A SYSTEMS APPROACH TO IMPROVING SUBCARRIER PERFORMANCE

BY:

Geoffrey N. Mendenhall, P.E.
Vice President of Engineering
Broadcast Electronics, Inc.
Quincy, Illinois

BROADCAST ELECTRONICS INC

4100 N. 24th ST., P.O. BOX 3606, QUINCY, IL 62305-3606 U.S.A., TELEX: 250142, CABLE: BROADCAST, PHONE (217) 224-9600

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BACKGROUND INFORMATION

This technical paper is oriented toward helping the radio or TV station engineer better understand how each individual element in the transmission system affects subcarrier performance. By breaking the transmission system down into its individual parts, the contribution of each sub-system can be measured and specified into an overall error budget for the complete transmission system.

The following components affect subcarrier performance through the system:

1. SCA / SAP / PRO generator.
2. Stereo generator.
3. FM exciter.
4. Composite STL (when used).
5. All transmitter RF amplifiers.
6. Antenna system (including diplexers and combiners).
7. Multipath and other propagation phenomena.
8. Receiving antenna, IF passband, and demodulators.

This paper will concentrate on the components which are part of the transmission system.

Topics covered in this presentation are:

1. Basic theory of subcarrier transmission.

2. Spurious frequency components interfering with the subcarrier spectrum.
3. Stereo generator effects.
4. Baseband and STL requirements.
5. Effects of composite baseband processing.
6. FM modulator linearity requirements.
7. FM / Aural power amplifier bandwidth requirements.
8. Optimization of power amplifier tuning.
9. System test procedure and setup.
10. Subcarrier receiver characteristics.

The information in this paper is equally applicable to FM broadcast subcarriers or TV-MTS subcarriers.

INTRODUCTION

The recent de-regulation of broadcast subcarrier usage has spurred a new interest in using subcarriers for data transmission and paging services in addition to the more conventional audio services. FM and TV broadcast stations are permitted to "piggy-back" up to two additional audio or data channels on the main carrier of the station. Subcarriers added to FM broadcast stations are Subsidiary Communications Authorizations (SCA) while subcarriers added to a TV stations's aural carrier can be either a Secondary Audio Program (SAP) or a non-public channel for Professional use (PRO).

HOW SUBCARRIERS ARE ADDED TO THE BROADCAST SIGNAL

Subcarriers are added to the main broadcast FM or TV aural carrier by a technique called frequency domain multiplexing, which allows the additional subchannels to be separated from each other and from the main channel by use of specific frequency bands for each subchannel.

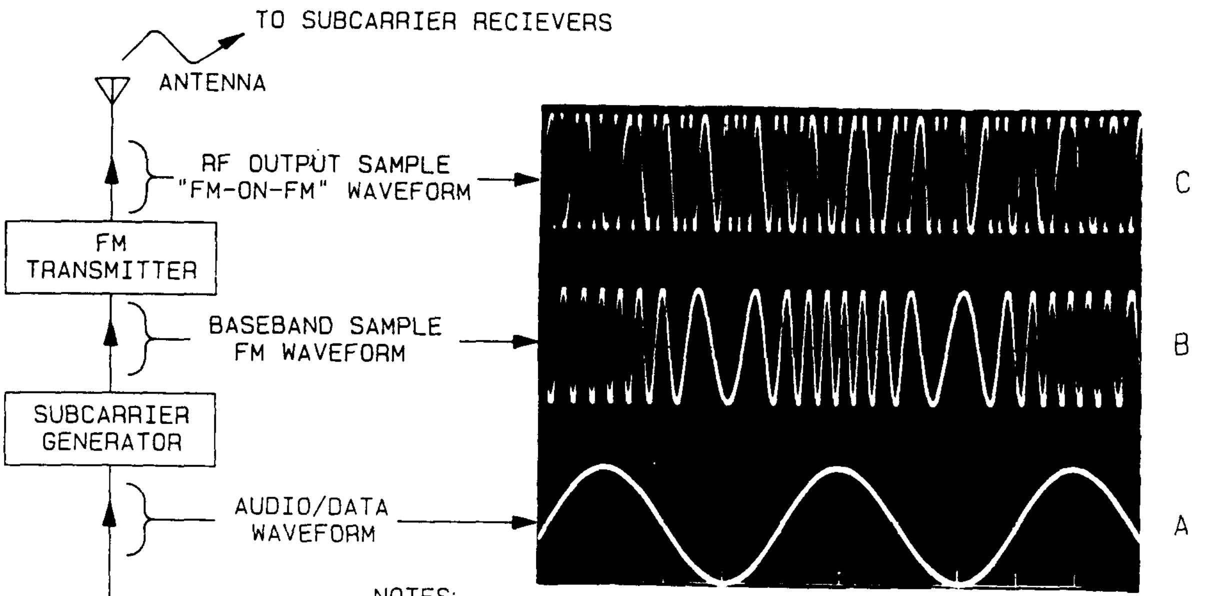
In the case of an FM station broadcasting in stereo with two subcarriers, the frequencies typically used are 67 kHz and 92 kHz for the two subcarriers. The main channel and stereophonic information are transmitted in the frequency band extending from 30 Hz to 53 kHz while the subcarrier information is transmitted above this frequency range in a band extending from 54 kHz to 99 kHz. The subcarriers each modulate the main FM carrier by a maximum of 10% of the total modulation or about 20 dB below main program levels. This means that the effective coverage of each subcarrier will not be as great as the main channel since the subcarrier does not have the full use of the transmitted power. The sum of all the different components being transmitted is called the composite baseband.

Each subcarrier is frequency modulated, which in turn, then frequency modulates the main transmitter carrier. This type of "FM on FM" system is not easy to analyze and fully understand. For example, the main carrier is typically deviating a constant plus and minus 7.5 kHz (10% of the total carrier deviation) by a subcarrier while the subcarrier's frequency is itself being deviated up to plus and minus 6 kHz by the audio or data being fed into the subcarrier modulator. Figure-1 depicts the "FM-ON-FM" system used for subcarrier transmission.

The key points to remember are that the deviation of the main carrier is dependent only on the level of the subcarrier and is not effected by the modulation applied to the subcarrier while the deviation of the subcarrier is dependent only on the modulation applied to the subcarrier and is not related to main channel deviation.

TRANSMITTING THE SUBCARRIER

The subcarrier is added to the broadcast signal by connecting a subcarrier generator to the FM (aural) exciter located in the broadcast transmitter. The subcarrier generator accepts audio and/or DC coupled data inputs and provides a frequency modulated subcarrier at its output.



NOTES:
AMPLITUDE OF "A" AFFECTS FREQUENCY DEVIATION OF "B"
AMPLITUDE OF "B" AFFECTS FREQUENCY DEVIATION OF "C"
AMPLITUDE OF "A" DOES NOT AFFECT AMPLITUDE OF "B"
AMPLITUDE OF "A" DOES NOT AFFECT FREQUENCY DEVIATION OF "C"

FIGURE 1. "FM-ON'FM"

This generator may also have additional features which allow automatic muting of the subcarrier transmission under certain conditions, multiple audio/ data inputs, active filtering of the inputs, and modulation indicators. Since the subcarrier generator is located at the broadcast transmitter, it is usually supplied by the broadcaster. The FM exciter must have a wideband input to accept the subcarrier and add it to the rest of the baseband for FM modulation onto the main radio frequency carrier.

COMPATIBILITY OF SUBCARRIERS WITH STEREO CHANNEL

The center frequency and modulation index of each FM subcarrier must be selected and controlled so that the occupied bandwidths of the subcarriers do not interfere with the stereo subchannel which extends to 53 kHz in the FM stereo system (47 kHz in TV-MTS) or with each other. Figure-2 illustrates the frequency spectrum allocations for the various components within the composite baseband of an FM broadcast station.

