TRANSMITTER PERFORMANCE REQUIREMENTS

FOR SUBCARRIER OPERATION

BY

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I. INTRODUCTION.

Stereophonic subcarrier operation has made FM broadcasting the profitable radio medium of today. SCA subcarriers, on the other hand, have not attained the same level of acceptance, partly because of crosstalk with the main programming channels, and partly because of the desire to maintain maximum modulation levels. The key to optimal subcarrier performance requires examination of the entire transmitting system and subsequent correction of the bandwidth and distortion limitations of all stages through the chain. This approach was used during the development of a new line of FM transmitters. Specific design improvements in FM exciter linearity, stereo and SCA generator spectral purity, and amplifier bandwidth and stability have allowed new levels of performance with simplified field adjustments.

Subcarriers commonly use either AM-on-FM modulation (as in stereo) or FM-on-FM modulation (as in traditional SCAs). Both processes are complicated by the principle that frequency modulation requires transmission of an infinite number of sidebands for perfect demodulation of information. In practice, however, the information on FM can be carried in a broadcast channel with acceptably low distortion. There are two different frequency bands involved: 1) The composite baseband, which contains the modulating audio plus one or more amplitude or frequency modulated subcarriers, and 2) the FM carrier frequency band of the transmitter.

Waveform linearity, amplitude bandwidth, and phase linearity must be maintained at acceptable limits in the baseband chain from the audio inputs through subcarrier generators to the FM exciter modulated oscillator. From here, the FM carrier is usually amplified in a series of class C nonlinear power amplifiers, where most amplitude variation is removed. However, the amplitude and phase responses of all the networks which follow must also be controlled to minimize degradation of the subcarriers.

Figure 1b shows the effects of a narrowband RF bandpass filter on the RF spectrum of a composite signal consisting of a stereophonic subcarrier modulated only on the left channel with 4.5 kHz and with a 67 kHz unmodulated SCA subcarrier. The only distortion evident on the spectrogram is the loss of some sidebands greater than 150 kHz from the center frequency and amplitude differences between the lower and upper sideband pairs. Figure 1d shows the corresponding effects observed on the demodulated baseband spectrum for the same signal. Note the creation of many undesired intermodulation terms which could cause crosstalk into both the stereophonic and SCA subcarrier bands.

