodrich, "The vidicon—A photoconductive camera tube," *Electronics*, vol. 23, pp. 70–73; May, 1950.

[6] H. Borkan, "Simultaneous signal separation in the tricolor vidicon," *RCA Rev.*, vol. 21, pp. 3–16; March, 1960.

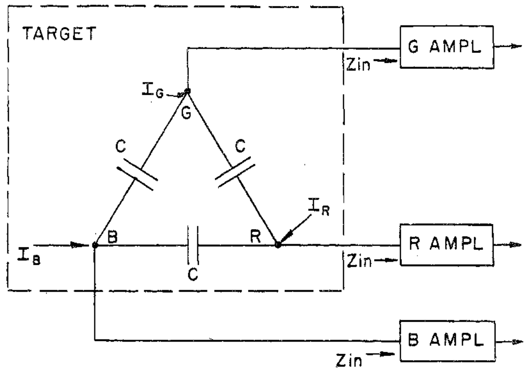

Fig. 9—Equivalent circuit of the tricolor vidicon target. The interset capacitance C (approximately 600 $\mu\mu$F for the target used in the two-inch tube) causes cross-coupling of color signals unless special low-impedance preamplifiers are used.

whose value is about 600 $\mu\mu F$ in the two-inch target. This corresponds to a reactance of about 200 ohms at a frequency of 1.3 megacycles, the upper limit of desired signal separation. Thus, if one wishes to obtain separable color signals directly from the target, the amplifier input impedance should be small compared to 200 ohms. The conventional camera preamplifier has an input resistor of about 50,000 ohms, a value which gives a satisfactory signal-to-noise ratio. If one attempts to achieve the required low impedance by simply reducing the input resistor of the amplifier, the thermal noise and tube noise will rise in comparison to the signal to an excessively high value. This problem is solved, without requiring small input resistors, by using negative feedback in each preamplifier to reduce the input impedance.[6] By this means, satisfactory separation of the color signals with an acceptable signal-to-noise ratio has been obtained. However, the amplifier noise is higher than that obtained in a monochrome vidicon by a factor of approximately six for the two-inch tube, and three for the one-inch tube.

Although the interset capacitance results in an inevitable increase of noise level in each amplifier connected to the target, the visibility of the noise is somewhat less than would be the case if each channel were fed with an equal amount of noise from three independent noise sources. As shown in Borkan's paper,[6] a large component of the noise current in each amplifier is equal and opposite in phase to the vector sum of the noise currents flowing simultaneously in the two adjacent channels. The correlated nature of the noise has the fortunate consequence that much of the added noise can be confined to the chrominance channel and excluded from the luminance channel. In practice, a signal output of approximately 0.2 microampere in each color (0.6 μA total signal) is sufficient to produce a color picture which is substantially free of noise. Other methods of deriving a video signal with lower background noise from a multiple electrode target are discussed in the Appendix.

Performance

Laboratory models of the tricolor vidicon have been operated in an experimental color camera the same size as the black-and-white image orthicon camera. Motion picture film, color slides, and studio scenes have been used for tests. Both the one-inch and two-inch tubes have produced color pictures which, although not of broadcast quality, may be considered potentially useful for many applications.

Resolution and Uniformity

Color pictures transmitted by the tricolor vidicon have been photographed in black-and-white and in color. The results obtained are indicated in the photographs of Figs. 10 and 11 which were taken with a two-inch tube. Later results with the one-inch tube were of slightly better quality. Fig. 10 is a reproduction of a color picture as seen on a ten-inch black-and-white monitor with the applied signal formed by adding the separate signals from the red, green, and blue preamplifiers. Fig. 11 was obtained under similar conditions except that the signal from only the red channel is displayed. Limiting resolution of the tube itself was in excess of 400 lines for a vertical black-and-white test wedge. For these pictures the video pass

Fig. 10—Photograph of a color picture transmitted by a developmental tricolor vidicon. Three output signals were added together and displayed on a black-and-white monitor. The streaks are not inherent, but arise from nonuniformity in the evaporation grill used in fabricating the target.

