THE CATV MODULATOR

By

Alex B. Best
Commercial Communications
Scientific-Atlanta, Inc.

Prepared for Presentation to
Nineteenth Annual Convention
National Cable Television Association
Chicago, Illinois
June 19-22, 1970

THE CATV MODULATOR

Alex B. Best, Senior Engineer
Commercial Communications
Scientific-Atlanta, Inc.

The purpose of the modulator in CATV systems is to accept a source of video and audio or 4.5 MHz FM signal and convert these to a standard television signal. This source of information may be a camera, a demodulator, or microwave relay output. Because the CATV modulator performs the same function as a television transmitter, its specifications must conform very closely to those of a transmitter.

The block diagram of a CATV modulator is shown in Figure 1. The video enters the unit through the "video phase equalizer" module. The function of this module is to predistort the phase versus frequency characteristics of the video to conform to the standard FCC predistortion requirements required for color transmission. After leaving this module the video enters the video amplifier module through a second phase equalizer section. This second equalizer, which is an integral part of the video amplifier, predistorts the delay characteristics of the video to compensate for delay errors introduced by the vestigial sideband filter and other filters in the modulator itself.

The "video amplifier" amplifies and clamps the video signal. The synchronizing pulses are clamped to a reference level in order to ensure that the sync tip level applied to the "video modulator" does not vary with the average brightness content of the signal. The "video modulator" module accepts the video signal and modulates this information on a 45.75 MHz IF carrier. Through the use of a "Cowan bridge" type modulator differential gain and differential phase are minimized.

The output of the video modulator contains both the upper and lower sidebands. The "vestigial sideband filter" module, which is at the IF frequency, passes the lower sideband and rejects all but a small portion of the upper sideband in order to conform to the standard TV channel bandwidth. The vestigial sideband filter module also has provisions to accept a combined video and sound IF signal from an external source. When signals from an external source are being used, the 45.75 MHz oscillator is automatically disabled. The output of the vestigial sideband filter goes to the output converter for conversion to the desired channel. Additionally, a sample of the vestigial sideband filter output is available at the rear of the chassis. This output can be used to provide IF signals to a heterodyne signal processor such as the Scientific-Atlanta Model 6100 to replace absent off-air signals.

The Model 6300 modulator provides two audio options. The "A" option accepts balanced audio and converts this signal to a 4.5 MHz FM subcarrier. The importance of maintaining the audio subcarrier frequency at 4.5 MHz ±1 kc is discussed in a later section of this paper. The "S" option accepts a direct 4.5 MHz FM subcarrier input or a 4.5 MHz FM subcarrier and video combined input. One of the two 4.5 MHz FM signals mentioned above is then applied to a balanced modulator along with a sample of the 45.75 MHz oscillator. The output of this modulator is fed to a filter network tuned to 41.25 MHz which rejects the unwanted sideband. A portion of this sound IF signal is also available at the rear of the modulator chassis. The output of the filter network, which incorporates a front panel level control, is then fed to the output converter. In the Model 6300 CATV Modulator, the sound IF and video IF are upconverted in separate converters and then combined at the desired output frequency in a passive device. The reason for this approach to up conversion is discussed in detail later.

To be able to accurately set both FM deviation and percent AM video modulation, a sample of the 4.5 MHz FM subcarrier signal and the video IF signal enter the meter circuit module. Depending on the position of a front panel switch, the meter on the front panel will either indicate FM deviation in kc or AM modulation in percent.

If the output signal is to be phase locked to an off-air signal, an optional input converter and phase detector are required. The 45.75 MHz IF signal which is normally crystal controlled is then phase locked to the converted off-air signal. By using the same local oscillator signal for both down and up conversion, phase lock is achieved.

The remainder of this paper will discuss the areas of particular interest in the design of a CATV modulator.

Output Converter

The function of the output converter is to convert the video, sound, and color IF signals from the standard IF frequency centered at 44 MHz to any desired output channel. There are various techniques for achieving this desired frequency conversion; however, the most common way is to sum the picture, sound, and color signals, along with a local oscillator signal, and apply them to a nonlinear device. As an example, let us consider the situation shown in Figure 2. For the standard IF frequency centered at 44 MHz,

$$f_v = \frac{\omega_v}{2\pi} = 45.75 \text{ MHz}, \quad f_s = \frac{\omega_s}{2\pi} = 41.25 \text{ MHz and}$$

$$f_{lo} = \frac{\omega_{LO}}{2\pi} \text{ is the oscillator frequency required for}$$

the desired output channel. In our example, we will ignore the color subcarrier signal to simplify the problem and discuss the consequences of this simplification later.

The transfer function of any nonlinear device can be written as a power series expansion about its operating point (1). In the above example, i_o, the output current, can be represented by the equation

$$i_o = a_o e_{in} + a_1 e_{in}^2 + a_2 e_{in}^3 + a_3 e_{in}^4 + \ldots\ldots + a_{n-1} e_{in}^n$$

where a_0, a_1, a_2,....a_{n-1} are constants determined by the particular nonlinear device and its operating point. If now in the above equation we will substitute for e_{in} the sum of $A_{lo}\cos\omega_{lo}t$, $A_v\cos\omega_v t$, and $A_s\cos\omega_s t$ and expand each term, we will find frequency components in the output current i_0 which are equal to the three input frequencies of all three input signals and their harmonics, plus a dc term. In the above example we will expand the input signal only out to the fourth order, (it is assumed that the fifth and higher order terms are much smaller in magnitude than the lower order terms if the mixer is biased properly.) and consider only those frequency components within 6 MHz of the upper and lower edges of the desired output channels. In most output converters the filter network following the mixer is adequate to reject any frequency components which are outside these limts. The spectrum of the output voltage e_0, is shown in Figure 3. Here we have ignored two other terms whose frequencies are the same as the desired outputs. They are cross modulation terms and are extremely small compared to the desired outputs. Here $a_1 A_{lo} A_v \cos(\omega_{lo} - \omega_v)t$ is the desired output picture carrier and $a_1 A_{lo} A_s \cos(\omega_{lo} - \omega_s)t$ is the desired output sound carrier. From the coefficients of these two terms we can see that they are directly proportional to both a_1 and their respective IF levels. Since the desired output signal comes from a term in the power series expansion with the coefficient a_1, that is, the square law term, the mixer or nonlinear device should be biased so as to maximize a_1. The other two terms, one 4.5 MHz below the desired picture carrier and the other 4.5 MHz above the sound carrier, are spurious outputs and if large enough will create beats in adjacent channels of a multi-channel system. Upon examining the coefficients of these spurious outputs we conclude that they are generated from the fourth order term in the power series expansion. It is unfortunate that in most nonlinear devices the bias point which maximizes a_1 also maximizes a_3. Let us pause to consider here a few minutes the importance of the coefficients of these four output signals since the results have a practical application in most up-converters in existence today. For a particular video and sound IF input level, the desired output levels will be proportional to both a_1 and their respective input levels, A_v and A_s whereas the lower frequency spurious output will be proportional to a_3, A_s, and A_v^2 and the higher frequency spurious output proportional to a_s, A_v, and A_s^2. If we assume the normal amplitude difference between the picture and sound carrier of 15 dB, we find that the lower frequency spurious output will be 15 dB higher in amplitude than the other spurious output. We also conclude that since this higher amplitude spurious output is proportional to A_v^2 and A_s, for every dB that we raise the amplitude of A_v and A_s, the relative amplitude difference between the desired output and this undesired output will decrease one dB. For this reason most manufacturers recommend the use of a good bandpass filter on the output of their up-converts if the output level is run above a certain level.