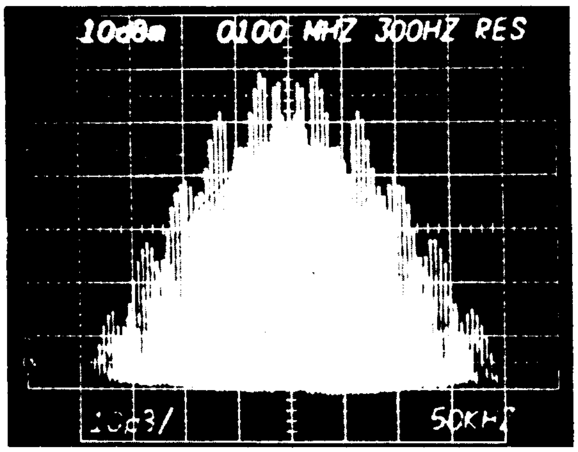

FIGURE 1a.
WIDEBAND RF SPECTRUM TO DEMODULATOR

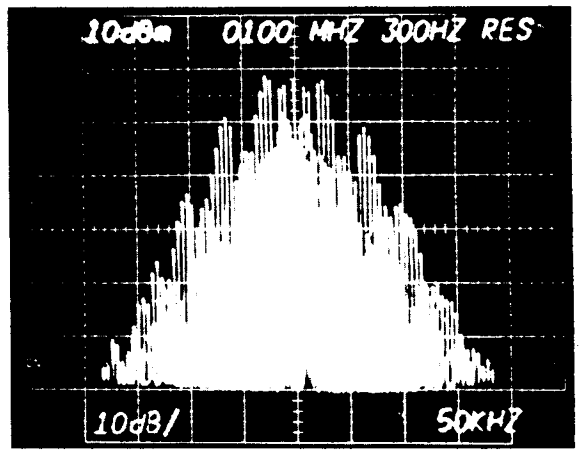

FIGURE 1b.
BANDWIDTH LIMITED RF SPECTRUM TO DEMODULATOR

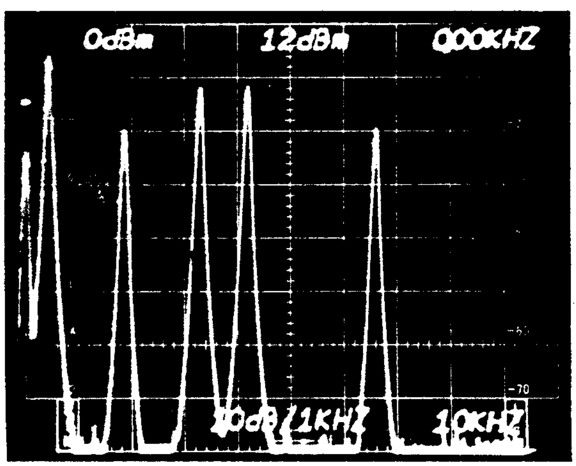

FIGURE 1c.
DEMODULATED BASEBAND SPECTRUM FOR WIDEBAND RF SPECTRUM

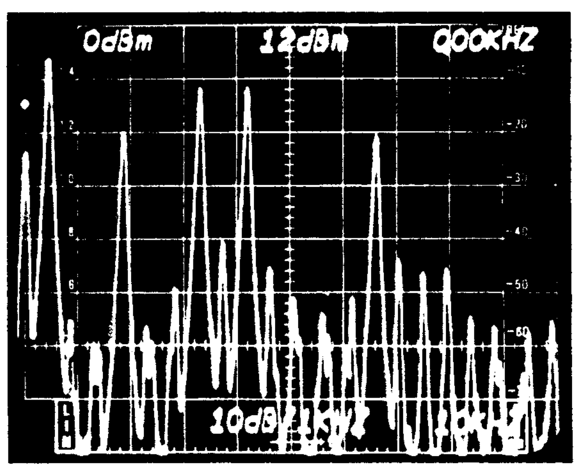

FIGURE 1d.
DEMODULATED BASEBAND SPECTRUM FOR BANDWIDTH LIMITED RF SPECTRUM SHOWING DISTORTION PRODUCTS

II. ELEMENTS OF FM BROADCASTING SYSTEM WHICH AFFECT SUBCARRIERS.

The following components affect subcarrier performance through the system:

1. SCA 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. Receiver antenna, IF passband, and demodulators

This paper will concentrate on components which are part of the transmitting equipment. Information pertaining to receivers, multipath, antennas, and combiner effects can be found in other articles and reports listed at the end of this paper.

2.1 SCA Generator.

The SCA generator frequency modulates a subcarrier with band-limited audio information or data. Audio frequency shift keying and direct FSK for data channels can be used with some new generators. Multiple narrowband or a single wideband SCA can be used in the baseband. The audio frequency response of the standard narrowband SCA must be tailored to prevent the FM sidebands of the SCA from overlapping the stereophonic sidebands by greater than -60 dB. With a 67 kHz SCA, to minimize crosstalk from the SCA into the stereophonic subchannel, the audio should be bandlimited to 4.3 kHz and the peak deviation of the subcarrier limited to 6 kHz or less. Various Bessel function tabulations have been prepared for use with 67 kHz FM SCAs, and can be found in the NAB handbook. Any system utilizing new center frequencies, multiple subcarriers, or different modulation forms will require careful spectral analysis of the baseband to assure minimum interference and maximum compatability with stereo.

The SCA generator should produce a subcarrier sinewave with low harmonic distortion, requiring minimal bandpass filtering as bandpass filtering of FM can generate additional unwanted intermodulation products in the demodulated SCA information. The audio input should be preconditioned by a filter, as mentioned above.

A modern high-performance SCA generator, shown simplified in Figure 2, uses a linear VCO IC. It produces a sinewave at any frequency from 39 to 95 kHz with less than 0.5 percent distortion. A 100 kHz low-pass filter is used on the output. The audio input is conditioned with a 6th order low-pass filter which is 3 dB down at 4.3 kHz. This filter may be bypassed for wider bandwidth SCAs or different preemphasis. A dc coupled data input is included for direct frequency shift keying. Note that the subcarrier output is faded on and off at a controlled decay rate rather than switched to prevent squelch noise with the SCA receiver.

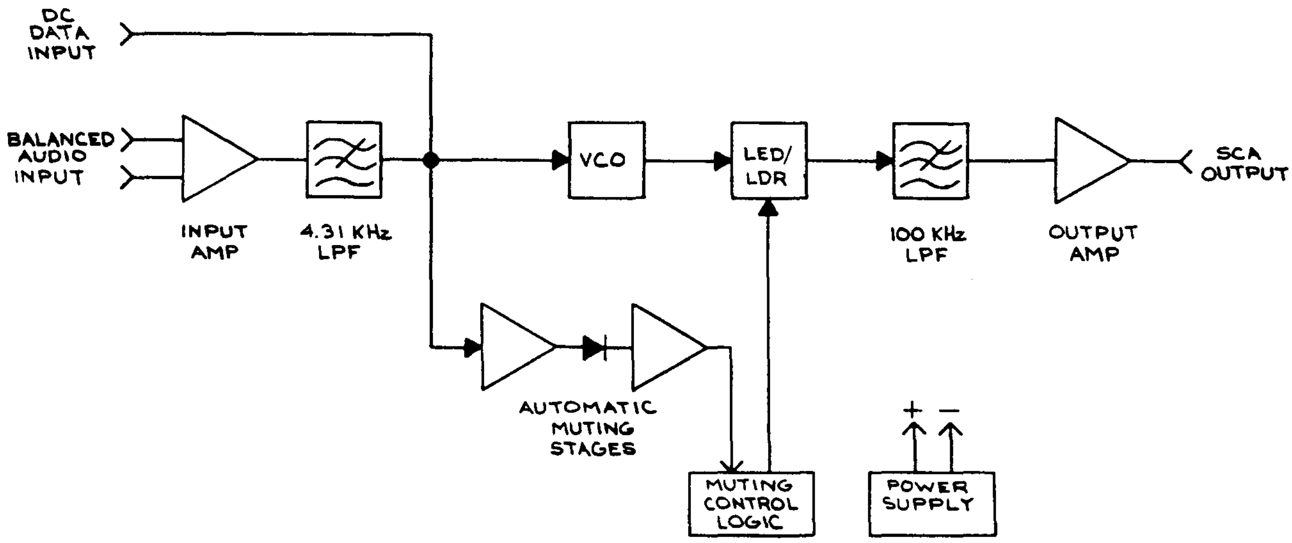

FIGURE 2. SIMPLIFIED BLOCK DIAGRAM OF FC-30 SCA GENERATOR

2.2 Stereo Generator.

The stereo generator must have good 38 kHz 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 SCA subchannel. For an SCA signal to noise ratio of -60 dB the stereophonic harmonics should be suppressed by -70 dB. This number allows for some degradation through the entire system. Manufacturers of stereo generators have traditionally chosen either linear or switching modulators.