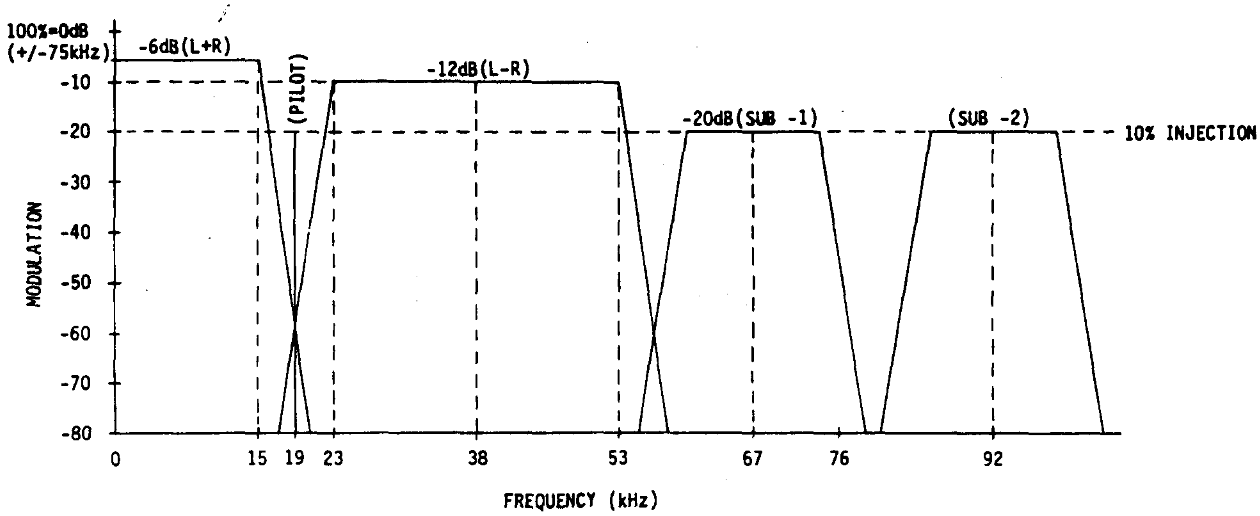


FIGURE 2. BASEBAND SPECTRUM ALLOCATIONS

The modulation index is usually controlled by restricting the audio or data input bandwidth to the subcarrier modulator with a low pass filter. The lower sidebands of the subcarrier are thereby restricted from extending down into the stereo subchannel where crosstalk from the subcarrier into the stereo channel would otherwise occur. In some cases the modulated subcarrier is fed through a bandpass filter to further restrict its occupied bandwidth. The use of a subcarrier bandpass filter after FM modulation introduces harmonic and intermodulation distortion to the subcarrier information in addition to affecting its amplitude and phase response. The use of a lowpass filter before modulation changes only the amplitude and phase response of the subcarrier information near the filter cut-off frequency. A properly designed subcarrier generator should provide adequate protection to the stereo subchannel using only lowpass filtering before the subcarrier modulator.

CROSSTALK INTO THE SUBCARRIERS

Just as the subcarrier sidebands must be prevented from extending down into the stereo subchannel, the stereo subchannel sidebands and their harmonics must be prevented from extending up into the spectrum allocated to the subcarriers where crosstalk into the subcarriers will take place. Minimization of crosstalk from the main and stereo subchannels into the subcarriers requires careful attention to the stereo encoding process, handling of the composite baseband, FM modulator linearity, and RF transmission bandwidth.

STEREO GENERATOR PERFORMANCE REQUIREMENTS

The stereo generator's characteristics play an important role in preventing interference to the subcarrier.

AUDIO INPUT FILTERING

Audio lowpass filters before the stereo modulator are necessary in all stereo generators. These sharp cut-off filters protect the mono subchannel, pilot, and stereo subchannel from spilling into each other by greatly attenuating audio components above 15 kHz. Audio input lowpass filters also restrict the upper sidebands of the stereo subchannel from extending up into the subcarrier frequency spectrum and are essential to preventing crosstalk into the subcarriers. If the pilot level is observed to be fluctuating on the stereo modulation monitor during modulation, the audio input filtering may be inadequate. Audio lowpass filters with delay equalization will keep overshoot to a minimum, while providing adequate protection to the pilot, stereophonic subchannel, and any additional subcarriers.

STEREO SUBCHANNEL MODULATOR

The second harmonic components of the stereophonic subchannel may fall directly on top of the subcarrier, so it is important to use a stereo generator that suppresses these undesirable components. The stereo generator must have good 38 kHz (2 f_H for TV) subcarrier suppression with modulation applied. Excessive 38 kHz leakage may cause additional 76 kHz regeneration in the system. The stereo generator must also have good 76 kHz (second harmonic) suppression. The second harmonic modulation sidebands should be attenuated as well, because they add crosstalk into the subcarriers. If crosstalk into a subcarrier operating at 20 dB below 100% modulation is to be 50 dB or better, the stereophonic subchannel harmonics must be suppressed by at least -70 dB allowing for some degradation through the entire system.

Manufacturers of stereo generators have traditionally chosen either linear or switching modulators. The linear modulators use balanced analog circuits that may require periodic adjustment of 38 kHz and 76 kHz null controls. These adjustments should be maintained if excessive 76 kHz becomes evident during spectrum analysis of the composite baseband. The switching modulator is popular because of better long-term stability. The modulator switching waveform requires filtering with a sharp cut-off 53 kHz linear-phase low-pass filter. This filter is a major design problem, because the passband amplitude ripple and phase non-linearities cause degraded high frequency stereo separation by adversely affecting the upper sideband of the L-R subchannel. A third type of stereo generator shown in Figure-3 uses a digital stairstep generator to synthesize the subcarrier and pilot simultaneously, eliminating any pilot phase variation. Digital synthesis produces an approximation to a sinewave with low harmonic content throughout the frequency range of interest. The composite lowpass filter only needs to provide a gradual rolloff beyond 100 kHz.