From the above conclusions, we see that if we wish to up-convert the sum of the video and sound IF signals without generating any spurious outputs, we should consider two important points. Number one is the nonlinear device selection and number two is the level of the signals at the mixer input. If, however, we now assume that we have been able to up-convert the sum of the video and sound IF signals to the desired output frequency without excessive amplitudes on the undesired outputs, we must still amplify these desired outputs to their final output level without generating more spurious outputs. With this in mind, let us now consider the situation shown in Figure 4.

If we follow the same steps as we did in the mixer, we will find the generation of the same two spurious output signals we did before; however, in the output amplifier they occur due to the third order term in the power series expansion. The spectrum of the output E_0 is shown in Figure 5. Here again we have ignored two cross modulation terms whose levels are extremely small compared to the desired output. Fortunately, the bias point which maximizes A_0, that is gain, in the output amplifier tends to minimize A_2 and therefore the amplification of the output signal without generating spurious outputs is not quite as difficult as up-converting them unless of course the signals get excessive in amplitude.

In all of the above discussions we have ignored the color sub-carrier signal in order to simplify the calculations. The justification for doing this is that in a normal CATV television signal the color-subcarrier signal is typically 10 dB smaller than the 15 dB down sound carrier and therefore the largest spurious output generated by this color signal is at least 10 dB smaller than the largest one generated by the sound. Since these color generated spurious signals lie very close to the ones generated by the sound signal, their relative amplitudes will change very little due to the filter characteristics.

The conclusion to be drawn from the above example is that it is extremely difficult to sum the sound, color, and video IF signals and up-convert them in a common mixer to the desired output channel without generating spurious outputs. Even if we up-convert the sound and video plus color in a separate mixer and then add them before amplification, we would still run the risk of generating spurious outputs, especially if large output levels are desired.

The most efficient output converter, i.e., one which minimizes the generation of spurious outputs, would be one which up-converts the video with color IF signal and sound IF signal in a separate mixer, amplifies them in separate amplifiers, and then combines them in a passive combiner. It is this up-conversion scheme which is used in the Scientific-Atlanta modulator.

Audio to 4.5 MHz Converter

According to the FCC specifications on a color television transmitter, the 4.5 MHz frequency spacing between the video and sound carrier must be held to a frequency tolerance of ± 1 kHz (2). Before we consider a method by which this accuracy can be achieved in a CATV modulator, let's consider the problems which could and do arise in present day CATV systems because of errors in this frequency separation. Shown in Figure 6 is a typical color television receiver response up to the video detector. In the course of color television field tests, it has been found that receivers need about 50 dB of on-channel sound attenuation in the IF channel in order to prevent the beat between the sound carrier signal and color subcarrier signal from appearing in the picture (3). Because the color sidebands extend up to within 320 kHz of the sound carrier, extremely sharp skirted notch filters are used to suppress this on-channel sound signal.

Now let's assume that we are manually fine tuning a color television receiver to Channel 8 which has as its input the output of the modulator with no adjacent channels present. To correctly fine tune this set we would adjust its local oscillator to place the on-channel sound signal in the deepest portion of its trap. If now our video-sound frequency spacing were incorrect due to the audio to 4.5 MHz converter, the consequences would be two-fold: first, if the frequency error was in a direction such as to reduce the spacing between video and sound carrier, it would be difficult to eliminate the 920 kHz beat between the sound and color signals and still obtain a sufficiently saturated color picture. Secondly, since all sets manufactured in the United States today use the principle of intercarrier sound detection, a sufficient error in this 4.5 MHz signal could cause a distortion in the detected audio signal.

In a typical CATV system we very seldom have the single channel situation discussed above, but in more cases than not have the situation shown in Figure 7. Here each channel is bordered on each side by another channel which is of equal magnitude.

Let us now assume that we are going to manually fine tune a color television set to Channel 8 which has present at its input the composite signal shown in Figure 7. In order to produce a picture on the screen which is free from beats, our problem is two-fold. Number one, we must adjust the local oscillator of the set so as to place the on-channel sound of Channel 8 in its sound notch to eliminate the 920 kHz beat mentioned above; and second, we must place the adjacent channel sound carrier, that is, the Channel 7 sound carrier, in the adjacent channel sound trap to eliminate the 1.5 MHz beat which could occur between the Channel 8 video carrier and the Channel 7 sound carrier. If now we assume that the traps are properly tuned in the television receiver, our main concern would be with the frequency separation accuracy of Channel 7 and Channel 8's sound carriers. Of course there are several sources of inaccuracies in the separation of these two carriers. Not only is there the possible error due to an audio to 4.5 MHz converter which is off frequency, but offsets to minimize co-channel, crystal tolerances in UHF converters and input and output converters are all possible sources of error.

Although the audio to 4.5 MHz converter in a modulator is only one of many possible sources of frequency error, it could, so to speak, be "the straw that breaks the camel's back" and mean the difference between a good quality channel or one which is extremely difficult to fine tune to eliminate the beats mentioned above.

The simplest and most common way to control the accuracy of the 4.5 MHz FM signal generated in a modulator is to apply this FM signal to a 4.5 MHz discriminator, filter out the audio components, amplify the resulting dc error voltage, and apply this dc voltage to the frequency determining element of the 4.5 MHz oscillator. Such a system is shown in Figure 8.

There are several possible sources of error in such a system. First, the output frequency is determined almost entirely by the zero crossing of the discriminator and to hold an accuracy of ± 1 kHZ on 4.5 MHz would require a zero crossing which is accurate to ± .022%. This is extremely difficult to maintain with conventional tuned circuits. Another problem with the system shown in Figure 3 is that a typical 4.5 MHz discriminator is very insensitive to a 1 kHz frequency variation and therefore would have to be followed by a high gain dc amplifier to reduce the error to below 1 kHz.

