

A New Beam-Indexing Color Television Display System*

R. G. CLAPP†, SENIOR MEMBER, IRE, E. M. CREAMER†, ASSOCIATE MEMBER, IRE,
S. W. MOULTON†, M. E. PARTIN†, ASSOCIATE MEMBER, IRE, AND J. S. BRYAN†,
ASSOCIATE MEMBER†, IRE

Summary – This paper describes a single-gun cathode-ray display system (the Apple System) for color television receivers based on the phenomenon of secondary emission. An index signal, derived from a secondary emissive structure built into the screen of the tube, continuously indicates the position of the scanning spot relative to the color phosphor structure. This positional information is combined with the color television signal, and the combined signal modulates the scanning spot in amplitude and phase in such a manner that the spot sequentially illuminates the primary colors in the appropriate amounts and proportions to reproduce the intended scene. This paper describes the general features of the system and the philosophy behind its development, and the derivation of the index signal and its utilization in the color-processing and grid-drive circuits.

Introduction

From its inception many years ago, the aim of the Philco color television development program has been to produce a color television display in which the picture tube and its external beam-controlling parts are as simple as possible. Most other color display

systems are based either on the premise that each of several color phosphors is excited by its own electron beam while being protected from the other beams by mechanical or electromechanical means, or, alternately, that a single electron beam is directed to several color phosphors by electromechanical means. These types of display require a mechanical structure within the tube and present problems in registration or focus, or both.

The beam-indexing system is based on the premise that a single electron beam can be used to excite the several color phosphors without auxiliary color deflection or beam shadowing. Instead of forcing the beam to land on a particular phosphor, the beam can be passed over all color phosphors in rapid succession and modulated in accordance with its position to produce the required color. Operation in accordance with this principle requires an indexing system to provide information concerning the whereabouts of the writing beam and a modulating system to provide the required beam modulation. The beam-indexing display system avoids the mechanical and registrational problems of other color

* Original manuscript received by the IRE, June 4, 1956; revised manuscript received June 28, 1956.

† Philco Corp., Philadelphia, Pa.

tubes, the implications of which are discussed at the conclusion of this paper.

Among the important advantages of the beam-indexing tube is its similarity to a black-and-white tube; in fact, in the absence of a chrominance signal, it cannot help making a good black and white picture. None of the writing beam in the Apple tube is intercepted or deflected in such a way as to waste any high-voltage power and there is no problem of matching the characteristics of three guns to obtain good color fidelity. As a result of these characteristics, a receiver using a beam-indexing tube can give performance superior to that of a three-gun-tube receiver. Moreover, in the opinion of the authors, the present system is potentially more economical than any other color receiver because it is simple in those portions where much of the cost of all television receivers is concentrated, and, in addition, has more possibilities of future improvement.

The two fundamental parts of the Apple system philosophy are *sequential writing* and *electrical indexing*. The expression *sequential writing* means that the beam passes successively over triplets of fine, vertical stripes of red, green, and blue phosphors, as shown in Fig. 1.

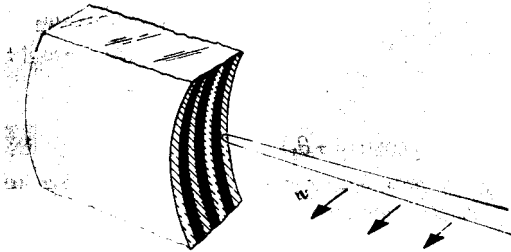


Fig. 1—Apple tube stripe structure.

A particular color is produced by modulating the beam during its passage over each triplet, according to the proportions of primaries of the desired color. The expression *electrical index* refers to a signal, derived from the luminescent screen of the Apple tube itself, that continuously gives information on the location of the beam. The beam current responds to two types of instructions: the color video signal from the transmitter and the index signal. The only circuitry unique to the Apple system is that required to perform these functions.