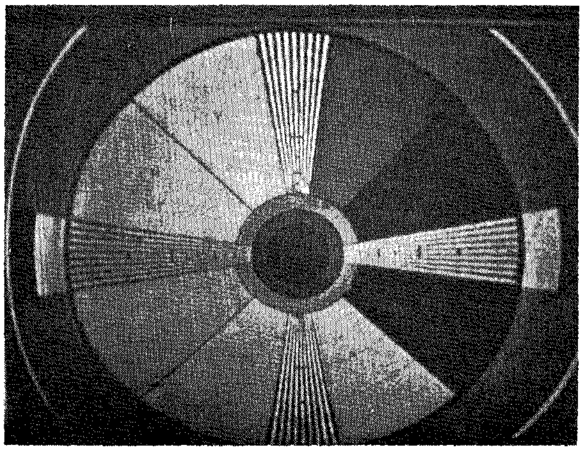

Fig. 11—Photograph of a test pattern transmitted by the red channel of a developmental tricolor vidicon.

band was limited to about 3.5 megacycles by means of low-pass filters to simulate the picture as viewed on a black-and-white receiver. The grainy appearance of these pictures is not caused by noise but by the nonuniform conductivity of the photoconductor. Later tubes were made which were quite free of grain even in the one-inch size.

The vertical streaks visible in some parts of the transmitted pictures shown in Figs. 10 and 11 are caused by nonuniformity in the evaporation grills used in making the experimental targets. If the grills were uniform, no streaks would be expected since the basic strip pattern is too fine to appear directly in the transmitted picture, even when the signal from each channel is examined separately. The frequency generated by a well-focused beam scanning across the strips is about 5.5 megacycles for the present target having 290 strips in each color. This frequency is not passed by the 3.5-megacycle video channel.

The finite number of strips results in a spurious moiré pattern in the vertical wedge of a test pattern. This effect has nothing to do with the scanning process, but arises from an optical beating between the scene and the strips. Since the moiré pattern is different in each channel, it results in a spurious background color superimposed over the fine vertical bars in the test pattern. In the tests made, this effect was not considered objectionable in actual operation, even with scenes having considerable detail.

The nonuniform vertical streaks visible in the photographs are a particularly troublesome problem in the fabrication of exceedingly fine strip patterns. Although somewhat better results were obtained later with the one-inch targets (by improved evaporation techniques) the uniformity of signal was not equal to that required for broadcast purposes.

Color Reproduction

The over-all spectral response of each color channel can be measured electrically by illuminating the face of the tube with monochromatic light. Measured curves are plotted in Fig. 12. No correction was made for the high red content of a 2800°K incandescent light source used with the monochromator. The curves are approximately equal to the product of the spectral response of the photoconductor and the transmission of the filters shown in Fig. 8. Of the total signal produced at any given wavelength, the major portion appears in the proper channel, but a small fraction is found in the adjacent channels. Color crosstalk may arise from a variety of causes which are discussed more fully in a later section. A slight dilution of color resulting from insufficient rejection of the unwanted color can be removed by electrical masking, but at the expense of signal-to-noise ratio. Although provision for electrical masking was made in the test camera, it was unnecessary with the best targets.

Sensitivity

The operating sensitivity of any camera tube depends to a large extent upon the characteristics of the photosensitive material. The structure of the tricolor vidicon assigns more stringent specifications to these characteristics than are necessary for the satisfactory operation of a conventional black-and-white vidicon. These specifications arise from smaller light input to the photoconductor for a given scene illumination, from capacitance between signal sets which raises the noise level, and from the need for good spectral response and color separation.

