SPATIAL-FREQUENCY ENCODING TECHNIQUES APPLIED TO A ONE-TUBE COLOR TELEVISION CAMERA

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ABSTRACT

An anlysis and experimental results are presented of a new color camera technique using a single camera tube. To avoid the difficult registration problem of conventional color cameras, the color information is encoded as the amplitude of two diffraction grating patterns. This is accomplished by imaging the colored scene onto a pair of colored diffraction gratings. The recovery of the color information is done by band-pass filtering of each channel followed by envelope detection. The three color signals are derived using linear combinations of the two decoded carriers along with the average signal which represents a weighted sum of all three colors.

The performance of the camera is determined by resolution, beats, crosstalk, and noise considerations. Many of these considerations are aided by proper design of the grating filter from the viewpoint of the two-dimensional spatial frequency spectrum of the encoded image. These considerations lead to the conclusion that the optimum configuration uses two gratings which are equal in periodicity and are at different angles. The final system uses a vertical red-absorbing grating and a 45° blue-absorbing grating, each having the same periodicity.

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INTRODUCTION

For the past few years Stanford Research Institute, under the support of RCA, Inc., has studied techniques by which color information can be encoded with black-and-white processes. The first experiments demonstrated the feasibility of recording color information onto black-and-white film through the use of a spatial-frequency carrier technique. Later a similar approach was used in conjunction with a single vidicon television camera to create a color television signal. This paper reports the results of the television camera portion of that research project.

Color television cameras today have limited acceptance because they are expensive and difficult to maintain. This is primarily because the output signal is derived from three separate camera tubes. This problem necessitates rugged and accurate construction to provide proper optical registration, as well as stable, accurately controlled circuits to ensure tracking of the three scanning beams. A number of attempts have been made to minimize these difficult problems; for example, a four-tube camera was developed for the purpose of making the broad-band luminance signal immune to registry errors by deriving it from a single camera tube rather than from the sum of the red, green, and blue cameras.[1] The colored edges caused by misregistration of these three tubes, however, continues to be a

1. H. N. Koznowski and S. L. Bondell, "Recent Developments in Color Television Camera Equipment," IEEE Trans. on Broadcasting, Vol. BC-9, pp. 31-36, February 1963.

problem. Another approach uses field-sequential color cameras employing moving color filters in the optical path of the camera.[2] Field-sequential cameras require accurate field storage devices, such as magnetic discs, to provide a compatible parallel readout of the serial red, green, and blue information. Even when done properly, the system suffers from color breakup for objects that move and therefore occupy different positions during successive field scans. Some field-sequential systems have been operated at field rates higher than standard to avoid color breakup. These systems, however, require expensive scan converters and usually suffer a resolution loss.

Another class of television cameras exists, including the one described here, where the various colors are encoded on spatial-frequency carriers or grating structures. This class represents the most successful approach to the registration problem to date. Two subclasses can be described. One subclass of these employs an optical filter consisting of alternating vertical lines of color filter material. The chrominance information modulates a subcarrier in phase and amplitude. The color signal is then extracted by sampling the video signal at the appropriate time for each color. The principal difficulty with this system is the severe requirement on scan linearity, since no reference exists for the sampling signal. A similar approach has been used employing two registered camera tubes where one tube supplied the luminance signal and the other contained a coarse structure of alternating red and blue lines.[3] This coarse line structure was adequate, since only relatively narrow-band chrominance information was derived from this tube. The tube with the grating structures supplied the red and blue signals; the green signal was derived by subtracting the red and blue signals from the luminance signal output of the

2. C. G. Lloyd, "Chromacoder Colorcasting," IRE Trans. on Broadcast Transmission Systems, Vol. PGBTS-1, March 1955.

3. P. S. Carnt and G. B. Townsend, Color Television, London: Iliffe Books Ltd., 1961, p. 72.

other camera tube. The scan-linearity requirement is somewhat relaxed by the wide color stripes, but the camera is still far from ideal because of the remaining scan-linearity problem and the need to register the two tubes.