The linear modulators may use balanced analog circuits with adjustable 38 and 76 kHz null controls. These adjustments should be maintained if excessive 76 kHz becomes evident using spectrum analysis of the baseband. The switching modulator is popular because of less critically toleranced components and good long-term stability. However, the modulator waveform usually requires filtering with a steep cutoff 53 kHz low-pass filter. This filter is not a trivial design, because passband amplitude ripple and phase non-linearities cause degraded high frequency separation by adversely affecting the upper sideband of the L-R subcarrier.

The stereo generator shown in Figure 3 uses a digital stairstep generator to synthesize the subcarrier and pilot simultaneously, eliminating any pilot phase variation. Appropriate components are added in the synthesis to approximate a sinewave with lower harmonic content. The composite low-pass filter then has a gradual rolloff, with the -3 dB point beyond 100 kHz. Separation is better than 50 dB at 15 kHz. In this design, subcarrier suppression is specified at -75 dB and the 76 kHz sidebands are -80 dB below 100% modulation. At 57 and 95 kHz, the third and fifth pilot harmonics, suppression is -80 dB or more.

Audio input low-pass filters are necessary in all stereo generators. These "brickwall" filters protect the pilot and subcarrier by greatly attenuating audio components above 15 kHz. Some designs have filters which ring or overshoot on transient program waveforms due to poor passband group delay. This overshoot can be measured as overmodulation. Without audio low-pass filtering, increased spectrum occupation and spill over into the SCA band occurs. If the pilot level is observed fluctuating during modulation, defective filtering may be suspected. The FS-30 generator uses carefully aligned 5-pole active low-pass filters with controlled delay equalization to keep overshoot below 2 dB, while providing adequate protection to the pilot, stereophonic subcarrier, and SCA subcarrier.