A better scheme, and the one which is used in the Scientific-Atlanta modulator, is the one shown in Figure 9. Here accurate center frequency control is obtained by comparing the output of the 4.5 MHz oscillator with an accurate standard, in our case a 4.2 MHz crystal oscillator, and applying the low frequency difference signal to low frequency discriminator whose stability has a much smaller percent effect on the 4.5 MHz output signal. By using a discriminator whose zero crossing is at 300 kHz, an accuracy of only ± .33% is now required in order to maintain the output 4.5 MHz signal to within ± 1 k. This type of stability can easily be obtained with conventional tuned circuits. Also, this lower frequency discriminator offers a considerable improvement in sensitivity over one at 4.5 MHz. In actual practice, this particular design held the 4.5 MHz FM signal to within ± 500 cycles from -20° F to + 120° F.

Envelope Delay

To produce a faithful image at the television receiver kinescope, all of the frequency components which make up the video signal must have an equal time delay from their source of origination, such as a camera to the display device, in our case, the subscriber's home receiver kinescope. The majority of any variation in time or envelope delay is concentrated in the IF and video amplifier sections of the receiver and the vestigial sideband filter of the transmitter. The pictorial results of this delay distortion are three-fold: first, the variation in envelope delay between the high and low video frequency components causes preshoots and undershoots in the rapid transitions between luminance levels of the picture. This can lead to excessive ringing and smears in the picture. Second, a variation in envelope delay over the range occupied by the color signals, that is, the I and Q color difference signals, causes cross talk which results in color errors at the transitions of the color portion of the picture. Third, a variation in envelope delay between the color portion and luminance portion of the complete signal will upset the time coincidence of these signals at the home receiver and, if severe enough, will produce the so-called "funny paper" effect.

To eliminate this source of distortion in the Scientific-Atlanta modulator, a video delay equalizer is inserted at the video input to the modulator. This equalizer not only corrects for the delay errors generated within the modulator itself, but also corrects for the errors generated by the "average home receiver." To this end, the envelope delay of the "average receiver" has been determined and the inverse of this delay curve is specified by the FCC to be the delay required for a color television transmitter (4). Shown in Figure 10 is the required envelope delay distortion and its tolerances. The FCC specifications reads: A sine wave, introduced at those terminals of the transmitter which are normally fed the color picture signal, shall produce a radiated signal having an envelope delay, relative to the average envelope delay between 0.05 and 0.20 MHz, of zero microseconds up to a frequency of 3.0 MHz; and then linearly decreasing to 4.18 MHz so as to be equal to - 0.17 microseconds at 3.58 MHz. The tolerance on the envelope delay shall be ± 0.05 microseconds at 3.58 MHz. The tolerance shall increase linearly to ± 0.1 microsecond, down to 2.1 MHz, and remain at ± 0.1 microsecond down to 0.2 MHz. The tolerance shall also increase linearly to ± 0.1 microsecond at 4.18 MHz (5).

The phase equalizer in the Scientific-Atlanta modulator is comprised of two sections. One section is built in front of the video amplifier and clamper circuit and is an integral part of the video modulator module. This phaze equalizer compensates for the delay errors generated within the modulator itself. The second section of the phase equalizer compensates for the delay errors generated by the average home receiver and is an optional plug-in module through which the video signal passes before going to the video modulator module.

Differential Gain and Phase

Differential gain is defined as a change in the level of the 3.58 MHz color subcarrier as the level of the luminance signal on which it rides is varied from blanking to white. Differential gain is normally expressed in dB or percent. Differential phase, normally expressed in degrees, is defined as a change in the phase of the 3.58 MHz color subcarrier as the luminance level is varied from blanking to white. The test signal most commonly used to measure both differential gain and phase is shown in Figure 11. Here, the 3.58 MHz signal is riding on either a ramp or stairstep luminance level with the 3.58 MHz signal beginning at the blanking level and ending at a luminance level corresponding to white level of 12½% of sync tips.

The pictorial effects of differential gain and phase are related to the broad area color portions of the picture. Errors in differential phase causes incorrect hues in the picture and errors in differential gain affects the color saturation of the picture. It is interesting to note that the pictorial effects of differential gain and phase are entirely different from those of envelope delay which show up as errors in the transitional regions of the picture.

In the CATV modulator the common cause of differential gain and phase is non-linearities which occur in the video amplifier and video modulator sections. Through careful design of these areas of the modulator, differential gain and phase can be kept below 1 dB and $\pm 1^{o}$ respectively at 87.5% modulation.

Phase Locking Capability

As channel space becomes more and more crowded in CATV systems, it is inevitable that there will be some programs carried on the cable system which occupy the same channel as a local transmitter. If the channel carried on the cable has originated from a modulator whose output frequency is crystal controlled, but not phase locked, there will be a slight but unavoidable frequency difference between the cable signal and the local transmitter signal. The result of this frequency difference, due to either stray pickup in the TV receiver or leakage into the cable system itself, is a co-channel interference beat. As a general rule, this interference beat is visible all the way to the Grade B contour and beyond (6). A block diagram of a modulator which has the capability of being phase locked to an off air signal is shown in Figure 1. As shown in the block diagram, a sample of the signal to which the output of the modulator is to be phase locked is converted down to the standard IF frequency in a crystal controlled oscillator. This IF picture carrier is then fed to a phase detector along with a sample of the output of the 45.75 MHz varactor turned oscillator. The output of the phase detector is a dc voltage which is proportional to phase difference between the two IF signals. This dc control voltage is then applied to the varactor diode in the 45.75 MHz oscillator. This 45.75 MHz phase locked signal is then used as the IF picture carrier in the modulator. To complete the phase locking scheme, the oscillator for the output converter must have identically the same frequency as that of the input converter and therefore a sample of the input converter oscillator is fed to the output converter to be used for up conversion. In the absence of an input signal, the 45.75 MHz oscillator becomes crystal controlled to insure against frequency drift which could cause interference in adjacent channels.

Through the technique of phase locking, this co-channel beat can be eliminated completely. The stray pickup problem will now cause a leading ghost in the received picture, but this ghosting is generally restricted to some sets within the Grade A contour (6).