The other subclass of systems employs frequency multiplexing, where the various color components appear at different frequencies and can be conveniently separated by electrical filtering.[4,5] These systems are quite immune to the normal changes in scan linearity, since the resulting frequency changes are not large enough to significantly alter the selectivity characteristics of the filters. The difficulty with these stems from crowding of the frequency spectrum. The various color encoding carriers are created by colored gratings in an image plane that cause the color information to modulate a carrier. These carrier frequencies, in addition to any beats between them, must not fall within the luminance and chrominance pass bands. If all of these grating structures consist of vertical lines, the problem of beats is difficult to avoid. The resultant grating frequencies when scanned should be outside the luminance pass band. Any attempt at meeting these requirements would require a camera tube with ultrahigh resolution, far beyond that required for the conventional broadcast standards.

This paper describes a novel system that makes efficient use of the two-dimensional resolution capability of a camera tube and avoids the problem of beat visibility.[6] Thus a conventional vidicon camera tube achieves sufficiently high performance that the limiting component in the overall system is still the color receiver.

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4. U.S. Patent No. 2,733,291, R. D. Kell, January 31, 1956.
5. "Electronics Abroad," Electronics, Vol. 40, pp. 235-236, January 1967.
6. U.S. Patent No. 3,378,633, A. Macovski, April 16, 1968.

SPATIAL FREQUENCY SPECTRUM

We first examine the two-dimensional spatial-frequency spectrum of the camera to see where the additional color information can be added. In television systems, assuming ideal camera devices and reproducers, the resolution in the horizontal direction is limited by the bandwidth, and that in the vertical direction is limited by the number of scanning lines. If we restrict our discussion to U.S. standards, it is convenient to express both vertical and horizontal spatial frequencies in terms of equivalent electrical frequency in megahertz. For example, the maximum resolvable horizontal spatial frequency f_x , given a bandwidth of f MHz, is given by

$$f_x = \frac{f}{v} \quad ,$$

where v is the horizontal scan velocity in unit distance per μs . Using this same notation, any spatial frequency in any direction can be expressed as an equivalent electrical frequency divided by v . This notation is convenient in that it is independent of the camera-tube dimensions. The maximum resolvable vertical spatial frequency is given by

$$f_{y\ max} = \frac{N}{2L} \quad ,$$

where N is the number of active scanning lines and L is the raster height. This can be expressed in terms of equivalent electrical frequency by multiplying the above expression by v , the scanning velocity. For the U.S. standards

$$N = 485, \text{ and } L = (\tfrac{3}{4})53.0\ \mu s \cdot v \quad .$$

Then

$$f_{y\,max} = \frac{6.1\ \text{MHz}}{v} \quad .$$

The equivalent electrical frequency is 6.1 MHz.

Figure 1 shows one quadrant of a two-dimensional spatial-frequency spectrum with the axes dimensioned in equivalent electrical frequency (MHz). The spatial-frequency capability of the vidicon camera is shown as a quarter-circle of radius 6 MHz. The U.S television standards appear as a square with sides of 4 MHz. (The real equivalent frequency of 6.1 MHz derived earlier must be multiplied by the Kell factor to obtain the nominal vertical resolution.) The average color-receiver capability is shown as a rectangle with f_x approximately 3 MHz and f_y established by the standards at 4 MHz. These numbers are only approximate and are used to show that a significant portion of the vidicon capability is not being used. Further, this type of diagram shows where the available resolution capability lines in the spatial-frequency spectrum. Third, it allows one to compute directly the spatial and temporal frequency of beat patterns that appear in the picture when stripe or grating structures are used.

ENCODING OPTICS

In color television, two narrow-band sources of chrominance information must be added to the wideband luminance signal in order to fully define the desired image. In the camera described here, color information is encoded as amplitude modulation onto spatial-frequency carriers using colored gratings. Figure 2 shows the simplest embodiment of such a system. Lens L_1 images the scene to be televised onto a filter plane. The relay lens, L_2 , images the filter plane onto the vidicon photocathode. The filter is a colored grating structure comprising alternate vertical stripes of cyan filter separated by transparent stripes. Disposed at some convenient angle to the cyan stripes is a grating of alternate yellow and transparent stripes. Assuming ideal filters, the cyan material passes blue and green light and blocks only the red portion of the spectrum. Thus the cyan grating is a grating only to red light. Similarly, the yellow grating acts only on the blue component of the incoming light, passing the red and green components undisturbed.