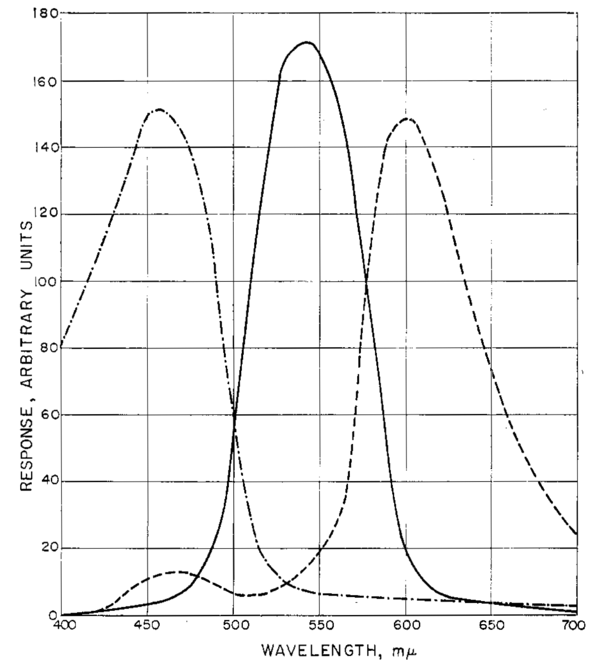

Fig. 12—The over-all spectral response of a developmental tricolor vidicon target. The target was illuminated with monochromatic light and the amplified output signals measured on an oscilloscope. (The ordinates were raised to the 1.4 power to correct for the less-than-unity gamma characteristics of photoconductor.)

In the black-and-white vidicon, the lower limit to the illumination of the photoconductor required to produce a satisfactory picture is determined by the signal needed to reduce lag (blurring of moving objects) to an acceptable level. The signal-to-noise ratio of the output is entirely satisfactory. But because of the increased noise output arising from the interset capacitance, the illumination of the tricolor vidicon photoconductor must be higher in order to produce an adequate signal-to-noise ratio.

In the tricolor vidicon, the illumination of the photoconductor is only about one-tenth the illumination of the target because of the transmission efficiency of the combination of filter and signal strips and the spectral transmission characteristics of the filters. Effective sensitivity is somewhat further reduced by the geometry of the signal strips. As a result of the nature of the color target, the light level incident upon it for acceptable operation must be 25 to 50 times as large as is required for a black-and-white vidicon using the same photoconductor. The losses are high, but are only two or three times greater than the losses which may be taken in the usual three-tube color camera because of low efficiency of the optical system of dichroic mirrors, filters, and relay lenses.

The photoconductive layer must be thin compared to the width of the filter strips to permit good color seperation. It must have a low dielectric constant to minimize the capacitance lag and the interset capacitance which affects the noise level. The smaller target performs better in both these respects with a given photoconductive layer. Tricolor vidicons of the two-inch size, using a porous antimony trisulfide photoconductor, produced pictures with good signal-to-noise ratio and acceptable lag for motion picture films and slides when ample light was available. In the studio, such tubes were tested with an $f/1.9$ lens and 400-foot candle illumination on the scene, but the depth of focus was too shallow and the lag too great for most purposes.

With photoconductor layers deposited in high vacuum, tricolor vidicons have demonstrated much higher sensitivity. However, they have not been suitable for this application because of spectral response and high dielectric constant. The best over-all performance is obtained in the one-inch tube with a photoconductor which consists of a thin layer of porous antimony trisulfide overlaid by a very thin layer of high-vacuum deposited antimony trisulfide. Subjectively, noise-tolerable pictures were obtained with 700- to 1000-foot candle illumination on the scene, twice as much as is used with a three-tube image orthicon camera, and an $f/2.8$ lens (providing the same depth of focus as the image orthicon camera operating at $f/5.6$). Lag was low, but target defects such as spots and striations were conspicuous because of the high target voltage necessary for maximum sensitivity.

Target Design Factors Affecting Color Purity

Comparison of the measured video signal response curves (Fig. 12) with the spectral transmission of the filter strips (Fig. 8) shows that the color separation in the video signal was somewhat less efficient than in the filters themselves. The problem of color purity is a crucial one in development of a practical tricolor camera tube. A number of design factors, intimately related to the performance of the color target, are listed below. The extremely fine dimensions of the targets and the relative difficulty in fabricating experimental samples make a complete and simultaneous evaluation of all such factors extremely difficult.