The signal required to produce the color picture on the beam-indexing tube resembles very closely that required by the FCC standard color television system. That is, the Apple system produces a high-quality black-and-white picture from the luminance signal and, by adding a high-frequency chrominance component to the luminance signal, produces colors. As will be shown, the similarity of these signals to the transmitted signals enables the beam-indexing tube to utilize the broadcast signal efficiently, with a minimum of color processing circuitry.

An important requirement of the system is good spot size. Obviously, when producing saturated primary colors, the spot size at peak beam current must be small enough to minimize the beam current that hits adjacent phosphor stripes. The means of obtaining small spot size are described in the companion paper.¹

Several different forms of Apple display systems have been examined, which have their relative advantages and disadvantages. Rather than to describe these several forms, it seems preferable to discuss in detail one specific form of the system. The form chosen is that which was employed in the receiver shown at the Comité Consultatif International des Radiocommunications demonstration held in March, 1956. For the rest of this paper and for the two subsequent papers the philosophy and circuitry of this particular receiver will be described, although it will be recognized that there are many other ways by which color pictures can be made following the broad Apple concept.

DERIVATION OF THE INDEX SIGNAL

The index signal is obtained from the tube by means of the structure shown in the insert in Fig. 2, where a line, called the *index stripe*, of a material having high secondary emission compared to the aluminized coating, is placed behind every red line. The secondary emission current produced as the beam crosses these index stripes is collected and amplified, resulting finally in a signal at the same frequency as that at which the beam must be varied to produce colors. This beam, which actually produces the picture, is called the *writing beam* to distinguish it from the *pilot beam* which derives the index information as described later in this paper.

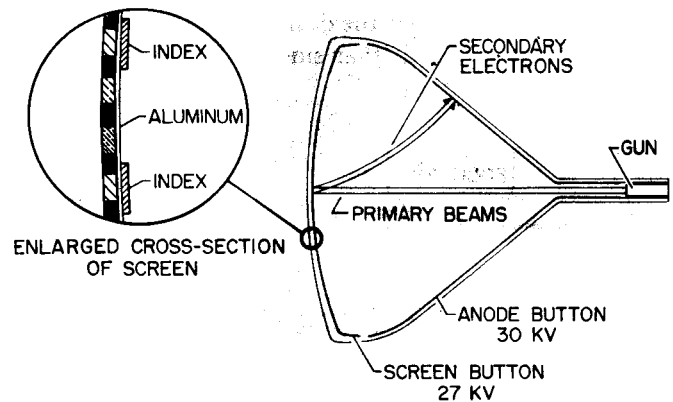


Fig. 2—Cross section of Apple tube.

The waveform produced by the index structure is shown in Fig. 3, which is an idealized curve of secondary emission ratio vs beam position. The equation representing such a structure scanned by a beam of constant amplitude is a Fourier series in cosines. The only term of interest is $A_1 \cos \theta$, the fundamental component. If the phase of this single component in the index current

¹ Companion paper, G. P. Barnett, F. J. Bingley, S. L. Parsons, G. W. Pratt, and M. Sadowsky, "A beam-indexing color picture tube - the Apple tube," p. 1115, this issue.

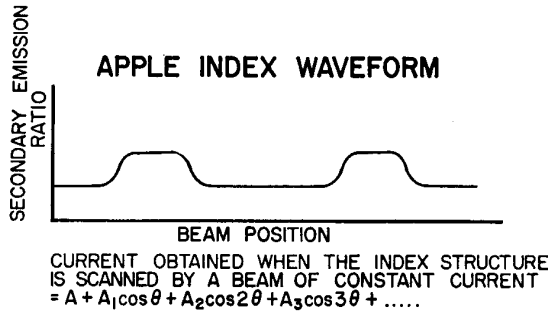


Fig. 3—Apple index waveform.

is preserved, sufficient information will be available. Amplitude variations of the coefficient A_i are removed by means of limiters.

However, the writing beam is not of constant amplitude. The variations that produce color also produce an ac component of the secondary emission current at the same frequency as the desired index signal, and at any phase with respect to it. Since this ac component produces a perturbation of the desired index phase, the secondary emission current may not be used directly as the index signal.