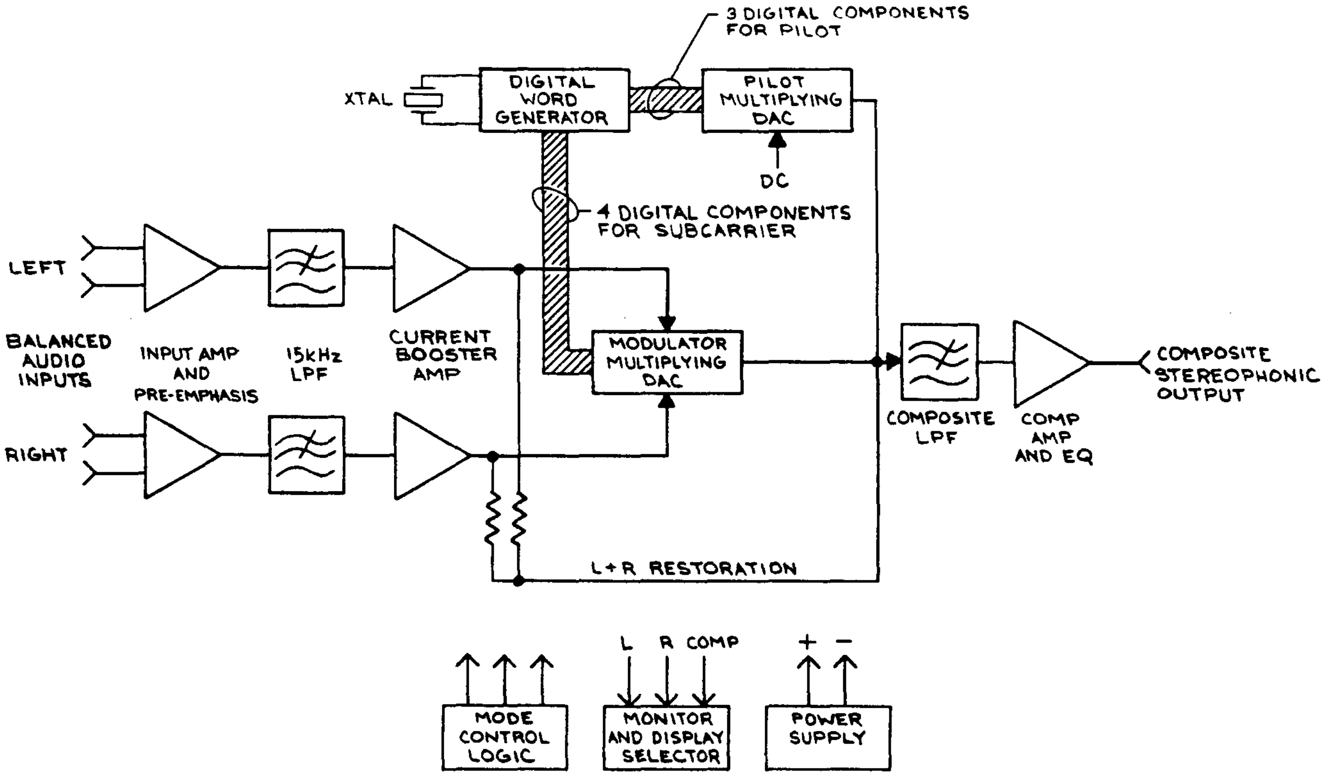

FIGURE 3. SIMPLIFIED BLOCK DIAGRAM OF FS-30 STEREO GENERATOR

2.3 FM Exciter.

The exciter characteristics are foremost in importance for good subcarrier performance. The frequency modulated oscillator in most current units consists of a varicap diode VCO. The voltage-to-capacitance transfer function of these devices is not linear over the wide range used, so linearization may be necessary. Non-linearities in the FM oscillator can, by altering the waveform of the baseband signal, create distortion in the demodulated output at the receiver. A secondary effect of this distortion may include stereo crosstalk into SCA. Modulator linearization using a piecewise approximation pre-distortion network has reduced harmonic and intermodulation distortion to less than 0.05% in the FX-30 exciter (Figure 4). All exciter stages after the oscillator operate as broadband amplifiers with minimal bandwidth limitations.

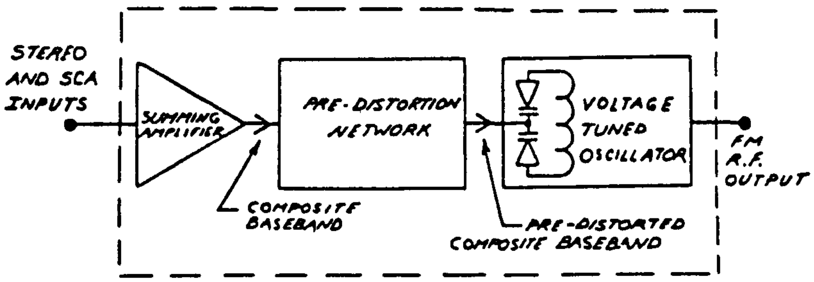

FIGURE 4. SIMPLIFIED BLOCK DIAGRAM OF LINEARIZED FM MODULATOR

2.4 Composite STL.

The composite STL is really a transmission subsystem within a system. STL transmitter requirements are identical to those of the FM exciter and power amplifiers detailed in this paper. For minimum degradation of the composite signal it is recommended that all SCA channel information be fed into the exciter at the transmitter. Telephone company landlines or another narrowband link can usually handle the program bandwidths of SCAs. This reduces the technical burden of maintaining very low intermodulation performance through the entire STL modulation/demodulation process. However, the STL should have a flat bandwidth through 53 kHz for minimum stereophonic subcarrier degradation. For stereophonic separation of 50 dB, it is necessary to maintain a composite amplitude flatness of ±0.04 dB and phase linearity within ±0.2 degrees through 53 kHz in the baseband. Many exciters and STLs cannot meet this requirement. The stereo generator should be engineered to compensate for this deficiency through the use of a built-in composite equalizer with low and high frequency adjustments. The range of amplitude correction of the FS-30 stereo generator is shown in Figures 5a and 5b. These figures show the maximum boost and cut with the low (Figure 5a) and high (Figure 5b) frequency controls at both ends of their ranges.

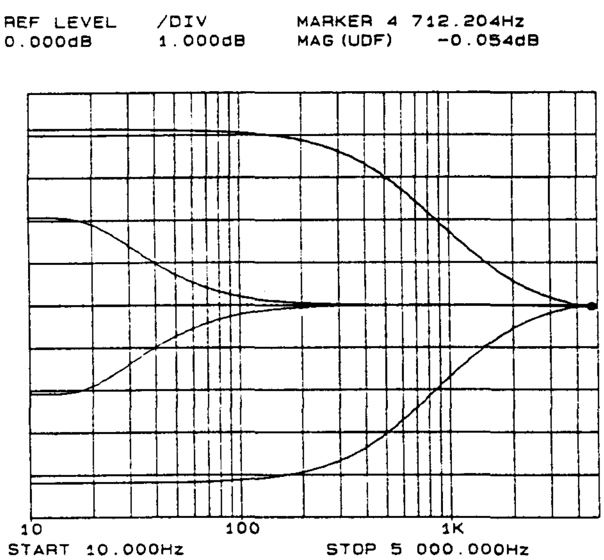

FIGURE 5a.
RANGE OF FS-30 LOW FREQUENCY EQ

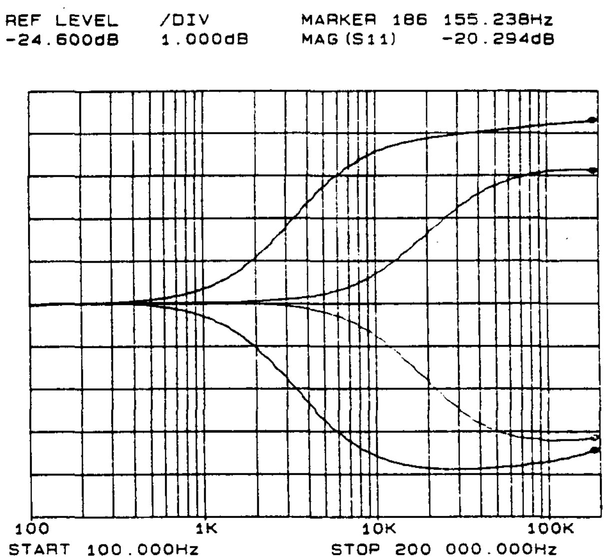

FIGURE 5b.
RANGE OF FS-30 HIGH FREQUENCY EQ

2.5 RF Power Amplifiers.

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. A new generation of class C bipolar and MOSFET broadband amplifier stages exhibit both high efficiency and greater than 20 percent bandwidth to cover the FM broadcast band. These solid-state amplifiers may be combined for higher power. Tuned output band-pass filters may still be necessary when operated in a dense RF environment to prevent intermodulation from being generated in the PA modules.