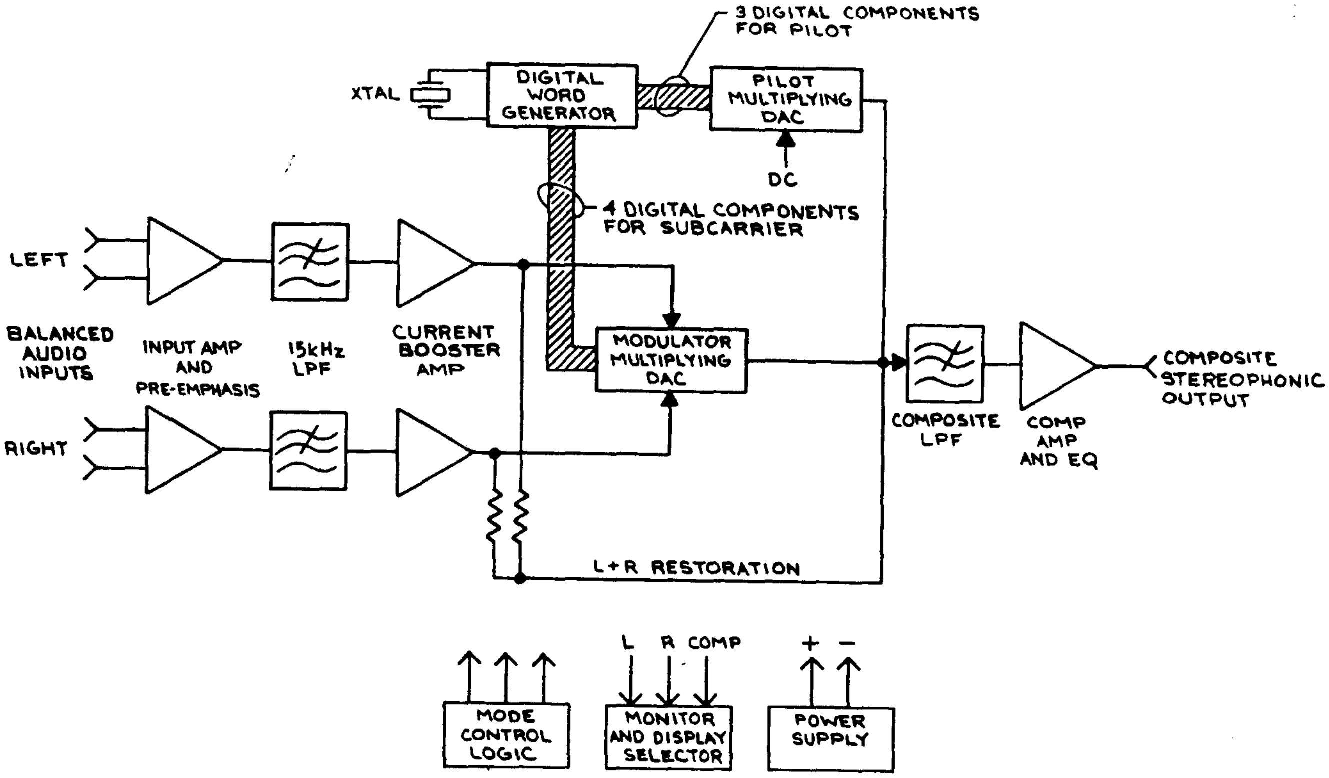


FIGURE 3. SIMPLIFIED BLOCK DIAGRAM OF FS-30 STEREO GENERATOR

Stereo separation is still better than 50 dB at 15 kHz while suppression of harmonic and spurious components that would ordinarily interfere with the subcarriers is better than other types of stereo generators. Second harmonic sidebands, pilot harmonics, and spurious products in the subcarrier spectrum are 80 dB below 100% modulation reducing crosstalk into the subcarriers by as much as 20 dB.

COMPOSITE STUDIO TO TRANSMITTER LINKS

The composite STL is really a transmission sub-system within a system. STL transmitter requirements are identical to those of the FM exciter. Since the STL has its own modulated oscillator, the same modulator linearity considerations that apply to FM exciters also apply to the STL transmitter.

The IF bandwidth and demodulator characteristics of the STL receiver will also affect subcarrier crosstalk. If possible, is recommended that all subcarriers be fed directly into the FM exciter at the transmitter. Telephone lines or other narrowband radio links (including separate high frequency STL subcarriers above 100 kHz) can usually handle the program bandwidths used to feed the subcarrier generators. This technique reduces the burden of maintaining very low intermodulation performance through the entire STL modulation/demodulation process.

Distortion of the composite baseband signal can also be caused by harmonic (THD), steady state intermodulation (IMD), and transient intermodulation (TIM) distortion within any composite amplifier stages. These types of distortion have the greatest effect on subcarriers because the resulting harmonic and intermodulation products interfere with the subcarriers. The composite amplifiers must have sufficient feedback bandwidth to accept baseband frequencies to 100 kHz and should slew symmetrically to minimize slew-induced distortion. The TIM performance becomes largely a matter of operational amplifier selection and circuit configuration.

Although flat composite amplitude and phase response is very critical to maintaining stereo separation, subcarriers are not affected by moderate ripple in the amplitude and phase response. This is because the information in the subcarriers is transmitted in a relatively narrow bandwidth and is not time dependent on the main channel.

COMPOSITE BASEBAND PROCESSING

In an effort to achieve maximum modulation density (loudness), some FM broadcasters use composite processing (after the stereo generator and STL) to remove the low energy overshoots in the amplitude of the composite waveform caused by complex audio input filtering.

Overshoots have no effect on any audio performance parameter other than achieving the last dB in loudness. Composite processing is not recommended for use with subcarriers. The use of any non-linear devices, such as clippers or limiters in the composite line will alter not only the peak amplitude of the baseband, but also the frequency spectrum of the baseband. This generates several types of distortion at the stereo receiver and increases crosstalk into the subcarriers. Figure-4A and Figure-4B show the waveform and spectrum of unprocessed baseband while Figure-4C and Figure-4D show the same waveform and spectrum after 1.25 dB of composite clipping. Figure-4D shows harmonic and intermodulation products filling the spectrum reserved for the subcarriers. Also note that during clipping the stereo pilot has been stripped from the composite waveform.

Effects of Composite Processing on Subcarriers.

1. Intermodulation of all baseband frequency components causing extraneous spectral components which interfere with the subcarriers.

2. Harmonic distortion of baseband causing re-generation of stereo subchannel second harmonic sidebands with resulting degradation of crosstalk.

3. Generation of harmonics of the pilot causing interference to subcarriers.

The received stereo audio is high in intermodulation distortion and non-correlated information due to aliasing of the extraneous spectral components added by composite processing. Crosstalk and interference to the subcarriers has also increased due to composite processing. If minimum crosstalk into the subcarriers is the goal, composite processing should not be used. Audio processing should be performed before the audio is multiplexed into baseband.

BASEBAND WITHOUT CLIPPING

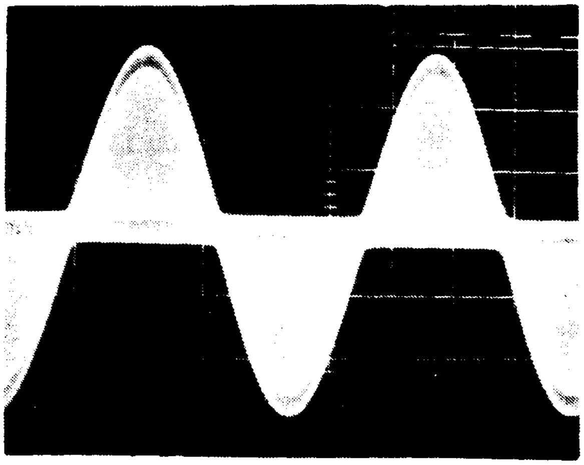


Figure 4A

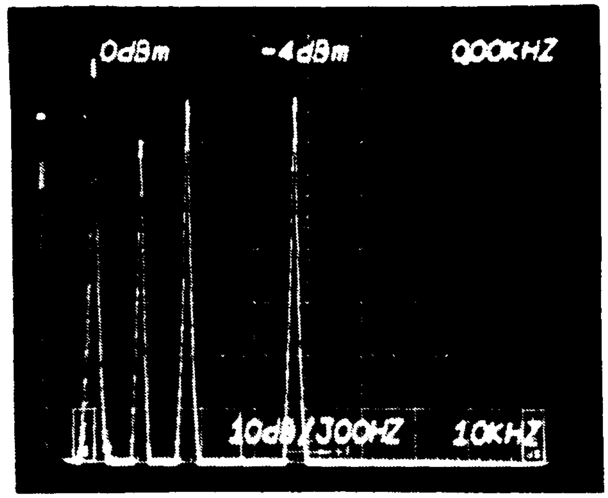


Figure 4B

(OUTPUT FROM BEI FS-30 STEREO GENERATOR
ONE CHANNEL ONLY MODULATED @ 10KHz)