The problem is overcome by the use of frequency separation. A second beam of low current, called the pilot beam, is introduced. Its beam current contains a constant amplitude component of frequency, F , called the pilot carrier-frequency; F is chosen to be above the video- and color-frequency range. An idealized diagram of the single gun which produces the two beams is shown in Fig. 4. Two sidebands are produced as the beams sweep over the index stripes, formed by the component F beating against the desired $A_1 \cos \theta$ component of the index function. Either sideband contains the desired phase information.

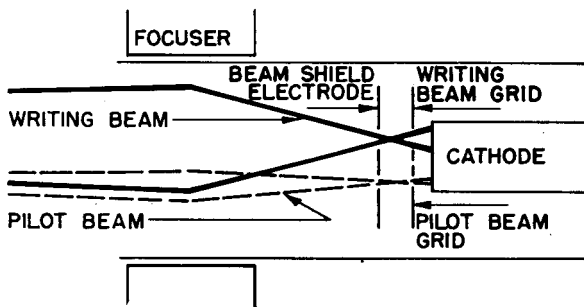


Fig. 4—Idealized cross section—Apple gun.

The pilot beam is aligned so that it always strikes the same color line as the picture writing beam. If the pilot carrier were made a part of the writing beam, gun non-linearity might cause intermodulation between the pilot carrier and writing frequency signal. The side-bands produced by this intermodulation would have the same frequencies as the desired sidebands and might contaminate the index signal. One easy solution to this problem is the use of two beams. The pilot beam illuminates the luminescent screen at a low, constant level which affects

the contrast pilot ratio slightly. This back-ground illumination is generally about 1/2 foot-lambert. A highlight brightness of 40 foot-lamberts allows a contrast ratio of 80 to 1.

THE APPLE CONTROL CIRCUITS

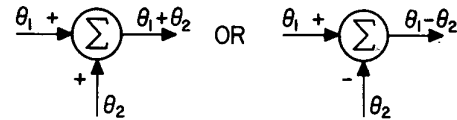
The index signal from the Apple tube must be amplified, combined with instructions from the transmitter and restored to the writing frequency, that is the frequency at which the beams cross the triplets, and then applied to the writing-beam grid of the tube to produce a color picture. Throughout these operations the phase of the index signal must be preserved.

A simple mixer is shown in the upper part of Fig. 5, in which the output voltage is the product of two input signals. Considering only the output terms as the sum or difference of the input frequencies, the output phase is the linear sum or difference of the two input phases, depending on which output sideband is considered.

$$E_1 \cos(\omega_1 t + \theta_1) \xrightarrow{e_1} \boxed{e_3 = e_1 e_2} \xrightarrow{e_3} \frac{E_1 E_2}{2} \left\{ \begin{array}{l} \cos[(\omega_1 + \omega_2)t + \theta_1 + \theta_2] \\ + \cos[(\omega_1 - \omega_2)t + \theta_1 - \theta_2] \end{array} \right\}$$

$E_2 \cos(\omega_2 t + \theta_2) \xrightarrow{e_2}$

A MIXER WHOSE OUTPUT VOLTAGE IS THE PRODUCT OF THE TWO INPUTS



THE SAME MECHANISM REPRESENTED AS A LINEAR ADDITION OR SUBTRACTION IN THE PHASE DOMAIN

Fig. 5—An analysis of the operation of a simple mixer in the phase domain.

Thus, in the phase domain, a heterodyning process is an addition or subtraction of phases. This is shown diagrammatically in the lower part of Fig. 5. The Apple index mechanism is just such a mixer, whose output is the product of the pilot beam current and the index function; and it is necessary to retain only one of the sidebands produced at the screen to obtain the essential phase information. A second heterodyning with the pilot carrier frequency is necessary to restore the side-band frequency to the original index frequency which is needed for writing colors. The block diagram of Fig. 6 shows the Apple indexing system. First, a pilot oscillator at 41.7 mc drives the pilot beam grid. The useful

sideband output at 48.1 mc is amplified in the sideband amplifier and then goes to a mixer. Here it is heterodyned with the pilot oscillator output, producing the 6.4 mc signal for the writing grid.