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.

III. POWER AMPLIFIER CIRCUIT DESIGN.

3.1 Bandwidth Considerations.

As mentioned earlier, the FM signal theoretically occupies infinite bandwidth. In practice, however, truncation of the insignificant sidebands (typically less than 1 percent of the carrier) makes the system practical by accepting a certain degree of signal degradation. The input and output tuned circuits of the PA limit the bandwidth of the FM signal. 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. For a single-tuned circuit, the bandwidth is proportional to the ratio of capacitive reactance to resistance:

$$BW \cong \frac{1}{2\pi R C} \cong \frac{X_C}{R_L} \qquad \text{(eq. 1)}$$

where BW = bandwidth between half-power points
R_L = load resistance (appearing across tuned circuit)
C = total capacitance of tuned circuit (includes stray capacitances and output or input capacitances of the tube)
X_C = capacitive reactance

The load resistance is directly related to the RF voltage swing on the tube element. For the same power and efficiency, the bandwidth can be increased if the capacitance is reduced.

3.2 Grounded-Grid Versus Grid-Driven Operation.

Since the input capacitance of tube amplifiers in a grounded-grid configuration is smaller than that of a grid-driven configuration by as much as 50 percent, an investigation was carried out in 1982 to determine the advantages of using a grounded-grid circuit for a tetrode tube amplifier. Input capacitances of typical tubes are shown in Table 1.

TABLE 1

TUBE TYPE	Cin (pF) Grounded Grid	Grounded Cathode
4CX3000A	67	140
4CX3500A	58.5	111
4CX5000A	53	115
8990/4CX20,000A	83	190

Prototype input circuits were developed for grounded-grid and grid-driven operation of a 5 kilowatt PA using the Eimac 4CX3500A tetrode. A series of measurements were made to evaluate the performance of grounded-grid versus grid-driven operation of the tetrode PA with respect to gain, efficiency, amplitude bandwidth, phase bandwidth, and synchronous AM under equivalent operating conditions. Measurements were made at normal and reduced plate voltage for both saturated and unsaturated PA operation. Saturation is noted when little change in output power occurs with increasing drive power. Maximum efficiency occurs at this point. The PA gain and efficiencies are tabulated in Table 2. Swept amplitude and phase responses of the different PA configurations are shown in Figures 6a thru 6d.

The significant findings of the tests and measurements are as follows:

1. When driving the PA into saturation, the bandwidth of the PA is limited by the output cavity bandwidth in the grounded-grid amplifier. The PA bandwidth in the grid-driven amplifier is limited by the input circuit Q, which is basically determined by the extent of swamping resistance used. PA bandwidth under saturation can be improved in either configuration by reducing the plate voltage as evident from equation (1). However, this involves a trade-off in efficiency with a smaller voltage swing. For example, in the grid-driven saturated configuration a 25 percent bandwidth improvement was observed with 1.4 dB loss of PA gain and 2.3 percent efficiency loss with reduced plate voltage.

2. When the PA is not driven into saturation, the grounded-grid amplifier does not appear to give any bandwidth improvement over the grid-driven amplifier at the 0.25 dB points (see Figures 6c and 6d). At the 3 dB points however, there is a slight ($\cong$ 15%) improvement in bandwidth when using the grounded-grid unsaturated PA.

TABLE 2

MEASUREMENTS FROM 5KW PA IN GRID-DRIVEN (GD) AND GROUNDED-GRID (GG) CONFIGURATION

CONFIGURATION	GD	GG	GD	GG	GD	GG	GD	GG
PA CONDITION	---- SATURATED ----				---- UNSATURATED ----			
RF POWER OUTPUT (W)	4900	5000	4800	4900	3225	3350	3325	3200
PLATE VOLTAGE (V)	5220	5200	4500	4480	5320	5315	4550	4600
PLATE CURRENT (A)	1.27	1.26	1.49	1.4	0.81	0.9	1.08	1.0
DRIVE POWER (W)	140	280	190	340	70	170	70	175
EFFICIENCY (%)	73.9	72	71.6	72.7	74.8	66.5	67.7	65.8
GAIN (dB)	15.4	12.5	14.0	11.6	16.6	13.0	16.8	12.6
SYNCHRONOUS AM (dB)	-54	-56	-56	-58	-46	-48	-51	-52