As the vidicon is scanned, two carriers are generated, because the red component of the light causes a vertical grating pattern on the vidicon faceplate and the blue component causes a diagonal grating pattern. The two gratings must be used in such a fashion that the resulting grating signals, as well as the beat between the two signals, will have acceptably low visibility in the luminance pass band. In addition, the grating spatial frequencies must be within the camera resolution limits so that the grating signals can be resolved with adequate signal-to-noise ratio. As shown in Figure 1, the cyan (red encoding) grating is placed in a convenient portion of the spectrum on the f_x axis. This point appears on the f_x axis, since the x-component of its spatial frequency is 5.0 MHz and the y-component is zero (vertical lines). The yellow (blue-encoding) grating is placed diagonally at an angle of approximately 45°. It has the same spatial frequency as the red-encoding grating. Thus both gratings have the same spatial frequencies located at the edge of the camera resolution limit and create electrical frequencies that are outside the luminance pass band of the receiver. Although the beat between the two carriers occurs at the relatively low electrical frequency of 1.5 MHz, it has a spatial frequency of 3.8 MHz. The spatial frequency and angle of the resulting beat pattern can be determined from Figure 1. The distance between the two points corresponds to the spatial frequency of the beat, and the direction of the line connecting the two points indicates the axis of the resulting beat. Although the electrical frequency of the beat is well within the luminance pass band, its visibility is low because of the high spatial frequency. With ideal cyan and yellow gratings and a linear camera, no beat will be visible. Since ideal yellow and cyan filters do not absorb in the same part of the spectrum, there is no color that will interact with both gratings, creating a product action and thereby producing beats. With practical filters, however, each filter has some absorption in its pass band and some attenuation in its stop band so that a beat is generated. In addition, the nonlinearity of vidicon cameras will create a beat wherever both red and blue signals are present simultaneously. However, the cameras that have been built show that the relatively small beat amplitude and its high spatial frequency combine to make the beat essentially invisible.

The relay lens system shown in Figure 2 represents the most straightforward arrangement of lens, filter plane, and vidicon. Alternative methods exist. For example, the encoding filter could be placed inside the vidicon envelope, directly against the photoconductor. It could also be placed outside the camera, with a fiber optics faceplate used to place the filter into optical contact with the vidicon photocathode. The relay lens has the advantage that a simple, unmodified vidicon can be used. The relay lens arrangement also allows one to employ a large, coarse filter structure, since the relay lens can be used to demagnify the filter. A field lens would be included in the optical design to achieve higher light efficiency. The disadvantages of the relay lens approach are the added cost and size of the lens itself.

DECODING ELECTRONICS

When the two-color encoding gratings are disposed as described above, the two resulting carrier frequencies are in the ratio of $\sqrt{2}$ to one. The frequencies chosen were approximately 5.0 and 3.5 MHz. The spectrum of the vidicon signal and the filters used to separate the various components are shown in Figure 3. A system block diagram is shown in Figure 4.

The bandwidths around each color carrier provide 0.5 MHz chrominance bandwidth, which represents typical home-instrument performance. Larger bandwidths can be used but give greater overlap in the spectrum and increased crosstalk between the various channels. The most serious crosstalk in the system occurs when high-frequency luminance signals appear in the lower-frequency (3.5 MHz) color channel. This crosstalk appears as a blue edge occurring where high-frequency luminance signals are present, such as sharp luminance transitions. The solution to this problem, as would be expected, is to make the recovered 3.5-MHz color signal large compared to the luminance crosstalk. The amplitude of the color signal is increased by using an efficient grating having good absorption in the desired region. High-frequency luminance information can be reduced by using astigmatic optics (a weak cylindrical lens) that limit the high-frequency response in the horizontal direction only. The models that have been built show that crosstalk can be reduced to a negligible level. After the various channels are separated, the high-frequency luminance response can be restored using horizontal aperture compensation.[7]

LINEARITY CONSIDERATIONS

The linearity of this system has been studied both analytically and experimentally. We first consider the linearity problem caused by the nonlinear transfer characteristic of a vidicon. Assuming a constant gamma,

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7. G. M. Glasford, Fundamental of Television Engineering, New York: McGraw-Hill, Inc., 1955, pp. 484, 495-497.