BASEBAND AFTER 1.25dB COMPOSITE CLIPPING

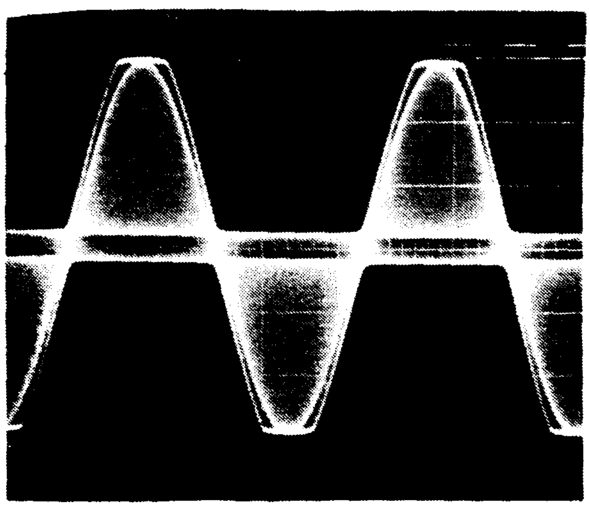


Figure 4C

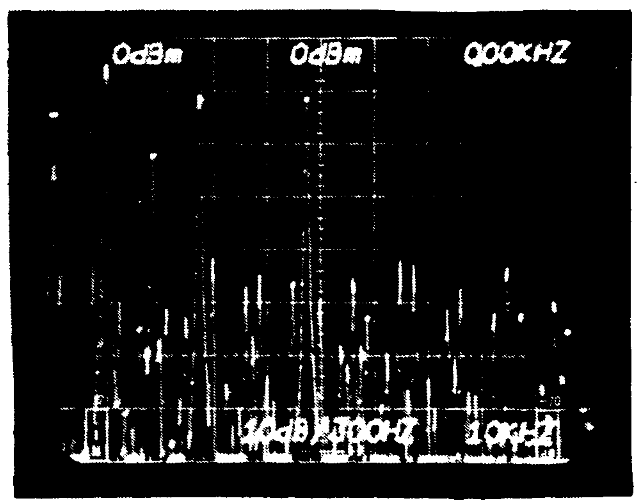


Figure 4D

(OUTPUT FROM BEI FS-30 STEREO GENERATOR FOLLOWED BY 1.25dB
OF COMPOSITE CLIPPING-ONE CHANNEL ONLY MODULATED @ 10KHz)

FM EXCITER PERFORMANCE REQUIREMENTS

The exciter characteristics are important for good subcarrier performance. The composite baseband signal is translated onto a frequency modulated carrier by the modulated oscillator. Frequency modulation is produced by applying the composite baseband signal to a voltage tunable RF oscillator. The modulated oscillator usually operates at the carrier frequency and is voltage tuned by varactor diodes, operating in an LC circuit.

To have perfect modulation linearity, the RF output frequency must change in direct proportion to the composite modulating voltage applied to the varactor diodes. This requirement implies that the capacitance of the varactor diodes must change as nearly the square of the modulating voltage. Unfortunately, the voltage versus capacitance characteristic of practical varactor diodes is not the desired square law relationship. All varactor-tuned oscillators have an inherently non-linear modulating characteristic. This non-linearity is very predictable and repeatable for a given circuit configuration, making correction by complementary predistortion of the modulating signal feasible. Suitable predistortion can be applied by using a piece-wise linear approximation to the desired complementary transfer function. The predistortion network is cascaded with a non-linear voltage-tuned oscillator to produce a linearized FM modulator.

Non-linearities in the FM oscillator can, by altering the waveform of the baseband signal, create distortion in the demodulated output at the receiver. Any distortion of the baseband signal caused by the modulated oscillator will have secondary effects on stereo and subcarrier crosstalk, which are quite noticeable at the receiver in spite of the rather small amounts of distortion to the baseband. For example, if the harmonic distortion to the baseband is increased from 0.05% to 1.0%, as much as 26 dB additional crosstalk into the subcarrier can be expected.

For illustrative purposes, Figure-5A, 5B, and 5C give representations of the fundamental and second order terms in the composite baseband spectrum with increasing amounts of harmonic distortion in the modulated oscillator. Figure-5B shows this spectrum after 0.05% harmonic distortion has been added to each component. Note that the second order stereo (L-R) sidebands are 78 dB below 100% modulation or about 58 dB below a 67 kHz SCA subcarrier with a 10% (-20 dB) injection level. With normal energy distributions in L-R and the subcarrier, crosstalk from stereo into the SCA will be more than 60 dB below the SCA subcarrier. Figure-5C shows the same baseband spectrum with 1.0% harmonic distortion. The second order stereo sidebands are only 32 dB below the subcarrier.

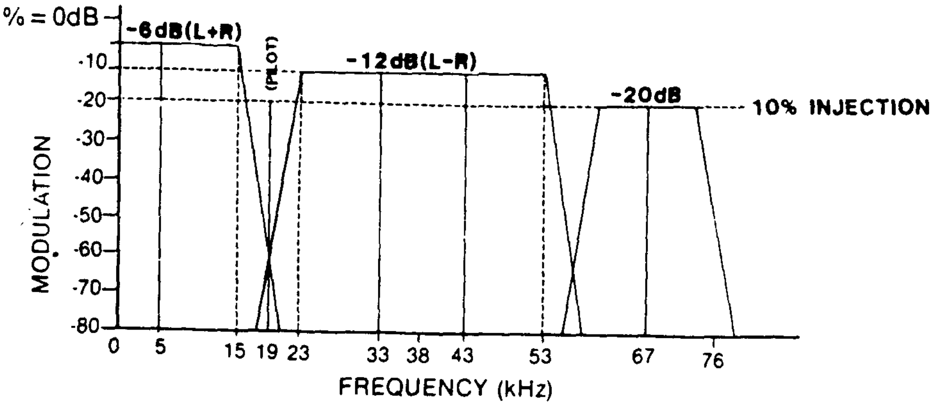
Crosstalk may now increase as much as 26 dB, depending on the respective energy distributions in (L-R) and the SCA subcarrier. Modulator linearization using a piecewise approximation pre-distortion network has reduced harmonic and intermodulation distortion to less than 0.05% in state of the art equipment. TIM distortion is usually not a factor in varactor tuned modulated oscillators. The modulation bandwidth capability is generally more than ten times the composite bandwidth and no negative feedback is used to maintain linearity.

Assuring that the composite baseband signal undergoes minimal distortion in the modulation process will suppress undesired harmonic and intermodulation products in the baseband, making the FM exciter transparent to the signals coupled into it.

THE RF PATH

The FM modulator converts the composite baseband signal into the frequency modulated RF signal containing a complex array of sidebands. The amplitude and phase of the FM sidebands are determined by the modulation index, while the frequencies of the sidebands are determined by the modulating frequencies.

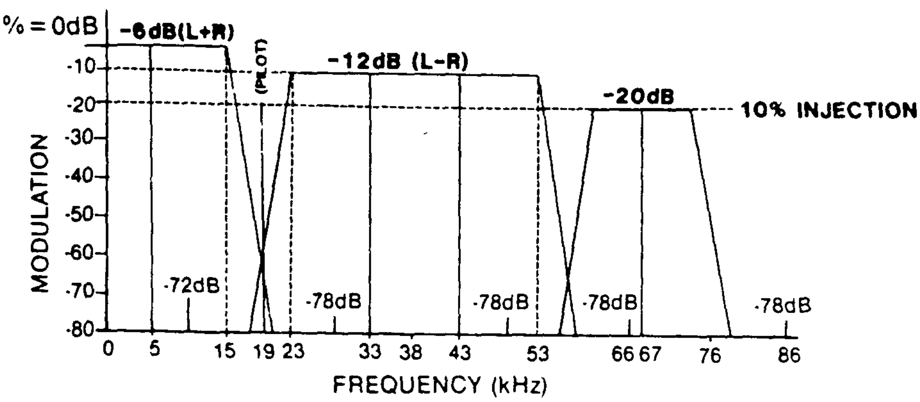
FIGURE 5A.



L OR R ONLY MODULATED 100% @ 5 kHz. UNMODULATED SCA @ 10% INJECTION

Ideal demodulated composite baseband spectrum with no modulator distortion.

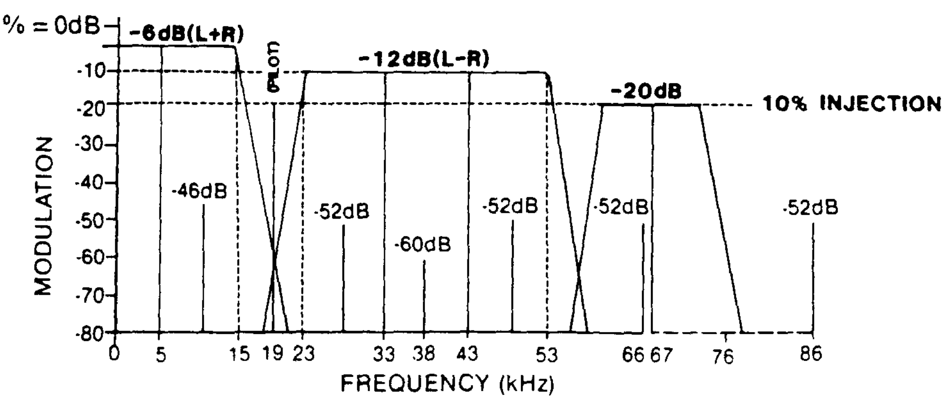
FIGURE 5B.