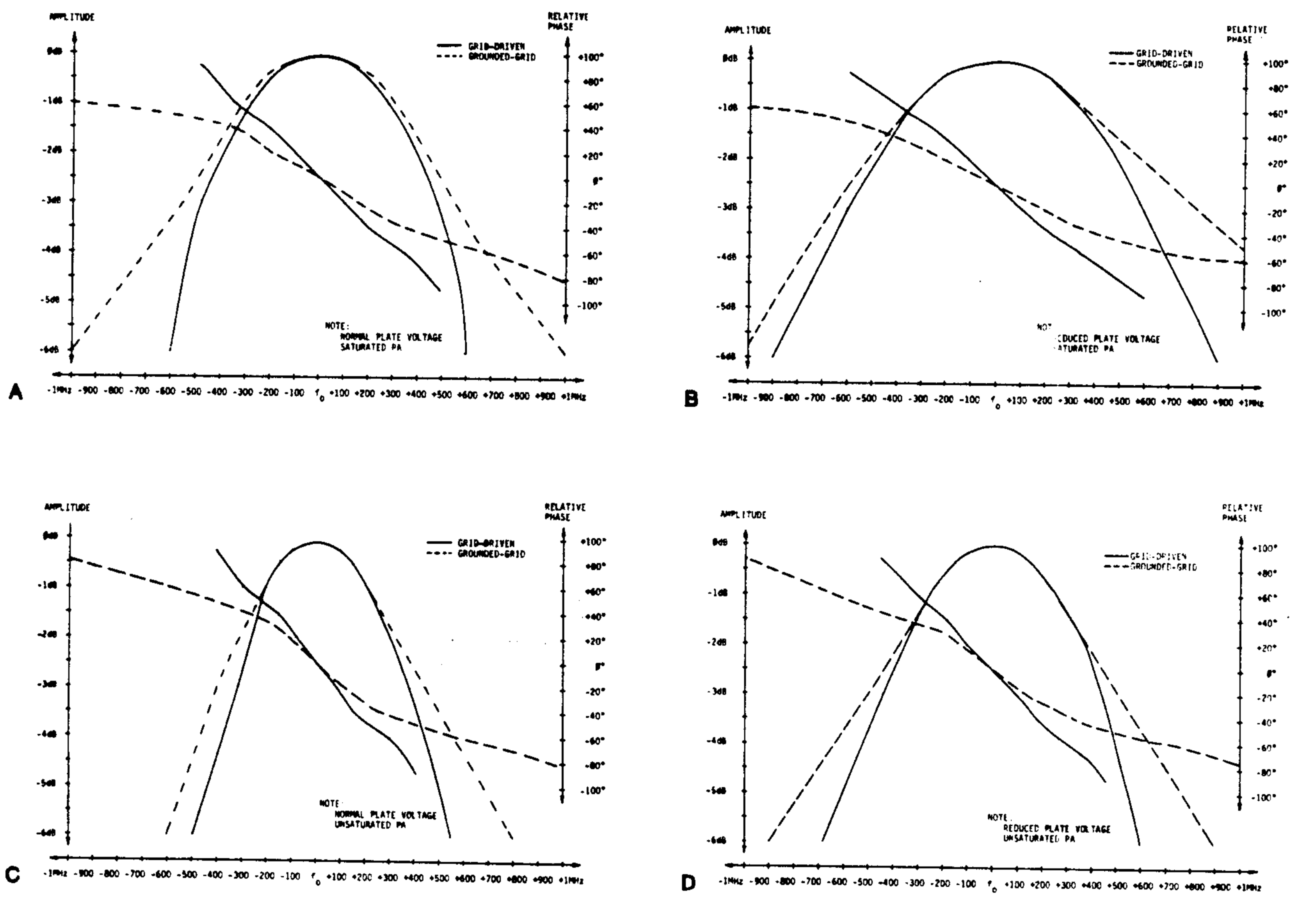

FIGURE 6. MEASURED AMPLITUDE AND PHASE RESPONSES OF GRID-DRIVEN AND GROUNDED-GRID TETRODE POWER AMPLIFIERS

3. A grounded-grid saturated PA improves bandwidth over a grid-driven saturated PA at the expense of amplifier gain. A 15 percent improvement in the PA bandwidth was observed while losing 3 dB of the amplifier gain. For a grid-driven amplifier, a 25 percent reduction of input circuit resistive swamping results in the same 15 percent bandwidth improvement at the expense of only 0.5 dB in gain.

4. The phase linearity in the 0.5 dB bandwidth appears to be better using the grid-driven PA. The grounded-grid PA exhibits a more nonlinear phase slope within the passband, yet has a wider amplitude bandwidth. This phenomenon is due to interaction of the input and output circuits because they are effectively connected in series in the grounded-grid configuration. The neutralized grid-driven PA provides more isolation of these networks, so they should behave like independent filters.

In view of the findings listed above (in particular item No. 3), the use of a tetrode in a grounded-grid configuration did not appear to be economically feasible. An additional intermediate power amplifier would have been required to fulfill the higher drive power requirements, thereby affecting the overall cost and reliability of the transmitter. The decision was made to use a grid-driven PA for our FM-3.5A and FM-5A transmitters. Bandwidth limitations of the grid-driven PA were overcome by swamping the input circuit and by developing a novel impedance-matching device to achieve optimum transfer of power from the driver stage into the PA. The loss of PA gain due to swamping was limited to 0.5 dB, while achieving bandwidth nearly equivalent to a grounded-grid amplifier, yet providing a more linear phase response.

3.3 Broadband Impedance-Matching.

A broadband impedance matching circuit was developed to match the high grid input impedance of a tetrode RF power amplifier to the 50 Ohm impedance of a solid-state driver. The conventional matching circuits used in transmitter applications are generally of the type known as L, π , or T networks. All of these circuits require interactive adjustment of one or more circuit elements to provide a satisfactory impedance match for each frequency and RF power level.