Modulation Meter

Now that local origination is becoming mandatory in many CATV systems, there will be an ever increasing need for the CATV operator to be able to quickly and accurately monitor and adjust both the percent AM depth of modulation on the video carrier and the deviation in kc on the FM sound carrier. At the television broadcast stations, these are set to be 87.5% and ±25 kc respectively. In CATV modulators it is important that these modulation standards be generally adhered to, or problems can arise. If the percent AM modulation on the video carrier reaches 100% because of variations in video levels at the input to the modulator or because the video modulation control is improperly adjusted, two problems occur: first, the "light" areas of the picture merge into a "saturated white" appearance; second, because the principle of intercarrier sound used in today's television receivers require both picture and sound carriers to be present, overmodulation of the picture carrier causes buzzing in the audio. On the other extreme, modulation percentages less than 87.5 % only cause a loss of contrast at the home receiver. For this reason, it is generally recommended that the percent AM modulation on the video carrier in CATV modulators be set at approximately 80%.

As mentioned above, the deviation on the sound carrier is normally set for ± 25 kc. If this deviation is set lower there will be a loss of volume at the home receiver. On the other hand, if this deviation is set too high, not only will the volume at the set be comparatively high, but the resulting increase in the bandwith of the sound signal [B.W. $\approx$ 2(frequency deviation + highest modulating frequency)] will make it more difficult to fine tune some sets to eliminate the 920 kc beat between the sound and color signals.

In the Scientific-Atlanta modulator, the percent AM modulation on the video carrier and deviation on the FM sound carrier can be accurately adjusted and monitored, all from front panel controls. This is accomplished in the following manner. A sample of the 4.5 MHz FM subcarrier is fed to a calibrated linear discriminator. The audio out of this discriminator is then peak detected and fed to a front panel meter which is calibrated to read FM deviation directly in kilocycles. Also, a sample of the 45.75 MHz modulated IF video carrier is fed to a detector circuit which removes the video modulation present on this carrier. The amplitude of this video signal is compared in a peak detector to that of the unmodulated IF carrier. The resulting dc voltage which is a measure of the percent

AM modulation, is then applied to the front panel meter, which is calibrated to read AM modulation directly in percent.

Conclusion

In the past few years modulators have been used primarily for converting a black and white video signal to a standard televion signal. The source of this signal was usually a camera on a time and weather channel or possibly the output of a camera used for local origination. In either case it was typically a situation where a low quality modulator would not limit the quality of the signal being delivered to the customer's receiver. This is not the case today. With local origination becoming mandatory in many situations, and with color cameras becoming available with reasonable price tags, the quality of the modulator must approach that of a broadcast transmitter.

This paper has discussed several unique design approaches for a CATV modulator. Through the use of these features in the design of a modulator, some of the technical problems which could compromise the resulting quality of the customer received picture have been overcome. By incorporating these features in a modern solid state CATV modulator, it not longer will be the "weak link" in the chain of equipment from the video origination point to the customer's kinescope.

(1) Frederick E. Terman, "Electronic and Radio Engineering", Fourth Edition, pp. 204-206.

(2) FCC Rules and Regulations 73.668.

(3) John E. Allen, "Beat Between Sound Carrier and Color Signal Components in a Television Receiver", Presented at AIEE Convention, November 4, 1953.

(4) G. L. Fredenall, "Delay Equalization in Color Television", Proceedings of the IRE, January 1954, pp. 258-262.

(5) FCC Rules and Regulations 73,687.

(6) A. S. Taylor, "On-Channel Carriage of Local TV Stations on CATV", IEEE Transactions on Broadcasting, December 1969, pp. 102-104.

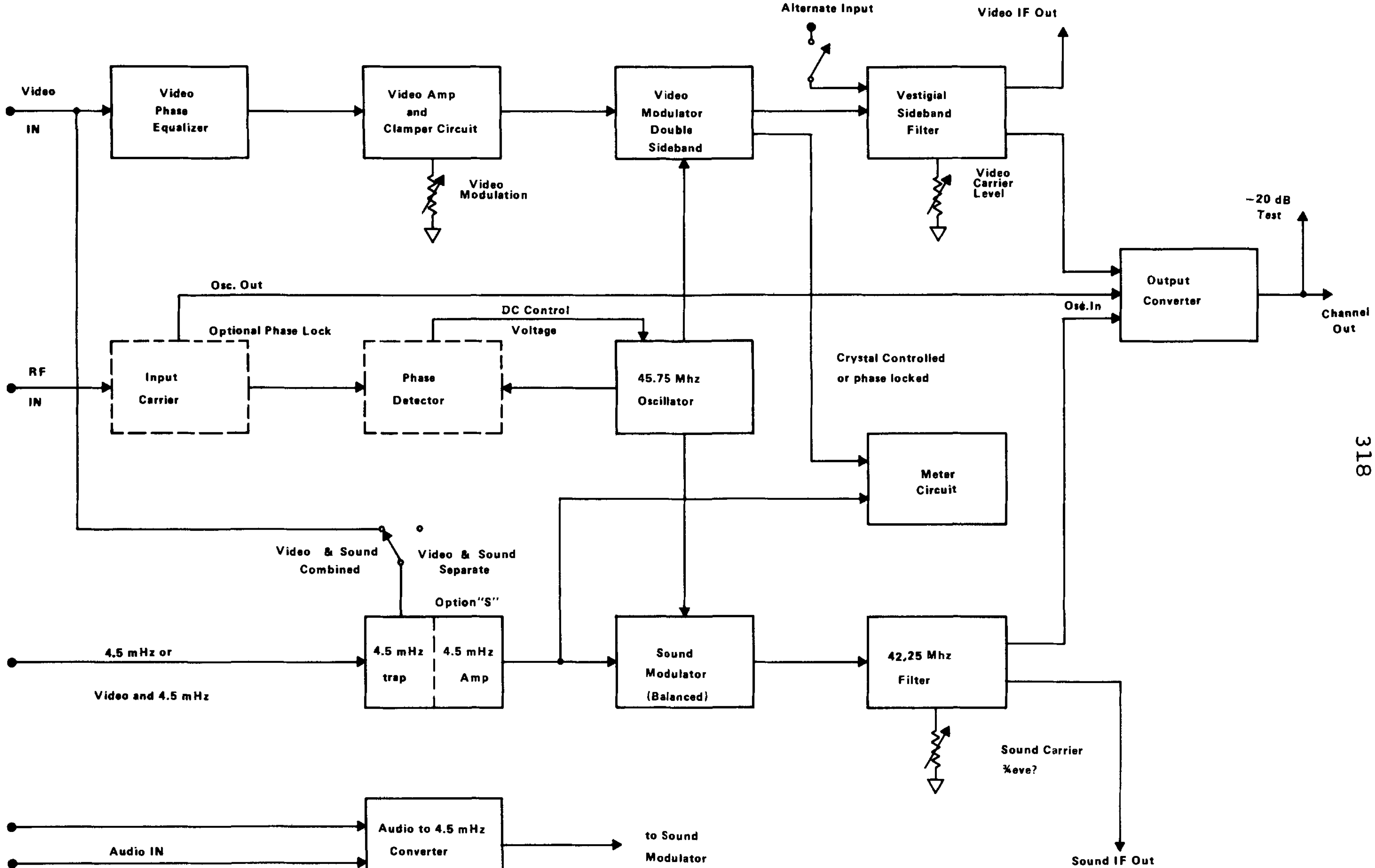
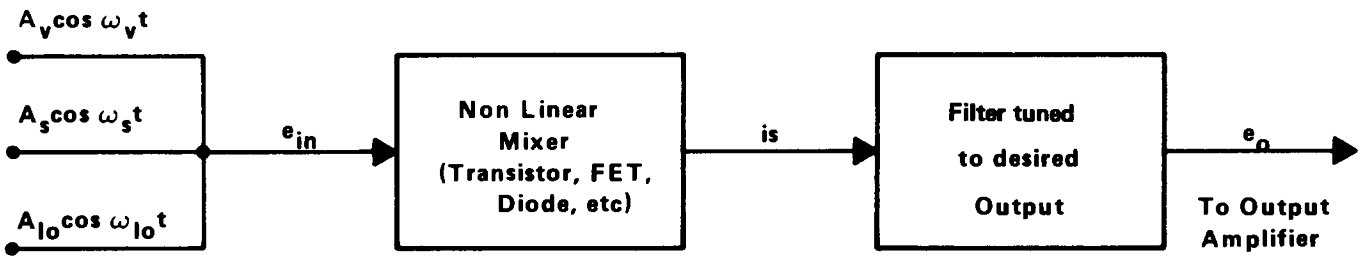