L OR R ONLY MODULATED 100% @ 5 kHz. UNMODULATED SCA @ 10% INJECTION.
INTERFERING SECOND HARMONIC STEREO SIDEBANDS ARE 58 dB BELOW SCA.
ONLY FUNDAMENTAL AND SECOND HARMONIC TERMS ARE SHOWN.

Demodulated composite baseband spectrum with 0.05% harmonic distortion in modulator.

FIGURE 5C.



L OR R ONLY MODULATED 100% @ 5 kHz. UNMODULATED SCA @ 10% INJECTION.
INTERFERING SECOND HARMONIC STEREO SIDEBANDS ARE 32 dB BELOW SCA.
ONLY FUNDAMENTAL AND SECOND HARMONIC TERMS ARE SHOWN.

Demodulated composite baseband spectrum with 1.0 % harmonic distortion in modulator.

The remainder of the FM transmitter consists of a chain of power amplifiers, each having from 6 to 20 dB of power gain. Ideally, the transmitter should have as wide a bandwidth as practical with a minimum of tuned stages. Broadband solid-state amplifiers are preferred to eliminate tuned networks in the RF path. Tuned output bandpass filters may still be necessary when broadband amplifiers are operated in a dense RF environment to prevent RF intermodulation products from being generated within the amplifier output stage. Higher powered transmitters in the multi-kilowatt range may use a single tube PA stage with high efficiency. The dollars/watt economics of single-tube transmitters outweigh the bandwidth benefits of solid-state transmitters at the higher power levels with present technology. Design improvements in tube-type power amplifiers have concentrated on improving bandwidth, reliability, and cost effectiveness.

THE FM SIDEBAND STRUCTURE

The frequency modulated RF output spectrum contains many sideband frequency components, theoretically an infinite number. They consist of pairs of sideband components spaced from the carrier frequency by multiples of the modulating frequency. The total transmitter RF output power remains constant with modulation, but the distribution of that power into the sidebands varies with the modulation index so that power at the carrier frequency is reduced by the amount of power added to the sidebands.

OCCUPIED BANDWIDTH

The occupied bandwidth of an FM signal is far greater than the amount of deviation from the carrier that one might incorrectly assume as the bandwidth. In fact, the occupied bandwidth is infinite if all the sidebands are taken into account, so that a frequency modulation system requires the transmission of all of these sidebands for perfect demodulation of information.

In practice, a signal of acceptable quality can be transmitted in a limited bandwidth, by allowing truncation of the insignificant sidebands (typically less than 1 percent of the carrier level) and accepting a certain degree of signal degradation. Design considerations in the transmitter RF circuitry make it necessary to restrict the RF bandwidth to less than infinity. As a result, the higher order sidebands will be altered in amplitude and phase. Bandwidth limitation will add to the distortion in any FM system. The amount of distortion in any practical FM system will depend on the amount of bandwidth available versus the modulation index being transmitted.

Consider the system shown in Figure-6A, where a perfect FM modulator is connected to a perfect demodulator via an RF path of infinite bandwidth. The demodulated baseband shown in Figure-6C contains no distortion components.

Figure-6B shows the effects of an RF bandpass filter on the RF spectrum of composite baseband consisting of stereophonic baseband modulated at 4.5 kHz only on one channel along with an unmodulated 67 kHz SCA subcarrier. The only distortion evident on the RF spectrogram is the attenuation of sidebands greater than 200 kHz from the center frequency and the amplitude differences between the lower and upper sideband pairs. Figure-6D shows the corresponding effects observed on the demodulated baseband spectrum for the same signal. Note the creation of many undesired intermodulation terms which will cause crosstalk into subcarrier bands.

As you can clearly see, the distortion in this FM system does depend on the amount of bandwidth available versus the modulation index being transmitted.

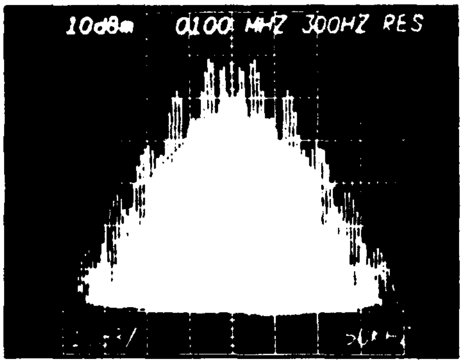


FIGURE 6A.
WIDEBAND RF SPECTRUM TO DEMODULATOR

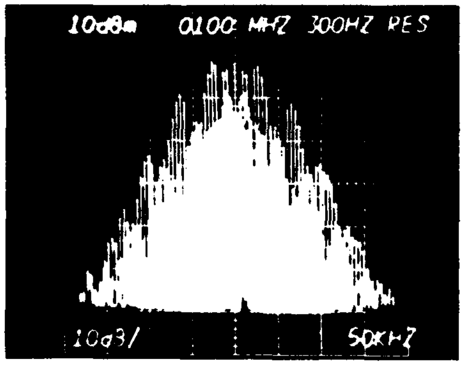


FIGURE 6B.
BANDWIDTH LIMITED RF SPECTRUM TO DEMODULATOR

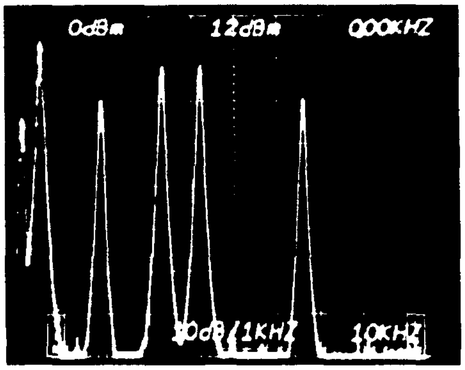


FIGURE 6C.
DEMODULATED BASEBAND SPECTRUM FOR WIDEBAND RF SPECTRUM

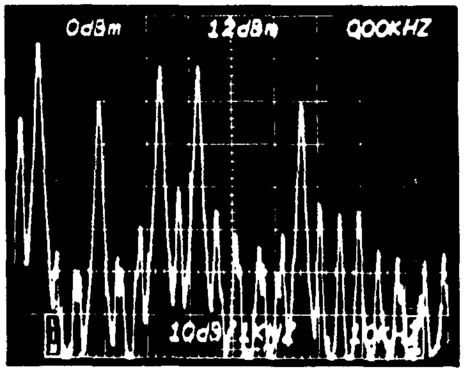


FIGURE 6D.
DEMODULATED BASEBAND SPECTRUM FOR BANDWIDTH LIMITED RF SPECTRUM SHOWING DISTORTION PRODUCTS

LIMITING FACTORS WITHIN THE FM TRANSMITTER

Relating the specific quantitative effect of the bandwidth limitations imposed by a particular transmitter to the actual interference to the subcarriers is a complicated problem indeed.

Some of the factors involved are:

1. Total number of tuned circuits.
2. Amplitude and phase response of the total combination of tuned circuits in the RF path.
3. Amount of drive (saturation effects) to each amplifier stage.
4. Non-linear transfer function within each amplifier stage.

The degree of bandwidth reduction is a design constraint which affects the gain and efficiency in all tuned PA stages. The bandwidth of an amplifier is determined by the load resistance across the tuned circuit and the output or input capacitance of the amplifier. The high input capacitance of a grid-driven final power amplifier is usually the limiting factor for the entire transmitter. As a result, the input tuning to final amplifier usually has a greater effect on subcarrier performance than the output tuning. Bandwidth limitations in a grid-driven PA can be partially overcome by resistive swamping in the input circuit and by utilizing a broadband input impedance matching device to achieve optimum transfer of power from the driver stage into the PA.