If the horizontal scanning velocity is constant, the index signal flows to the writing grid without any change of phase, and produces variations of the writing beam current so that it illuminates successive lines of the same color; this produces a solid field of uniform color. If, however, the horizontal scan increases or decreases in speed, the ac component of the beam current is retarded or advanced in phase and so produces a slightly different color. This phase change with changing sweep speed or index frequency is proportional to the slope of the phase-frequency characteristic (the envelope time-delay) of the index sideband amplifier. Sweep nonlinearities produce color errors which are the product of the amplifier time delay and the incremental index frequency change.

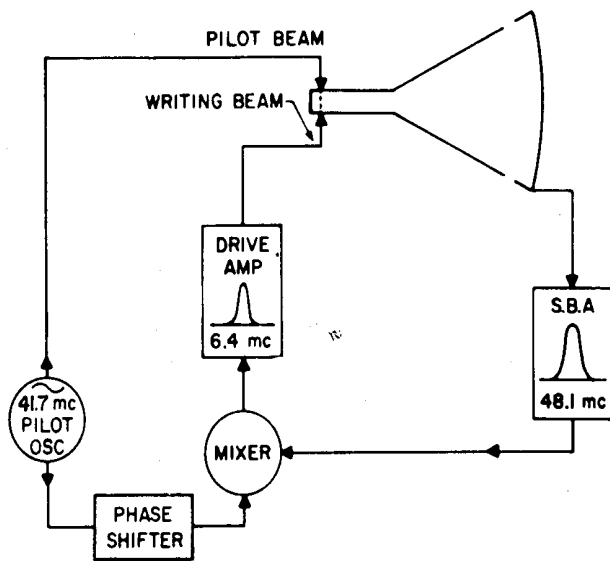


Fig. 6—Simple block diagram for generating flat fields.

In order to change deliberately the color of a flat field, it is necessary only to change the phase of the pilot carrier entering the mixer; this could be accomplished by the phase shifter shown in Fig. 6.

The optimum envelope time-delay of the sideband amplifier is affected by the possible contamination of the index signal by the writing beam. Fig. 7 shows the spectrum of the complete signal at the input to the side-band amplifier. The energy concentrations at one-half writing frequency above and below the useful sideband frequency are caused by harmonics of the writing frequency in the writing beam and video modulation of these harmonics.

For system stability the sideband-amplifier response must be well down at these points of energy concentration, for they represent interference to the index function

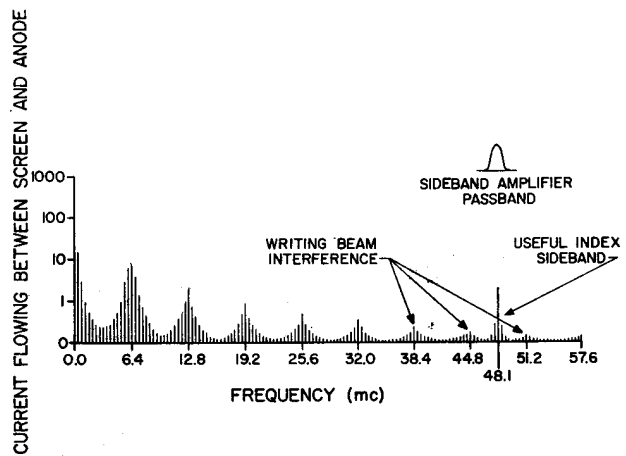


Fig. 7—The spectrum of the complete signal at the input to the sideband amplifier.

and can cause various forms of color interference. A design compromise must therefore be made in the selection of a sideband-amplifier response curve to have sufficient skirt selectivity to reject unwanted writing beam interference and yet have a short enough time delay to permit a realistic amount of horizontal sweep nonlinearity without too much color nonuniformity.