FIGURE 1

BLOCK DIAGRAM OF CATV MODULATOR

OUTPUT CONVERTER



Where $A_v \cos\omega_v t$ is the video IF signal

$A_s \cos\omega_s t$ is the sound IF signal

$A_{lo} \cos\omega_{lo} t$ is the local oscillator signal

FIGURE 2

COMMON UPCONVERSION TECHNIQUES

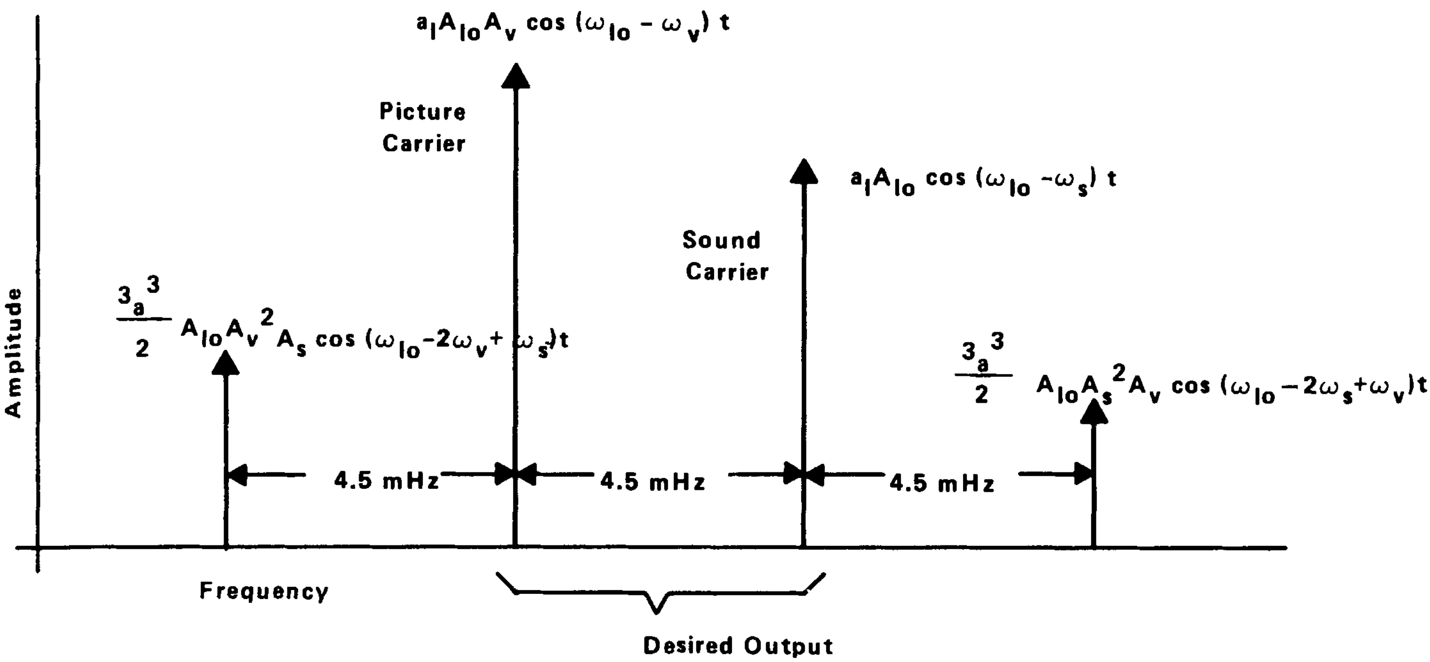
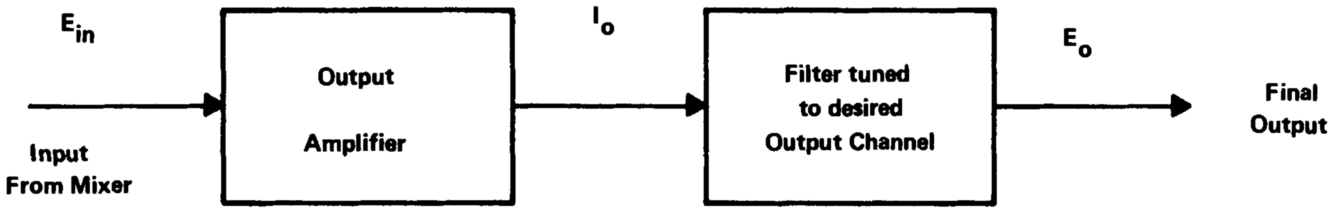


FIGURE 3

SPECTRUM OF MIXER OUTPUT e_o



$$E_{in} = a_l A_{lo} A_v \cos(\omega_{lo} - \omega_v)t + a_l A_{lo} A_s \cos(\omega_{lo} - \omega_s)t$$

and

$$I_o = A_o E_{in} + A_2 E_{in}^2 + A_2 E_{in}^3 + \ldots + A_{n-1} E_{in}^N$$

Where $f_{lo} - f_v = \dfrac{\omega_{lo} - \omega_v}{2\pi}$ = desired output picture carrier