The new impedance-matching circuit developed for the FM-3.5A and FM-5A transmitters 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. The impedance-matching device is shown in Figures 7 and 8.

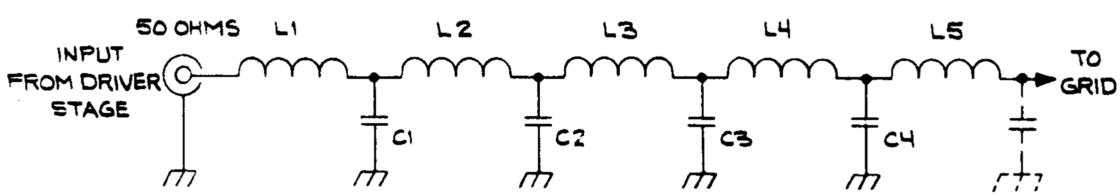

FIGURE 7. CIRCUIT DIAGRAM OF PA INPUT IMPEDANCE MATCHING DEVICE

This impedance-matching circuit improves transmitter operation and maintainability, 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 of RF power levels. The input-matching circuit eliminates separately mounted components which can be microphonic (sensitive to vibration) due to mechanical instability. By incorporating this new impedance-matching device, we have been able to improve the bandwidth, reliability and stability of the transmitter.

The typical performance figures of the FM-3.5A and FM-5A transmitters with regard to PA bandwidth, efficiency, gain, and synchronous AM (measured for 3500W and 5000W power outputs, respectively) are presented in Table 3.

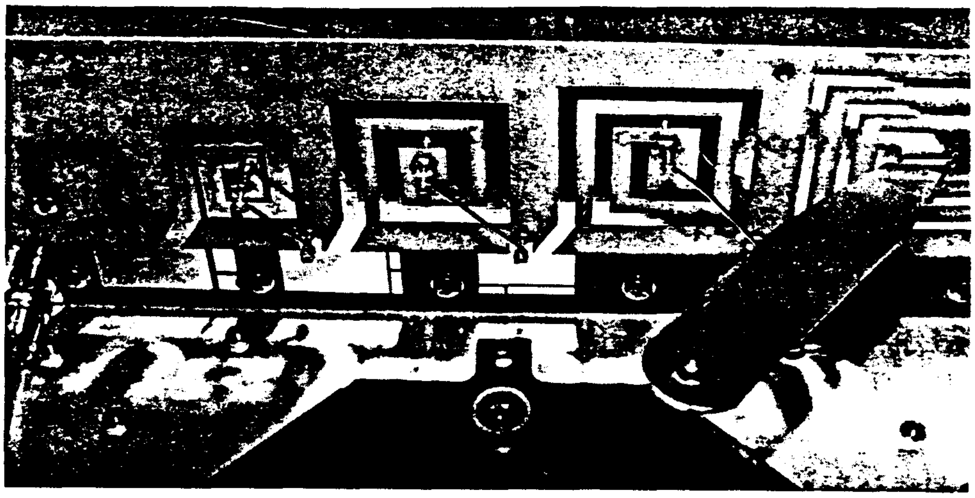

FIGURE 8. PHOTO OF INPUT MATCHING DEVICE. TUBE SOCKET GRID RING CONNECTION AT RIGHT OF CENTER, 50 OHM INPUT AT LEFT

TABLE 3

TYPICAL PERFORMANCE OF TRANSMITTER PAs

BE Model	3dB Bandwidth	Efficiency	Gain	Synchronous AM
FM-3.5A	1.2 MHz	75%	14.5 dB	-47 dB
FM-5A	1.3 MHz	75%	15.0 dB	-51 dB

3.4 Power Amplifier Cavity.

The vacuum-tube power amplifier is constructed in an enclosure containing distributed tank circuit elements for minimum loss. The efficiency of the PA depends on the RF plate voltage swing, the plate current conduction angle, and the cavity efficiency. The cavity efficiency is related to the ratio of loaded and unloaded Q as follows:

$$N = 1 - \frac{Q_L}{Q_u} \times 100 \qquad \text{(eq. 2)}$$

where N = efficiency in percent
Q_L = loaded Q of cavity
Q_u = unloaded Q of cavity

Loaded Q depends on the plate load impedance and output circuit capacitance. Unloaded Q depends on the cavity volume and the RF resistivity of the conductors due to skin effects. A high unloaded Q is desirable, as is a low loaded Q, for best efficiency. As the Q goes up, the bandwidth decreases. For a given tube output capacitance and power level, loaded Q decreases with plate voltage or with increasing plate current. This explains the improved bandwidth for the reduced high voltage measurements in Table 2 and Figures 6b and 6d.

Other methods popular in improving the bandwidth of PA output circuits include minimizing added capacitance, as manufacturers of quarter-wave cavities have attempted. The ideal case would be to resonate the plate capacitance alone with a "perfect" inductor, but practical quarter-wave cavities require either the addition of a variable capacitor or a variable inductor using sliding contacts for tuning. An inherent mechanical and electrical compromise in these designs has always been the requirement for a plate blocking capacitor and the presence of maximum RF current at the grounded end of the line where the conductor may be nonhomogeneous. A new approach to VHF power amplification uses a folded half-wave cavity design. This is shown compared to conventional designs in Figure 9. The half-wave line is tuned without the use of variable capacitors or sliding contacts. The blocking capacitor is unnecessary and the high current point is located in the central area of the tank line where no joints, fasteners, teners, or obstructions occur. This design is inherently more reliable, and due to the folded nature, requires only slightly more physical height than the quarter-wave design.