BROADBAND IMPEDANCE MATCHING

A broadband impedance matching circuit has been developed to match the high grid input (parallel) impedance of a tetrode RF power amplifier to the 50 Ohm impedance of a solid-state driver. Conventional L, PI, or T network matching circuits are normally used for this purpose. All of these circuits require interactive adjustment of one or more circuit elements to provide a satisfactory impedance match at each frequency and RF power level. The newly developed broadband impedance-matching circuit(*) consists of a combination of series inductor (L) and shunt capacitor (C) circuit elements, implemented as a printed circuit with inductors and capacitors etched into a copper-clad laminate. Multiple LC sections match the 50 Ohm source impedance to the high input impedance of the grid-driven RF power amplifier over a wide bandwidth by making the required transformation in a series of many small steps. This device is shown in Figure 7A and B. (*) PATENTED BY BROADCAST ELECTRONICS.

The broadband impedance matching circuit improves transmitter operation and stability, compared to previous methods. A single tuning control in the input circuit is sufficient to tune and match the 50 Ohm driver impedance to the high input impedance of the grid over the 88-108 MHz FM broadcast band with a 4:1 range in RF power level.

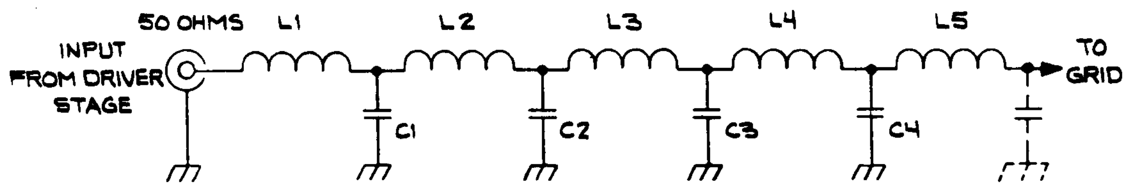


FIGURE 7A. CIRCUIT DIAGRAM OF PA INPUT IMPEDANCE MATCHING DEVICE

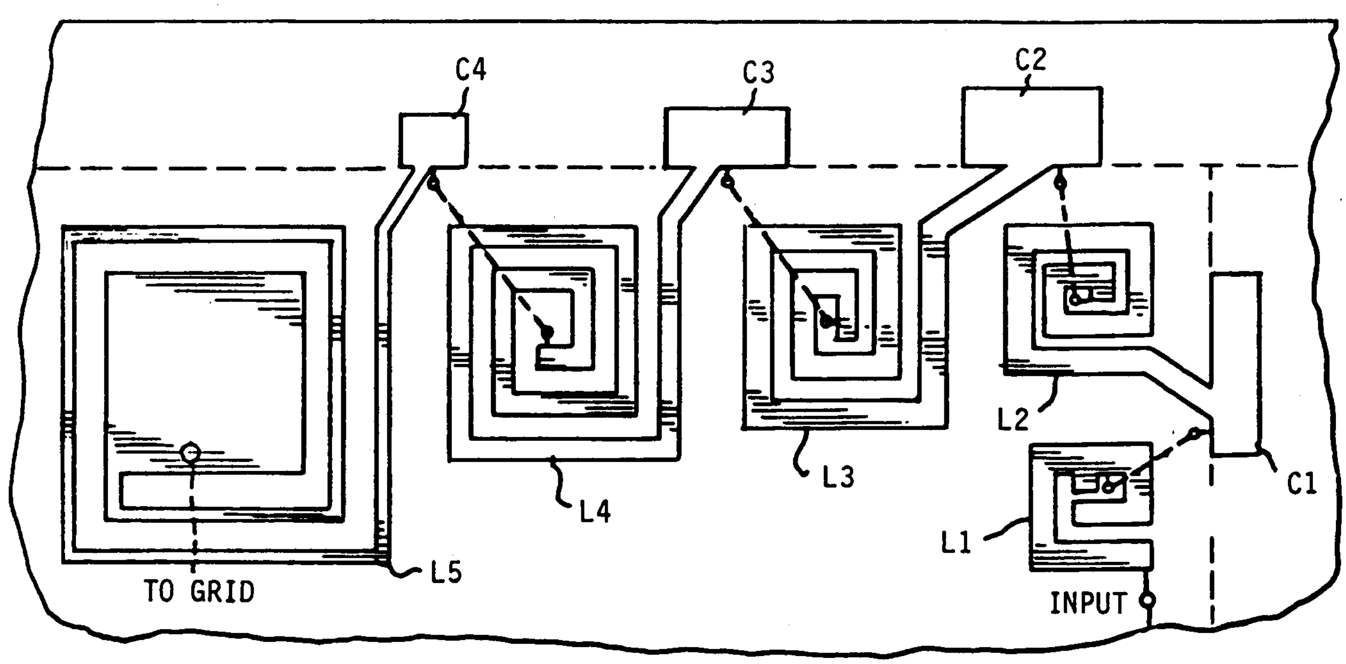


FIGURE 7B. INPUT MATCHING DEVICE

IMPROVEMENT OF THE RF PATH

Some RF bandwidth related factors which will improve subcarrier performance are:

1. Maximize bandwidth by using a broadband exciter and a broadband IPA stage.
2. Use a transmitter of single tube design or broadband solid state design where feasible.
3. Minimize the number of interactive tuned networks.
4. Optimize both the input circuit and plate circuit tuning for best possible bandwidth.
5. Use a broadband antenna system with low standing wave ratio on the transmission line.

ADJUSTING THE TRANSMITTER

All optimization should be done with the transmitter connected to the normal antenna system. The transmitter is first tuned for normal output power and proper efficiency according to the manufacturer's instruction manual. The meter readings should closely agree with those listed on the manufacturer's final test data sheet.

A simple method for centering the transmitter passband on the carrier frequency involves adjustment for minimum synchronous AM. Synchronous AM is a measure of the amount of incidental amplitude modulation introduced onto the carrier by the presence of FM modulation. This measurement is very useful for determining the proper tuning of the transmitter. Since all transmitters have limited bandwidth, there will be a slight drop-off in power output as the carrier frequency is swept to either side of the center frequency. This slight change in RF output level follows the waveform of the signal being applied to the FM modulator causing AM modulation in synchronization with the FM modulation. Minimizing synchronous AM will assure that the transmitter passband is centered on the channel.

Care must be taken when making these measurements that the test setup does not introduce synchronous AM and give erroneous readings which would cause the operator to mistune the transmitter to compensate for errors in the measuring equipment.

The input impedance of the envelope detector must provide a nearly perfect match so that there is a very low VSWR on the sampling line. Any significant VSWR on the sampling line will produce synchronous AM at the detector because the position of the voltage peak caused by the standing wave moves along this line with FM modulation. Unfortunately, the AM detectors supplied with some modulation monitors do not provide a good enough match to be useful for this measurement. Precision envelope detectors are available that present a good match (30 dB return loss) to the sampling line.

A typical adjustment procedure is to FM modulate 100% at 400 Hz and fine-adjust the transmitter's input tuning and output tuning controls for minimum 400 Hz AM modulation as detected by a wideband envelope detector (diode and line probe). It is helpful to display the demodulated output from the AM detector on an oscilloscope while making this adjustment.

Note that as the minimum point of synchronous AM is reached, the demodulated output from the AM detector will double in frequency to 800 Hz, because the fall-off in output power is symmetrical about the center frequency causing the amplitude variations to go through two complete cycles for every one FM sweep cycle. This effect is illustrated in Figure-8. It should be possible to minimize synchronous AM while maintaining output power and efficiency in a properly designed power amplifier.

The most sensitive test is to tune for minimum crosstalk into the subcarrier. Transmitter tuning becomes very critical to minimizing crosstalk into the subcarriers. Modulate one channel only on the stereo generator to 100% with a 4,500 Hz (7,867 Hz for TV) tone.