the transfer characteristic of a vidicon is given by

$$i = I^{\gamma} \quad ,$$

where i is the output current and I the incident light intensity. For a given color, the average light intensity on the photocathode will be A . Let the peak intensity of the fundamental component of the red encoding grating be P_r and that of the blue encoding grating be P_b . The resulting signal current is thus given by

$$i = (A + P_r \cos\omega t + P_b \cos\omega_b t)^{\gamma} \quad ,$$

where ω_r and ω_b are the carrier frequencies due to the red-encoding and blue-encoding gratings. This expression is expanded below in a series including terms up to the third order. The average value of the expression represents the luminance components, and the fundamental amplitudes of $\cos\omega_r t$ and $\cos\omega_b t$ represent the envelope-detected red and blue amplitudes. Harmonics and products of these frequencies are not important, since they do not contribute to the output. The resulting signal current is given by

$$i = A^{\gamma}\left\{1 + \frac{\gamma(\gamma-1)}{4}\left[\left(\frac{P_r}{A}\right)^2 + \left(\frac{P_b}{A}\right)^2\right]\right\}$$

$$+ A^{\gamma}\left\{\gamma\frac{P_r}{A} + \frac{\gamma(\gamma-1)(\gamma-2)}{24}\left[3\left(\frac{P_r}{A}\right)^3 + 6\frac{P_r}{A}\left(\frac{P_b}{A}\right)^2\right]\right\}\cos\omega_r t$$

$$+ A^{\gamma}\left\{\gamma\frac{P_b}{A} + \frac{\gamma(\gamma-1)(\gamma-2)}{24}\left[3\left(\frac{P_b}{A}\right)^3 + 6\frac{P_b}{A}\left(\frac{P_r}{A}\right)^2\right]\right\}\cos\omega_b t \quad .$$

The first term represents the Y , or luminance, output; the peak values of the second and third terms represent the red and blue outputs, respectively. Note that the relative amplitudes of these components (which determine the generated color) depend only on the <u>ratio</u> of the various peak-to-average values of the intensities, and not on their absolute intensity. Thus each color will track properly over the dynamic range. For example, if the balance is set up properly on any step of a neutral grey scale, it will remain balanced over the entire grey scale, since the relative amplitudes of luminance, red, and blue, (and therefore green) will be in the same ratio for all values of intensity.

Even though the ratio of the signals are not affected by the non-linear vidicon characteristic, the derived signals R-Y and B-Y can be adversely affected. As shown in Figure 4, the color and luminance signals are combined to form (R-Y) and (B-Y). The relative amplitudes of R and Y are adjusted to be equal for a white signal where $R = B = G = Y = 1$. In order to make (R-Y) zero for this condition, using a gamma of 0.5, the red signal must be made 3.28 larger than that of the Y signal. The magnitude of (R-Y) is given by

$$(R\text{-}Y) = A^{\frac{1}{2}}\left\{3.28\left[\frac{P_r}{A} + \frac{1}{32}\left\{3\left(\frac{P_r}{A}\right)^3 + 6\left(\frac{P_r}{A}\right)\left(\frac{P_b}{A}\right)^2\right\}\right] - 1 + \frac{1}{16}\left[\left(\frac{P_r}{A}\right)^2 + \left(\frac{P_b}{A}\right)^2\right]\right\}$$

This equation shows the nonlinear transfer characteristic between (R-Y) and $\left(\frac{P_r}{A}\right)$. Colors with relatively high values of $\left(\frac{P_r}{A}\right)$ (red and magenta) generate significantly higher color difference output than negative (R-Y) signals (green and cyan) that have low values of $\left(\frac{P_r}{A}\right)$. For example, using the constant luminance ratios, a unity-amplitude red signal has $A = 0.3$, $P_r = 0.3$ and $P_b = 0$ resulting in an (R-Y) output of 1.45. For a normalized cyan signal $A = 0.7$, $P_r = 0$ and $P_b = 0.1$ the (R-Y) output in this case is -0.834, showing the asymmetry of the system. The principal effect of this nonlinearity is to produce somewhat overly saturated reds and blues and somewhat desaturated greens. A simple gamma corrector on the color difference signals will correct this problem without hurting the color balance. Alternatively the entire signal, $i = I\gamma$, can be gamma corrected.