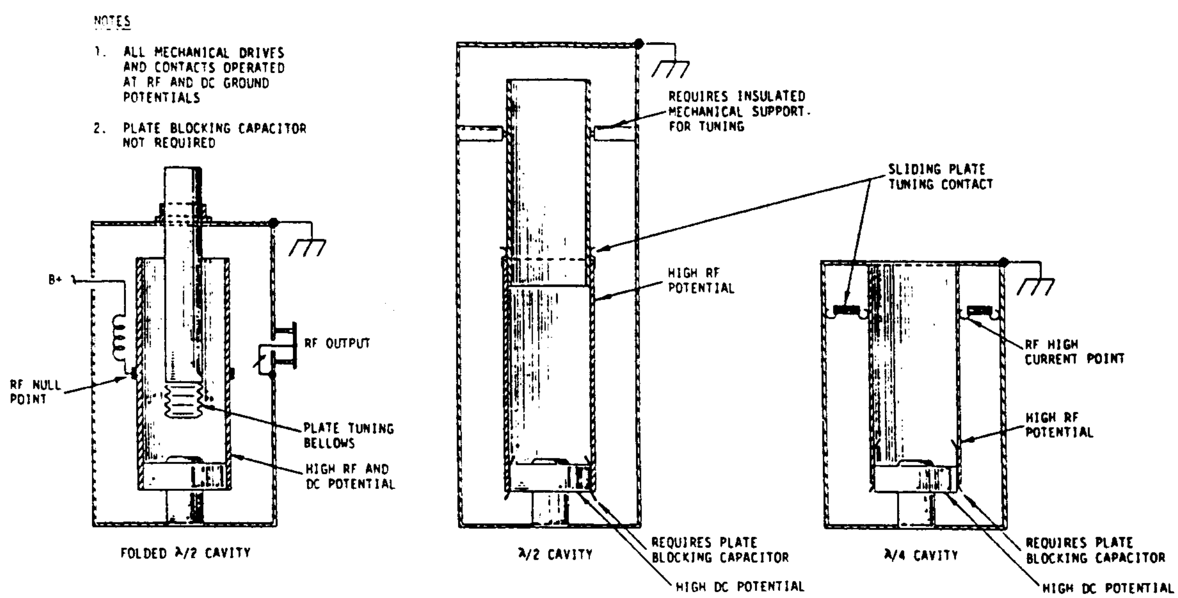

FIGURE 9. COMPARISON OF PA CAVITIES

The bandwidth of the PA cavity is optimized by a choice of the highest characteristic impedance mechanically allowable. The center conductor is sized for minimum impedance discontinuity and is directly clamped to the outer surface of the anode fins for best heat transfer. The secondary tuning line (with adjustable bellows) is sized to maintain a similar characteristic impedance without appreciable end-loading distributed capacitance. An inductive loop couples the strong fundamental magnetic field near the center of the cavity. The loaded Q of the cavity varies as the square of the effective loop area and inversely as the square of the distance of the loop center from the cavity center axis. This loop is positioned so that it links more or less magnetic field and determines the output loading of the transmitter. This unique approach yielded the bandwidths in Table 3 which provide excellent subcarrier operation.

3.5 PA Adjustments For Subcarrier Optimization.

The power amplifiers which have been discussed operate with improved reliability and power efficiency without compromising subcarrier performance. By providing a broadband input matching circuit with a single control, adjustment of these transmitters for optimal subcarrier performance (minimum crosstalk, maximum separation, etc.) is very repeatable. A typical adjustment procedure involves tuning the transmitter for minimum audio output from an envelope detector while FM modulating the transmitter to 100% with a single 400 Hz tone. When the minimum is reached, the audio output from the envelope detector will double in frequency to 800 Hz. This indicates correct tuning at the center of the passband. Tuning for best synchronous AM should simultaneously result in high efficiency. This also coincides with minimum stereo-to-SCA crosstalk. The rigid mechanical construction of both the input matching circuit and the folded half-wave cavity contributes to the overall electrical stability of the tuned circuits, a benefit for long-term SCA operation where constant "tweaking" is undesirable.

IV. CONCLUSION.

The development of new FM transmitting equipment requires attention to design details in bandwidth and linearity of all sub-systems, including the stereo and SCA generators, the FM exciter, and all RF amplifier stages. New techniques have been developed which reduce the number of controls throughout the transmitting system, minimizing field adjustment. The key design criterion for new transmitters is to optimize SCA and stereophonic subcarrier performance while retaining high reliability.

ACKNOWLEDGEMENTS.

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BIOGRAPHICAL INFORMATION

John T.M. Lyles is manager of the FM engineering section at Broadcast Electronics, Inc. in Quincy, Illinois. He has led the design efforts of several FM transmitters. Prior to this, he assisted in the design of modulation controllers and RF instrumentation at Delta Electronics, Inc., where he also managed the quality control department.

Mr. Lyles received a BSEE in 1978 from Virginia Polytechnic Institute and State University in Blacksburg, Virginia. He has held chief engineer positions at four radio stations in the Southeast. He enjoys consumer electronics and home computing and is a member of the Institute of Electrical and Electronics Engineers.

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