Typical design permits about a one-microsecond delay from the Apple tube screen to the writing grid. This delay produces about ten degrees of color error for a sweep nonlinearity of one-half per cent. Such linearity requirements, though severe, have been found to be practically realizable. Suitable circuits are described in one of the following papers.

PICTURE WRITING TECHNIQUES

In order to make the system of Fig. 6 show complete color pictures instead of solid fields of color, it is only necessary to vary dynamically the phase and amplitude of the pilot-carrier signal entering the mixer. The voltage on the writing grid is simultaneously varied at video frequency to control the luminance. The total current illuminating the three phosphors depends on the video frequency portion of the signal applied to the writing grid, and the way in which this current is divided among the three phosphors is determined by the amplitude and phase of the writing component of the grid signal.

Consider the tube to have infinitesimal spot size and line width so that it is a sampler of very narrow aperture. Let the lines be equally spaced, as shown at the top of Fig. 8. If the video-frequency and the color-writing frequency portions of the signal are as shown in the Figure, accurate color fidelity exists. The video frequency portion of the signal is the linear sum of gamma-corrected red, green and blue, and the color-writing signal is the sum of three equally spaced vectors. This signal is similar to the combined color video available at the second detector.

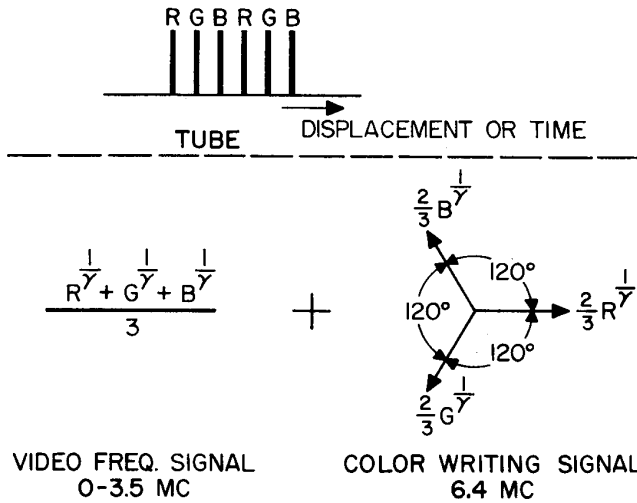


Fig. 8—Development of required signal for color writing.

The color subcarrier may be represented in terms of I and Q, or more conveniently for analysis of the present system, as shown on the left side of Fig. 9. The required drive signal is shown again on the right. Two differences exist. First, the received color subcarrier is not equi-angle; and second, the signal required to drive the tube must be locked to the stripe structure at 6.4 mc rather than to the 3.58 mc transmitted chrominance subcarrier. The color subcarrier can be simply corrected to the equi-angle form by an elliptic conversion or compensated for by unequal stripe placement on the tube, but the visible difference in the picture is less than 10 color degrees and it is customary to neglect this correction.

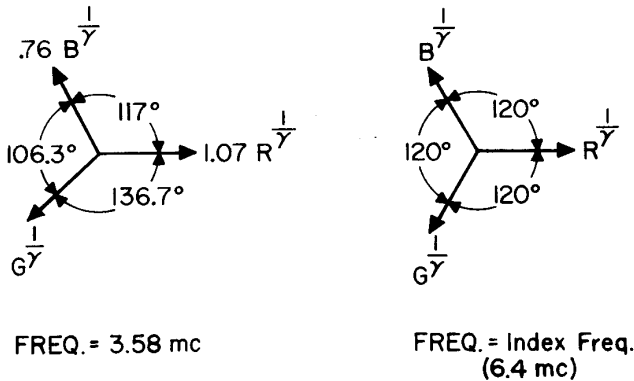


Fig. 9—Comparison of color subcarrier at second detector and required signal.