The color balance can also be adversely affected by nonlinearity in the envelope detector. The threshold effect common to envelope detection produces a reduced gain at low input levels. This results in reduced red and blue output in low-light areas, with a resulting shift to the green in these darker regions. The solution to this problem is to linearize the envelope detector. Two linearizing methods have been used successfully. First, one can ensure that the signals are large compared to the diode threshold. A second method uses a feedback type of envelope detector where the effective signal level is increased in the crossover region of the detector.

PERFORMANCE CHARACTERISTICS

Assuming idealized color-encoding filters, the spectral transmission averaged over the filter area is 0.5 in the red and blue portions of the spectrum and 1.0 in the green (see Figure 5). Together with the color characteristic of the vidicon these ratios produce a luminance signal having essentially the same characteristics as a constant luminance source.

The signal-to-noise ratios of the envelope-detected signals are comparable to that of the luminance signal. Although the peak value of the carriers is 10-20 percent of the full dynamic range of the camera, the color bandwidth is only 10-20 percent of the luminance bandwidth, thus providing comparable noise conditions. It is essential, however, that a number of steps be taken to ensure adequate noise performance. The camera preamplifier should be a low-noise FET preceded by a tuned filter to boost the response in the vicinity of the color carriers. Care should be taken in both light and electron optics to ensure that the grating structures are well resolved over the entire field. A vidicon that proved suitable for this task was the RCA 8507.

A highlight overload causes clipping of the color carriers. The resulting reduction in the reproduced red and blue signals is interpreted as green. To avoid this condition, an automatic target control system can be used that detects the peak video signal and thus prevents overload. Since a system of this type is poor for live-camera use, where a single specular reflection can darken an entire scene, automatic target systems that work on the average signal are normally used. To allow an overload to take place without color distortion, a circuit was used that disables the color-difference signals when an overload occurs, resulting in a clipped white highlight rather than a green one.