$f_{lo} - f_s = \dfrac{\omega_{lo} - \omega_s}{2\pi}$ = desired output sound carrier

FIGURE 4

OUTPUT AMPLIFIER

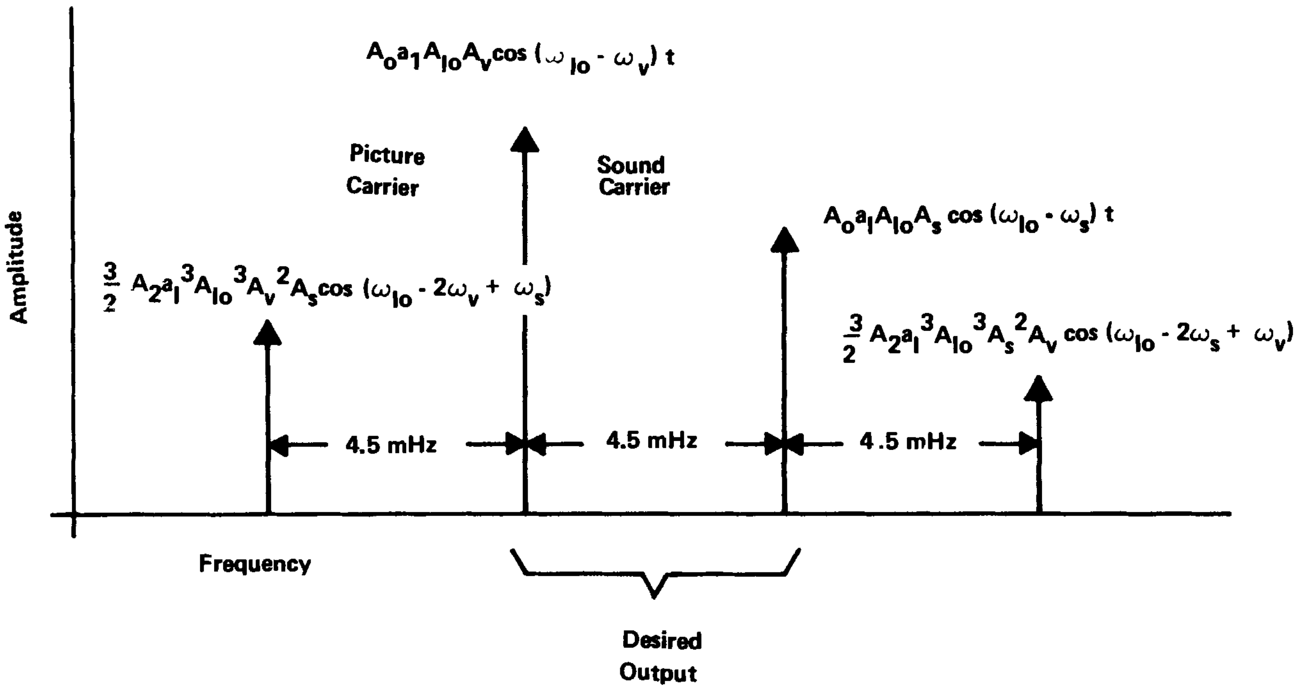


FIGURE 5

SPECTRUM OF AMPLIFIER OUTPUT E_0

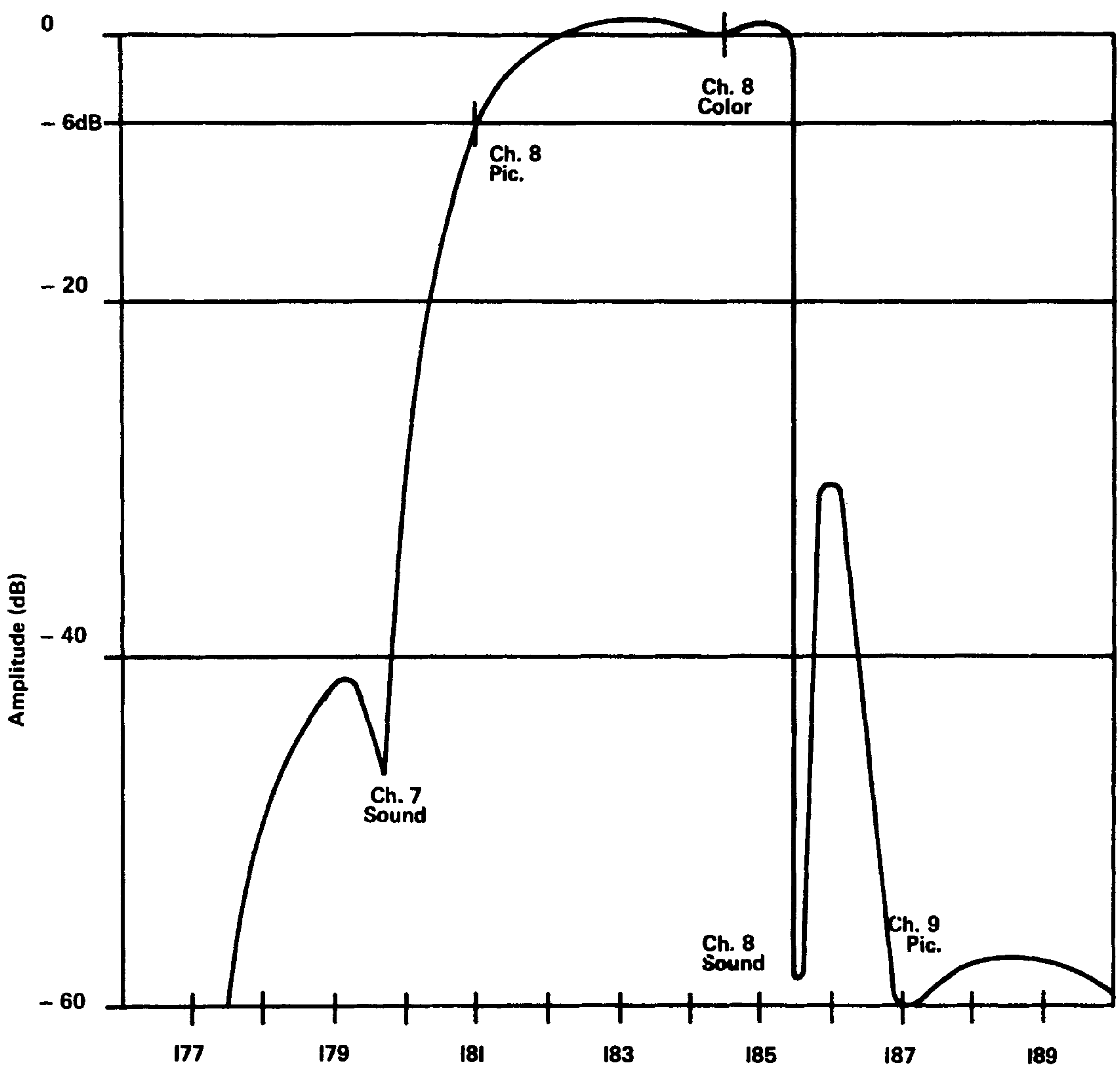