The conversion from 3.58 mc to 6.4 mc is achieved through heterodyning as shown in Fig. 10. The pilot-carrier signal required by the pilot-beam grid is generated by beating the 3.58 mc color reference signal against an oscillator 3.58 mc below the desired pilot-carrier frequency. The required pilot carrier entering the mixer is generated by beating the same oscillator against the

3.58 mc signal with color modulation. The mixer output is a signal at writing frequency locked to the color line structure but having the same amplitude and phase variations as did the original 3.58 mc color signal.

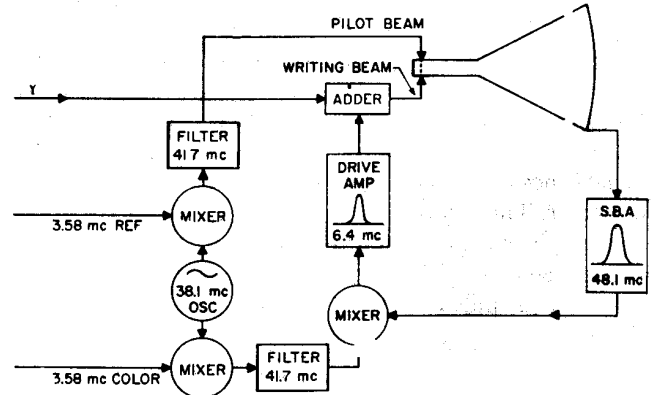


Fig. 10—Block diagram showing method of heterodyning to convert from 3.58 mc to 6.4 mc.

For the required video-frequency signal, the Y signal available at the second detector can be used as shown in Fig. 10. If slightly better colorimetric accuracy is desired, a monochrome correction signal of the type indicated algebraically in Fig. 11 can be added to the Y

$$\begin{aligned} & \underbrace{.30 R^{\frac{1}{\gamma}} + .59 G^{\frac{1}{\gamma}} + .11 B^{\frac{1}{\gamma}}}_{\text{"Y" SIGNAL AVAILABLE AT 2ND DETECTOR}} + \underbrace{.03 R^{\frac{1}{\gamma}} - .26 G^{\frac{1}{\gamma}} + .22 B^{\frac{1}{\gamma}}}_{\text{"MONOCHROME CORRECTION"}} \\ & = \frac{R^{\frac{1}{\gamma}} + G^{\frac{1}{\gamma}} + B^{\frac{1}{\gamma}}}{3} \\ & = \text{DESIRED SIGNAL} \end{aligned}$$

Fig. 11—Addition of "Y" signal at second detector and "Monochrome Correction" signal to produce desired signal.

signal converting it to "M."² It is derived by synchronously detecting the 3.58 mc color signal with the 3.58 mc reference signal as shown in Fig. 12. These are all the steps that are needed if the spot size and line width are reasonably near the infinitesimal ideal. The effect of greater spot sizes and line widths is a slight desaturation of the colors. However, two simple steps can be used to correct the situation. The mathematical details are outside the scope of this paper; they involve the gamma of the tube, the line width, the width of the spaces between lines, and the exact details of the spot growth with current. Let it suffice to say that with the present values

² M is called the monochrome signal and is commonly defined as $\frac{1}{3}R + \frac{1}{3}G + \frac{1}{3}B$.

of these parameters, simply increasing the chroma gain about 33 per cent and adding a second low-frequency signal called *saturation correction* results in almost perfectly accurate color fidelity. The saturation correction signal biases the tube negatively an amount proportional to the amplitude of the color subcarrier and has the effect of reducing the conduction angle, particularly on primaries. The saturation correction signal is derived from the same detector as the monochrome correction, but does not represent a sacrifice in brightness since the chroma gain has been increased. Differences caused by monochrome and saturation corrections are small and recent practice has been to ignore them.

COMPARISON OF THE INHERENT COMPLEXITIES OF VARIOUS TYPES OF COLOR TELEVISION DISPLAY

There are several broad areas within color television receivers, and in their production methods, which should be studied to determine what degree of complexity is inherent in the display device. These areas are those of physical devices, circuitry, and adjustment procedures.