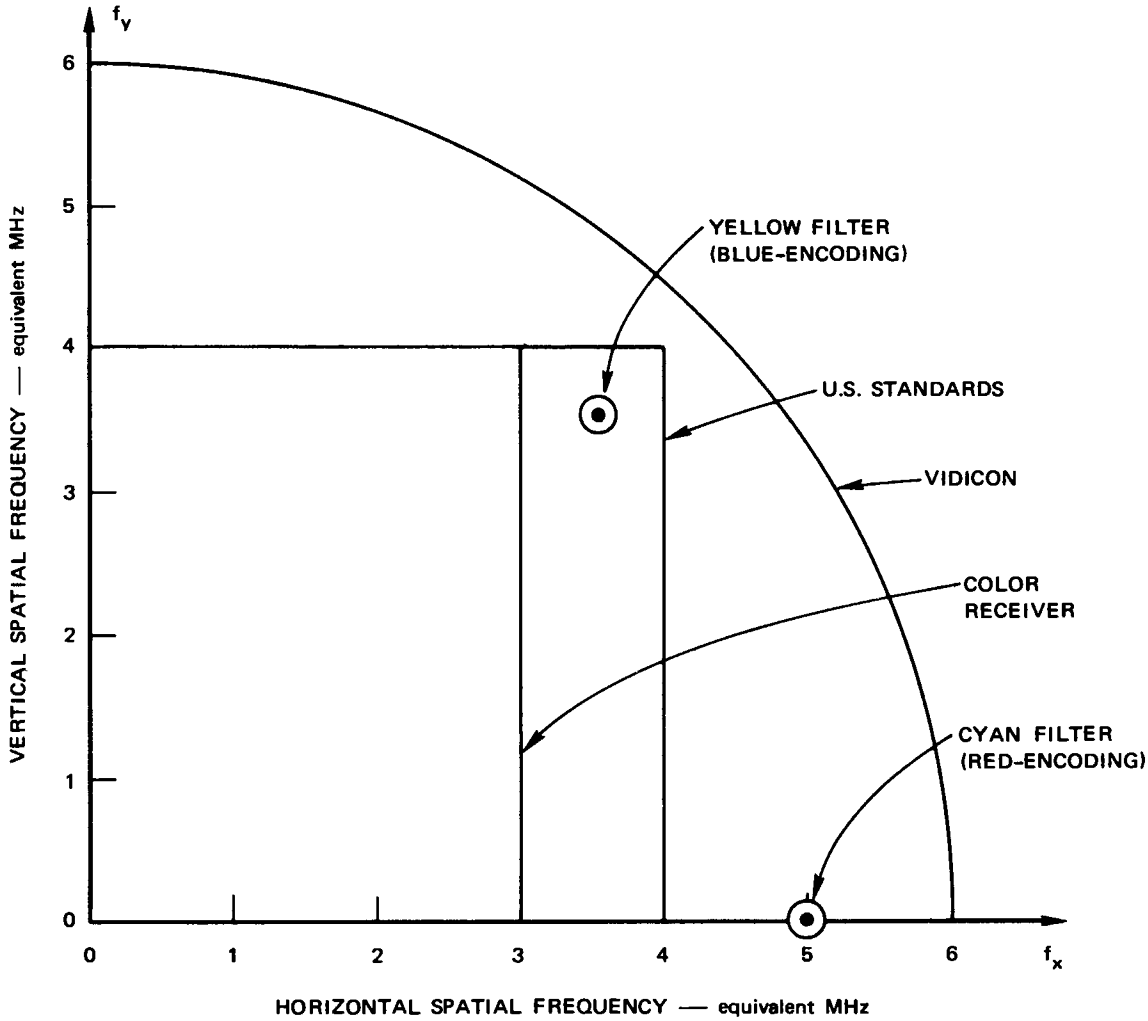
EXPERIMENTAL RESULTS

The luminance and color-difference signals were fed into a conventional color receiver used as a monitor. The reproduced picture was of home-entertainment quality, being limited only by the receiver bandwidth. The recently announced low-cost RCA color camera series, including the PK701, PK730, and the PFS710 film series, are based on the techniques described in this paper. These cameras were demonstrated at the CATV Conference in San Francisco in 1969.

CONCLUSIONS

A color television camera can be constructed using a single camera tube, thus eliminating registration problems and reducing costs. By making efficient use of the two-dimensional spatial frequency spectrum of the camera, the resolution requirements are little more than that of a black and white camera. Although the initial applications are in the area of industrial and educational areas, the basic concept should find its way into studio broadcast use.