FIGURE 6

CH. 8 RECEIVER REPONSE

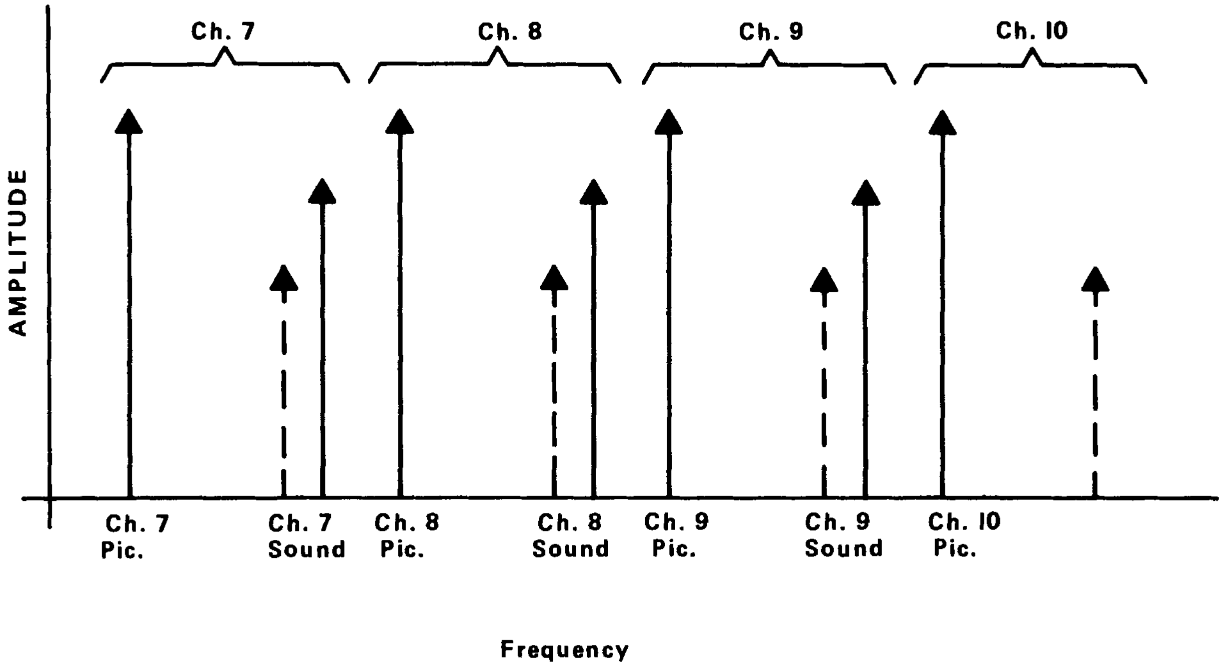


FIGURE 7

SIGNALS AT TELEVISION RECEIVER

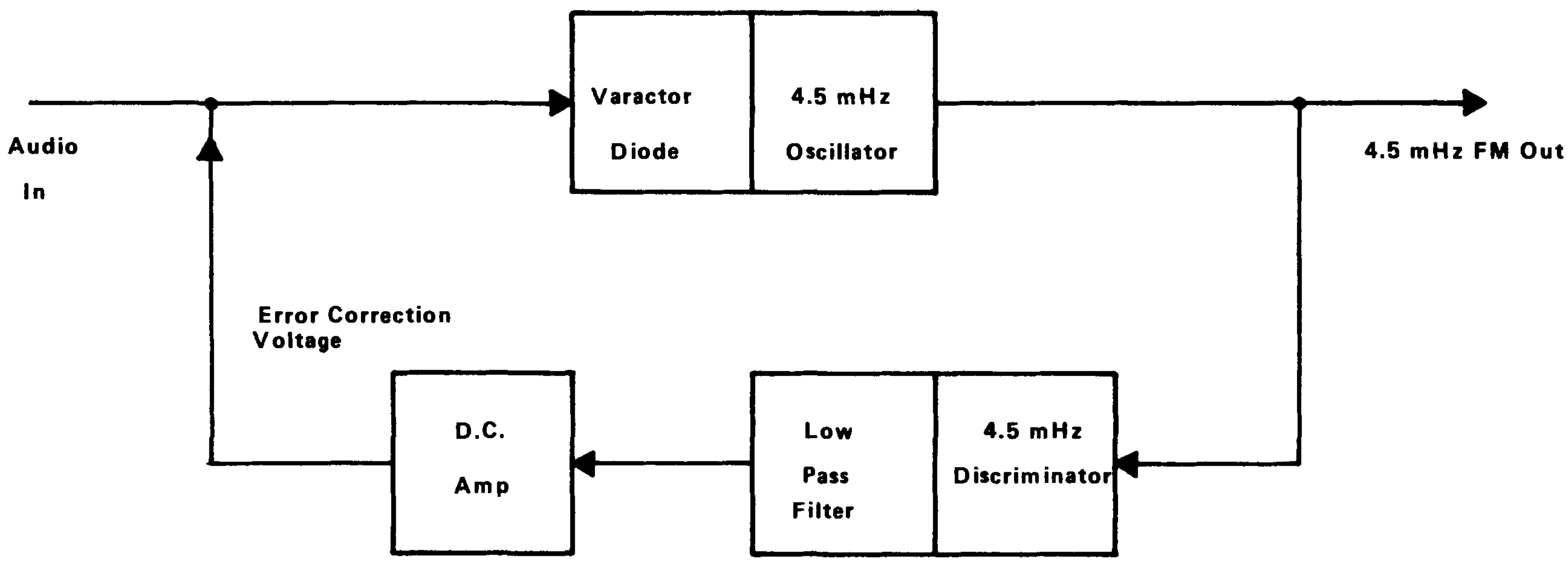


FIGURE 8

4.5 mHz SUBCARRIER CENTER FREQUENCY CONTROL

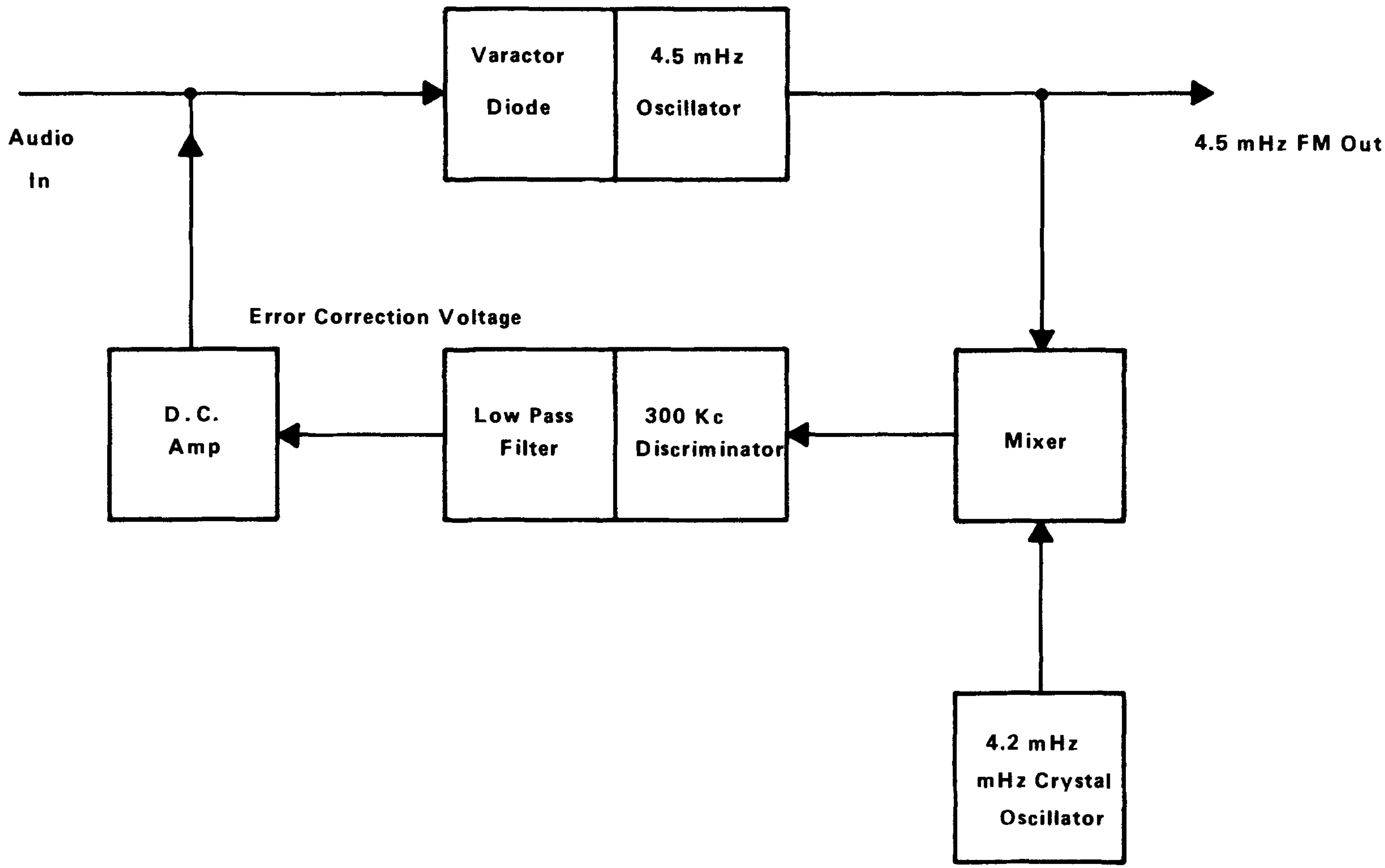