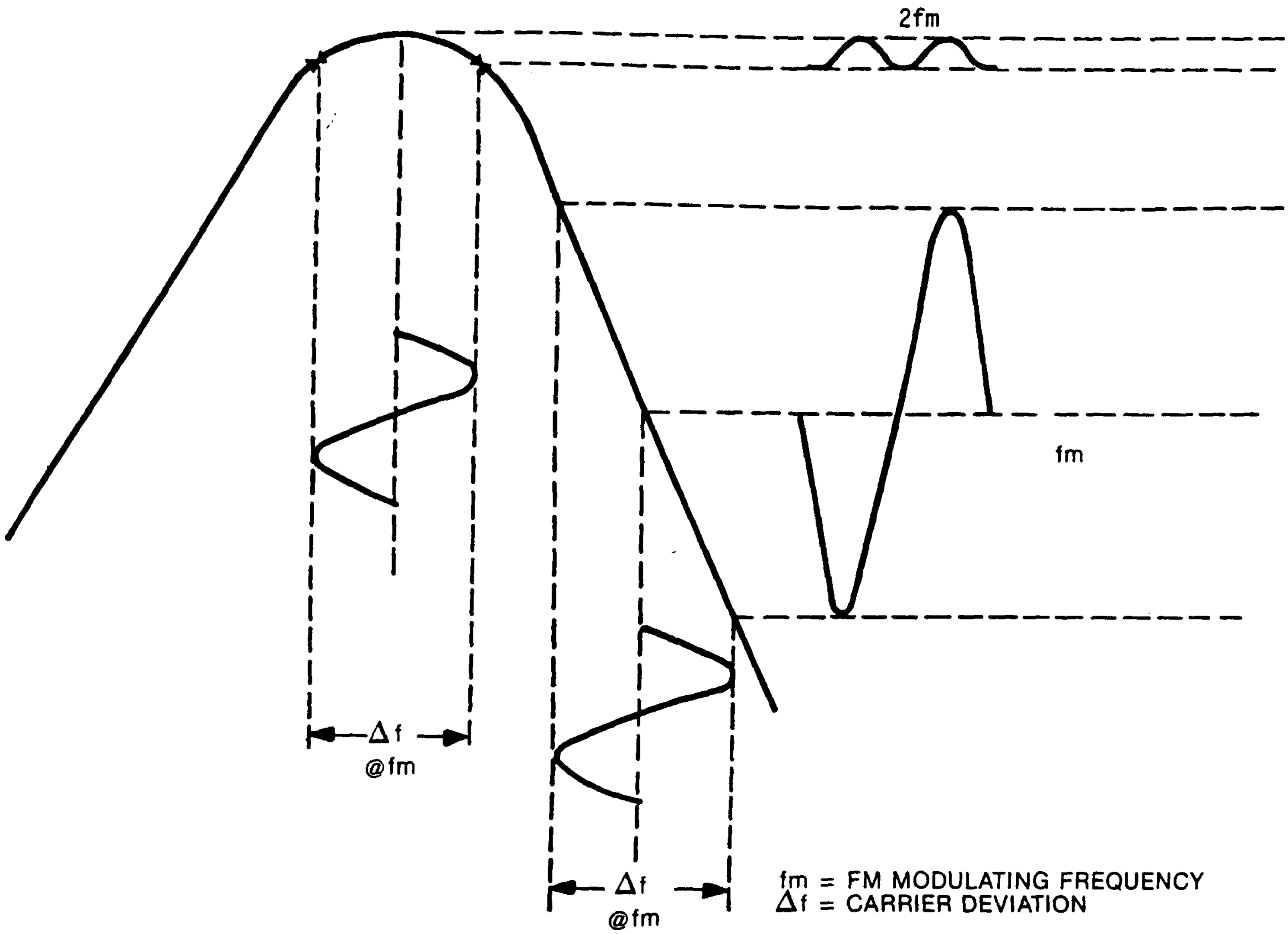


FIGURE 8. SYNCHRONOUS AM WAVEFORMS

This will place the lower second harmonic (L-R) stereo sideband on top of a 67.00 kHz SCA subcarrier (upper second harmonic (L-R) TV stereo sideband on top of a 78.67 kHz SAP). Activate the subcarrier at normal injection level without modulation. Tune the transmitter for minimum output from the subcarrier demodulator. This adjustment can also be made by listening to the residual subcarrier audio while normal stereo programming is being broadcast.

FIELD ADJUSTMENT TECHNIQUES

1. Tune for minimum synchronous AM noise.

2. Tune for minimum crosstalk into unmodulated subcarrier.

As mentioned previously, the input tuning is frequently more critical than the plate tuning. This is because the impedance match into the final amplifier tube's input capacitance becomes the bandwidth limiting factor. Even though the amplitude response appears flattened when the input is heavily driven into saturation, the phase response still has a serious effect on the higher order FM sidebands.

TEST EQUIPMENT SET-UP

Figure-9 shows a block diagram of the required test equipment setup for making composite spectrum and crosstalk measurements. Note that the composite baseband spectrum is checked at various points along the transmission path in order to verify the performance of each subsystem. Most of the measurements center around the use of a low frequency (10 Hz to 200 kHz) spectrum analyzer to determine the amount and location of distortion products added to the baseband signal as it passes through each stage of the overall system.

The modulation monitor or modulation analyzer used to demodulate the RF to composite baseband must have a highly linear pulse counting discriminator in order to avoid the introduction of distortion products during the demodulation process. The wideband subcarrier demodulator is essential to make crosstalk comparisons throughout the system. A narrower bandwidth subcarrier receiver is also useful in determining the amount of crosstalk introduced by the typical receiver.

A precision envelope detector with low input VSWR is included in the test setup so that the accurate synchronous AM waveforms can be observed while tuning the transmitter.