In the area of physical devices are the cathode-ray tube itself, the yoke, the focuser, any special auxiliary devices such as convergence coils, purity coils, and magnets, and any special magnetic or electric shielding which may be required. The penalty which one must pay for complexity in this area is primarily that of using more material in the receiver.

Examples of circuit complexities which are inherently associated with various display devices are the following: separate video channels for the three primary colors, abnormally wide bandwidths in any channel, regulated voltages, making two regulated voltages track each other, sweep circuits with remarkably good linearity, and the amplification of index signals. Complexity in this area leads to using more material, but it should be pointed out that apparent circuit complexity is liable to misinterpretation. The mere number of vacuum tubes in a receiver is often a very poor guide to evaluation of its true complexity. It is well known that in many cases the over-all complexity of a receiver can actually be reduced by adding tubes, provided the addition of tubes and circuits permits the removal of complicated tubes or circuits and simplification of adjustment of the receiver.

The third area, that of adjustment procedures, is the most difficult to evaluate quantitatively. The presence of the following factors is suggested as a true measure of complexity: large numbers of adjustments, either in the factory or those required of field service personnel, inter-related adjustments, adjustments whose effect is difficult to evaluate, adjustments requiring unusual test equipment, and adjustments which must be frequently repeated because of instability in the receiver or because of abnormal sensitivity to external effects. The penalties for complexity in this area are the use of more material, increased factory labor, more field service and, very often, inferior performance in the field.

There are three principal types of display to be considered: the 3-gun type represented by the shadow-mask and post acceleration tubes, the Lawrence tube, and the index type represented by the present form of the Apple tube.

The complexities of 3-gun tubes which are of most concern are those inherently associated with having three guns. The convergence of the three beams must be maintained all over the raster. This is difficult because the three beams have different centers of deflection and because of the effect of external magnetic fields, such as that of the earth. Maintenance of color purity all over the raster requires accurate control of

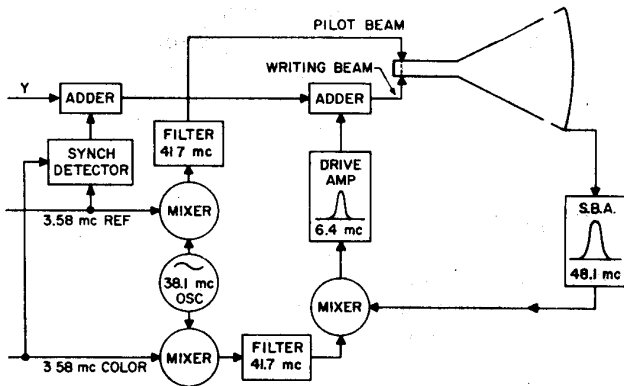


Fig. 12—Block diagram showing production of monochrome correction by synchronous detection of the 3.58 mc color signal with the 3.58 mc reference signal.

The block diagram shown in Fig. 10, then, represents the entire picture and index signal handling sections of the display. The only other parts which must be added, as shown in Fig. 13, are the sweeps, the high-voltage

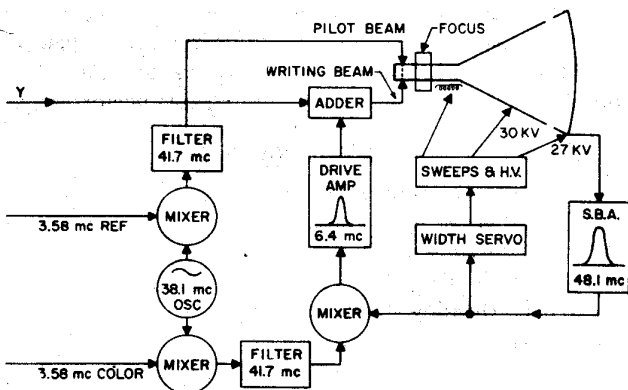


Fig. 13—Block diagram of receiver with sweep circuits and high voltage supply added.