Optical Effects

A fraction of the light entering the photoconductor which fails to be absorbed over the proper strip can be scattered within the photoconductor to an adjacent strip where it produces photocurrent. Alternatively, light passing through the photoconductor into the tube can be reflected back to the target. Light rejected by the multilayer interference filters will be reflected back toward the lens and may ultimately be scattered back to the target. In several respects, interference filters, in spite of their higher efficiency, are less desirable than absorption-type filters, because of their higher reflectance and shift of color with angle of incidence.

Photoconductive Phenomena

Any form of photocurrent excitation beyond the area in which the light is absorbed could contribute to color dilution. This would include lateral migration of charge carriers, diffusion of excitons, internal fluorescence, etc. No direct evidence for such phenomena occuring on the color target has been obtained. Color purity can be degraded by a conducting layer on the scanned surface of the photoconductor or by a barrier layer within the photoconductor, even though their effects on resolution may not be apparent.

Target Geometry

The photoconductor layer over the gap between the signal strips is less sensitive than over the strip since a weaker field exists in this region, but it is not completely insensitive. Charge deposited in a gap by the beam will produce a video signal which divides between the two adjacent strips. The fringe field along the edge of each strip contains a lateral component which will tend to spread the photocurrents toward the gaps. These effects become less significant if the photoconductor thickness is small compared to the gap width. A photoconductor thickness comparable to the center-to-center spacing of the strips will permit objectionable coupling of video signal even when the stored charge is centered over each strip. A porous photoconductor is desirable since its lower dielectric constant permits the target to be thinner for the same total capacitance.

Electron Beam Effects

The transverse fields near the target produced by the strip pattern may be expected to influence the landing of the low-velocity beam on the photoconductor. The effects of coplanar grid action and "beam bending" on color reproduction have been investigated. No direct evidence for distortion of color information has been found for operation under the usual conditions of low dark current. For high dark current operation, it can be demonstrated both by analysis and by experiment that beam bending can lead to a higher chroma than is present in the light image. Under extreme conditions the signal from the adjacent strips may actually go negative while the excited strips give a large positive signal.

Video Signal Crosstalk

Capacitance coupling of video signal from one set of strips to another can be minimized by the use of amplifiers having low-input impedance. Coupling from an individual strip to its neighbors will occur regardless of the amplifier impedance if the individual signal strip has too high a resistance or makes a poor connection to the bus bars at the top and bottom of the target.

Conclusions

A new tricolor camera tube capable of supplying three simultaneous color signals for use with a compatible color television system has been described. This tube, which employs a multiple-electrode target, is convenient to operate, has inherent image registry, and permits the camera to be simple and compact. The performance of the developmental cameras which have been constructed to date do not equal the three-tube image orthicon camera from the standpoint of sensitivity, color fidelity, and uniformity. In its present state, the tube is potentially useful for industrial and scientific purposes where sufficient light is available and structural defects do not obscure the information desired. To extend its range of application the development of more sensitive suitable photoconductors and improved methods of fabrication should be undertaken.

Appendix

Alternative Methods of Deriving Color Signals From a Multiple-Electrode Target

The increased noise level in connecting the preamplifiers directly to the color target prompted investigation of other methods of operation which are not limited by the interset capacitance. A number of tricolor vidicons were built with an electron multiplier which provides a return beam signal well above amplifier noise level. The color and brightness information can be obtained from the multiplier output signal by several possible ways.

The "driven target" method provides simultaneous color signals without requiring that the beam resolve the strips. Each set of target strips is driven by a high-frequency sine-wave voltage, phased 120° apart for the three sets of strips. The color information appearing in the output signal as an amplitude- and phase-modulated carrier is separated by the use of suitable filters and synchronous detectors. This method has been tested and found to yield signal-to-noise ratios several times higher than can be obtained with separate preamplifiers connected directly to the target. However, the driven target method of operation was much more critical to adjustment and made more severe demands on the electrical perfection of the target.

In tubes in which the beam has a spot size sufficiently fine to resolve the strips, it may be possible to derive the color information from the return-beam signal without "driving" the target. Although the frequency of the color carrier generated by the beam crossing the strips is a function of scanning linearity, an auxiliary reference signal obtained directly from one set of strips might be used to permit synchronous detection of the color information from the composite return-beam signal.

Acknowledgment

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