TEST SET-UP FOR COMPOSITE WAVEFORM AND SPECTRUM MEASUREMENTS

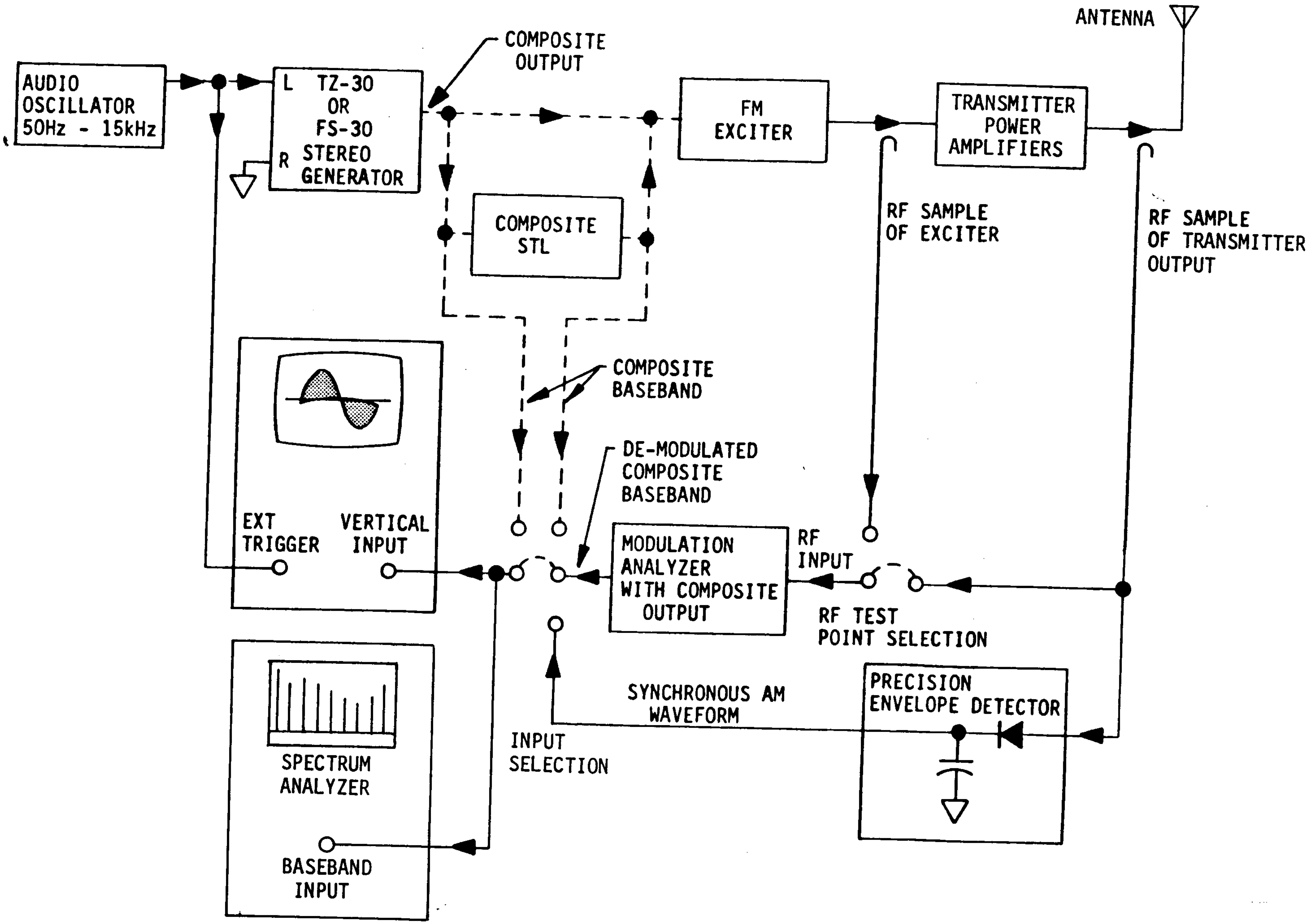


FIGURE 9

RECEIVING THE SUBCARRIER

The subcarrier receiver must first FM demodulate the entire baseband, filter out the desired subcarrier from the rest of the baseband components, and then FM demodulate the subcarrier information. This requires two IF strips and two FM demodulators. The first IF strip is usually operated at 10.7 MHz with a bandwidth of at least 250 kHz while the second IF strip is located at the subcarrier frequency (67 kHz, 78.67 kHz, 92 kHz, or 102.27 kHz) with a narrower bandwidth (typically 25 kHz or less). The first FM demodulator is usually a quadrature or pulse counting type while the second FM demodulator is usually a Phase-Locked-Loop to minimize interference from the main and stereo channels.

This dual demodulation process places some limitations on the performance of the subcarrier receiver. The amplitude and phase response of the IF filters will have a significant effect on the crosstalk into the subcarrier from the main and stereo channels. For instance, the crosstalk into the subcarrier can be improved by increasing the first IF bandwidth to 500kHz or greater when receiving conditions permit. The trade-off is reduced rejection of other RF signals. A highly linear first demodulator will help reduce regeneration of spurious products which interfere with the subcarrier. The second IF bandpass filter will reduce crosstalk into the subcarrier at the expense of increased distortion to the demodulated subcarrier information. This type of receiving system is also more susceptible to multi-path than a simple FM system. The subcarrier being received only has access to a maximum of 10% of the transmitter power. The additional noise factors introduced by the "FM on FM" nature of the system cause further degradation of the signal to noise ratio which may yield a total penalty in coverage of more than 20 dB when compared to main channel.

SUGGESTED SYSTEM ERROR BUDGET

The broadcast engineer is often faced with the problem of meeting subcarrier performance objectives without knowing exactly where to begin. The concept of breaking the entire transmission system (subcarrier generator to subcarrier receiver) into its parts is very useful in "zeroing in" on the problem areas. Systematic, step-by-step evaluation of each sub-system will allow development of an "error budget" for each point along the transmission path. The total system performance will depend on the sum of the individual errors along the way. Once acceptable performance parameters have been assigned to each sub-system (error budget), periodic checks will direct attention to the areas where the largest gains can be made.

For example, if the desired total system performance is:

1. Subcarrier crosstalk into stereo of better than 60 dB.
2. Subcarrier signal to noise ratio (including crosstalk) of 50 dB and distortion of less than 1.0% at an injection level of 10% (-20 dB).

The following error budget of key parameters effecting subcarrier performance might be appropriate.

Subcarrier generator:

Lower sideband suppression of 60 dB at upper limit of (L-R) subchannel. Subcarrier distortion of less than 0.5%.

Stereo generator:

Upper and harmonic (L-R) sidebands suppressed 75 dB in the subcarrier occupied bandwidth. Spurious suppression of 80 dB or better.

Composite baseband distortion:

THD and IMD of less than 0.025% (including STL) (no composite clipping).

FM exciter linearity:

THD and IMD of less than 0.025%.

Transmitter bandwidth:

3 dB amplitude bandwidth of at least 800 kHz
(modulated oscillator to transmitter output).

Antenna bandwidth:

1.5:1 VSWR bandwidth of at least 1 MHz.

BRINGING IT ALL TOGETHER

Subcarriers do offer an important new opportunity to transmit additional information over existing FM broadcast facilities. Whether subcarriers are used primarily for paging, data transmission to fixed points, or other applications remains to be seen. In any case, it is important that each sub-system be individually optimized before the complete transmission and reception system can perform properly. The complexity and technical limitations of the subcarrier system makes attention to details critical to the success of the operation.

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THE AUTHOR

Geoffrey N. Mendenhall earned his BEE degree from the Georgia Institute of Technology in Atlanta, Georgia.

Mr. Mendenhall has designed communications, telemetry, and broadcast equipment for several different manufacturers. His practical field experience has involved engineering and operations work for several radio and television stations.

Mr. Mendenhall is presently serving as Vice President of Engineering for Broadcast Electronics Inc. in Quincy, Illinois.

The author holds three U.S. Patents for electronic designs utilized in broadcast equipment and is a registered professional engineer in the State of Illinois. He has authored numerous technical papers and is a member of the AFCCE and the IEEE.

REFERENCES

Bott, H., "Analysis of Certain System Characteristics of Stereo and SCA Operation", IEEE Transactions on Broadcasting, Vol. BC-13, January 1967.

Crutchfield, E.B., editor, Chapter 3, NAB Engineering Handbook, 7th Edition, National Association of Broadcasters, 1985.

Denny, R.,Jr. "Report on SCA Operation", Proceedings of 37th NAB Engineering Conference, 1983.

Federal Communications Commission, "FM Subcarriers", Docket 82-536.

Hedlund, L., "Stereo and SCA Are Totally Compatible In FM Broadcasting", Communications News Magazine, April 1984.

Hidle, J., Priester, H., and Resnick, A., "Modulation Levels During SCA Transmission", Broadcast Engineering Magazine, February 1984.

Kean, J., "The Effect of Additional SCA Subcarriers on FM Stereo Performance and RF Protection Ratios", Proceedings of 37th NAB Engineering Conference, 1983.

Klein, H., "Issues Concerning Modulation Levels During FM SCA Operation", Proceedings of 37th NAB Engineering Conference, 1983.

Lanier, R., "FM SCA: An Engineering Perspective", Broadcast Management/Engineering, September 1983.

Mendenhall, G., "The Composite Signal-Key To Quality FM Broadcasting", Broadcast Electronics, Inc.

Mendenhall, G., "SCA Basics", Telocator Magazine, September/October 1983.

Middlekamp, L., "Stereophonic Separation In Transmission", IEEE Transactions on Broadcasting, Vol. BC-14, September 1968.

National Association of Broadcasters, Westinghouse Broadcasting and Cable Inc., and National Public Radio, "Increased FM Deviation, Additional Subcarriers and FM Broadcasting: A Technical Report", Comments on BC Docket No. 82-536, August 30, 1983.

Schrock, C., "FM Broadcast Measurements Using the Spectrum Analyzer", Tektronix Application Note 26AX-3582-3.