supply with outputs at 27 kv and 30 kv, the magnetic focuser with vertical dynamic focus, and the width servo. Not shown are the reference generator, the audio, the IF and the tuner.

the direction of arrival of the three beams, in the presence of the effects of external fields. Both convergence and purity vary from tube to tube. These effects have led to the use of relatively elaborate devices external to the tube to deflect the three beams, in addition to the normal sweeps. These complexities add to the material cost of the receivers, and may add as many as 25 adjustments in a typical shadow-mask receiver. These adjustments require judgment since they must be made by inspection of the effects of the adjustments on the picture; they are interrelated and they must be repeated if the physical position of the receiver is changed.

The use of three guns also imposes the requirement that the characteristics of the three guns be matched or compensated so as to produce good white balance at all brightnesses. Cathode-ray tube guns cannot easily be built with inherently matched characteristics, so circuit adjustments must be used. This adds four more critical adjustments which must be made while watching the tube face and which require judgment.

In the field of circuit complexity there is the requirement for color demodulators and separate channels for the three primary colors. The shadow mask type of three-gun tube has the further inherent disadvantage of inefficient use of high-voltage power, resulting in extra expense and complexity in the regulated high-voltage supply.

The various types of three-gun tube are relatively complex in themselves, both because of the three guns themselves and because of the other internal structures, shadow masks or grilles, required to direct the beams to the proper colored phosphors. None of these complexities exist in the single-gun index type displays.

The Lawrence tube has none of the complexities just discussed as applying to the three-gun displays, except the complexity of the tube itself and one aspect of the color purity problem. It has, however, two types of problem which are unique, and are inherent in its method of operation. One is the need for a high-power, synchronized switching signal. This causes extra circuit complexity and expense, and requires elaborate shielding to reduce radiation. The other is the need for special signal processing to obtain good colorimetry from a tube which deflects the beam sinusoidally over the color stripes. These complexities are largely in the field of circuitry. The Lawrence-tube adjustment procedures seem to be reasonably simple.

Index type displays, such as the present Apple system, have their own unique and inherent problems. One of the most important of these is the generation and amplification

of the index signal. The generation of the signal is built into the tube at the expense of very little complexity. The amplification and handling of the index signal requires a moderate amount of conventional circuitry and about 30 adjustments. These adjustments represent a source of complexity only in their number. They are not interrelated; their effect is easy to evaluate since they are simple maximizing or minimizing operations while reading meters; they require no unusual test equipment; and once set up, they are stable for long periods of time.

The present Apple system requires accurate control of horizontal linearity and width. This represents a complexity only in the area of circuitry. There are no elaborate devices nor adjustment procedures involved.

Another requirement of index-type displays is small spot size. This requirement is met partly by care in tube design, which does not in itself result in tube expense nor complexity, partly by some extra complexity in the yoke and focuser, and partly by the use of a high, regulated anode voltage. The latter two requirements make the high-voltage supply almost as elaborate as that for shadow-mask tubes. The yoke and focuser alignment procedures required for good spot size are much simpler than those required in shadow-mask displays for convergence and purity, and are comparable to good black and white practice.

The only other unique and inherent requirement of the present type of Apple display is that of beam tracking. It is met partly by characteristics built into the tube at no extra expense and partly by observing the same precautions in yoke and focuser alignment as are required for good spot size.

In weighing these considerations, one reaches the conclusion that any color set is substantially more complex than a black-and-white set. By comparing the various types and severities of the complications of the different displays, one further finds reason to believe that the beam-indexing system is considerably less complex than other systems of comparable performance.

ACKNOWLEDGMENT

Obviously, this development was not the work of a small number of individuals. A great many engineers have made significant contributions. In particular, the authors wish to acknowledge the contributions of William E. Bradley, David Brunner, Monte I. Burgett, Charles Comeau, Richard K. Gardner, Richard Gudis, Lincoln Hershinger, Carl Mutschler, Charles Simmons, and David E. Sunstein.