FIGURE 9

IMPROVED 4.5 mHz SUBCARRIER CENTER FREQUENCY CONTROL

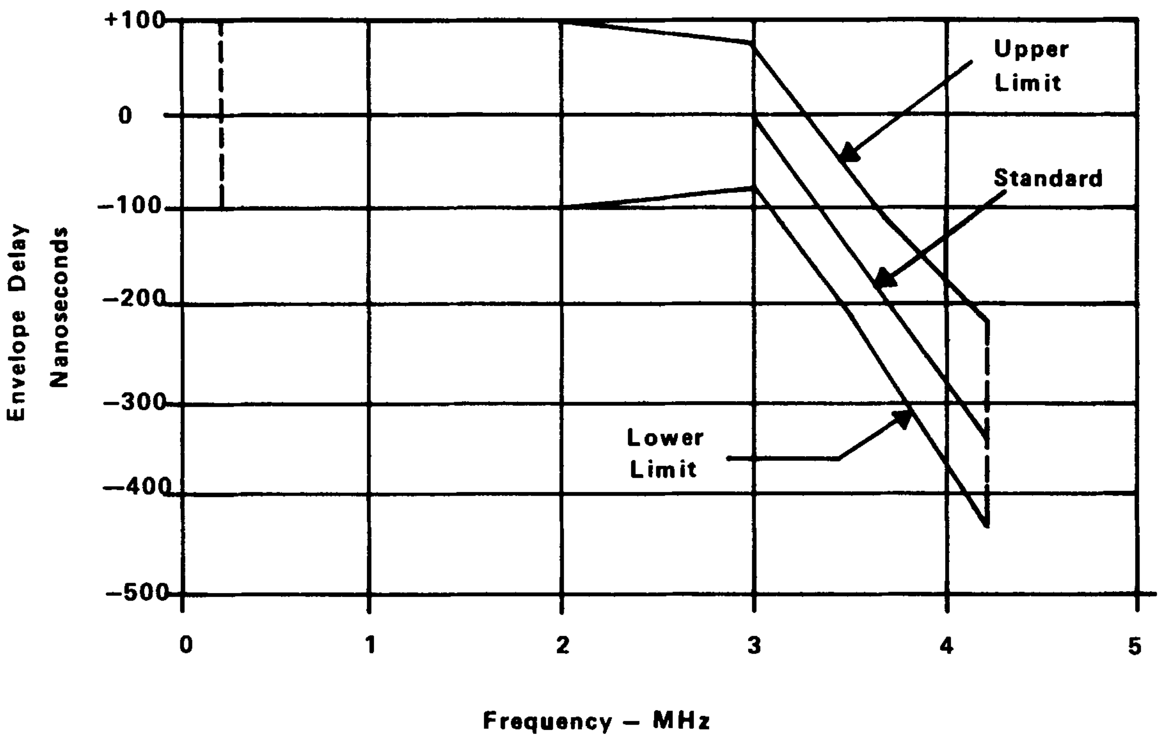


FIGURE 10

REQUIRED ENVELOPE DELAY PRE-DISTORTION AND TOLERANCES

FIGURE 11

DIFFERENTIAL GAIN AND PHASE TEST SIGNALS