List of Illustrations



TA-720522-49

FIGURE 1 SPATIAL-FREQUENCY DIAGRAM

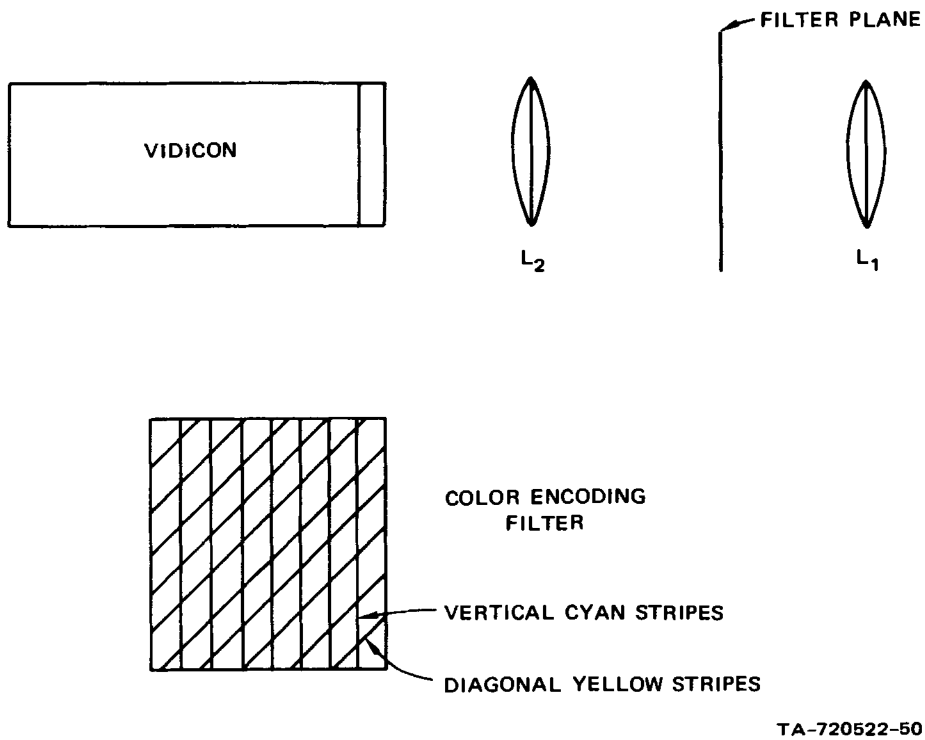


FIGURE 2 SINGLE-VIDICON RELAY-LENS TV CAMERA

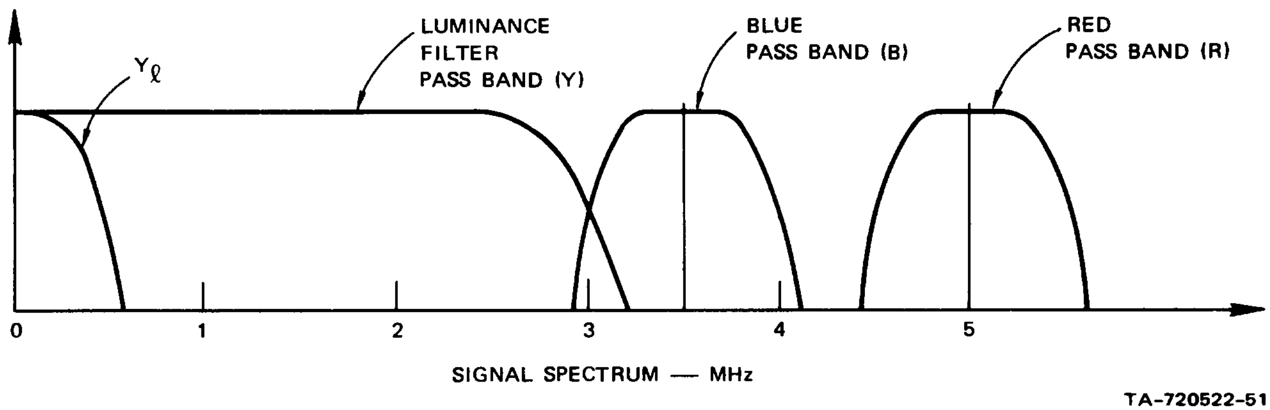


FIGURE 3 VIDICON SIGNAL SPECTRUM

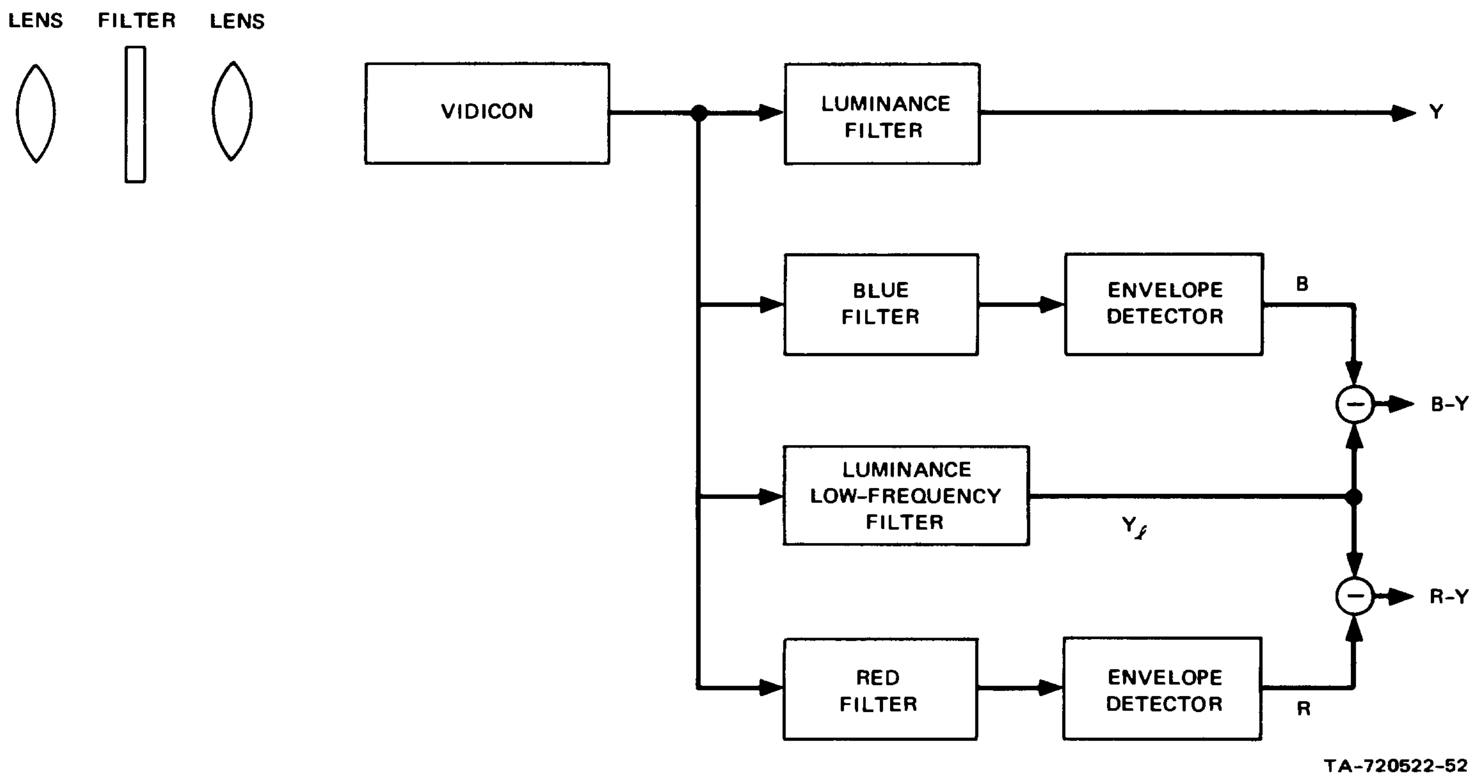


FIGURE 4 SYSTEM BLOCK DIAGRAM

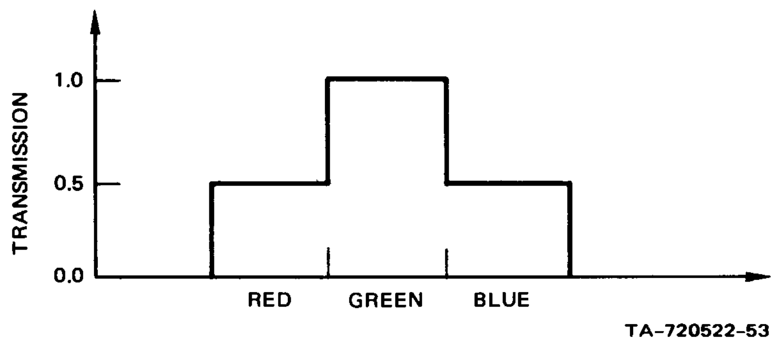


FIGURE 5 AVERAGE SPECTRAL TRANSMISSION OF COLOR-ENCODING FILTER

DISCUSSION:

Mr. Earle Jones: Thank you.

Mr. Greg Liptak: Thank you, Earle. One quick question that I might have is how does this perform under low light level conditions?

Mr. Jones: I'd have to answer--I would suggest that you talk to RCA, but I'll tell you what I think. The color television process inherently costs you something like 40% less than 1 F stop, that is if you can gather all the light in the optical system. They're evidently doing a pretty good job because I asked them down there yesterday and they said it would cost you about 1 F stop. So they use an 8507 Vidicon. The concept I heard here this morning where they take the color filter out and use it at low light level for black and white is new to me. I never heard of that before, but there is certainly no reason why you can't do it. As a matter of fact, someone here said that in a matter of an hour, you should be able to go back to color. Since there is absolutely no synchronization what-so-ever, you can move that filter any way you want to and get the same picture as long as you don't rotate it too much. You can rotate it slightly and there's no synchronous detection going on at all. I would say more like 30 seconds to go from back and white back to color.

Mr. Liptak: Very good--very pleased to hear you say that we're going to have a $2,000 to $3,000 color camera pretty quick.

Mr. Jones: Well, I didn't say that quick.