An FM Tuner Using Single-Gate MOS Field-Effect Transistors as RF Amplifier and Mixer

by

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Selection of the transistors for use in FM-tuner stages involves consideration of such device characteristics as spurious response[1], dynamic range, noise immunity, gain, and feedthrough capacitance. MOS field-effect transistors are especially suitable for use in FM rf-amplifier and mixer stages because of their inherent superiority for spurious-response rejection and signal-handling capability. This Note describes an FM tuner that uses an RCA-40468 MOS transistor as the rf amplifier and an RCA-40559 MOS transistor as the mixer. A conversion gain of 17.5 dB was obtained, to provide an over-all tuner gain of approximately 30 dB. RF and mixer circuit considerations pertinent to the design are discussed.

Performance Features of MOS Transistors

Spurious response in an FM tuner is caused by the mixture of unwanted signals with the desired carrier in either the rf stage or the mixer. This effect can be expressed mathematically by use of the Taylor series expansion of the simple transfer function of output current as a function of input voltage at the operating point, as follows:

$$i_o = I_o + \alpha e_s + \beta e_s^2 + \theta e_s^3 + \ldots \qquad (1)$$

where i_o is the instantaneous value of output current of the device; I_o is the dc component of output current; e_s is the rf signal voltage present at the input terminal of the transistor; and α, β, and θ are the coefficients of a Taylor series expansion. These coefficients are related to the first-, second-, and third-order derivatives of the transfer characteristic as determined by the bias point. It can be shown[2,3] that mixing action within the device is attributable to the second-order term (βe_s^2), and that cross-modulation and intermodulation result from third- and higher-order terms. Therefore, when a device has an inherent square-law transfer characteristic, i.e., the drain current varies as the square of the applied gate-to source voltage, third- and higher-order terms are zero and spurious response is eliminated. The transfer characteristic of MOS field-effect transistors more nearly approaches this ideal square-law relationship than the very steep exponential transfer characteristic of bipolar transistors.

The dynamic-range capability of MOS field-effect transistors is about 25 times greater than that of bipolar transistors. In an actual tuner circuit, this large intrinsic dynamic range is reduced by a factor proportional to the square of the circuit source impedances.[4] The net result is a practical dynamic range for MOS tuner circuits about five times that for bipolar types.

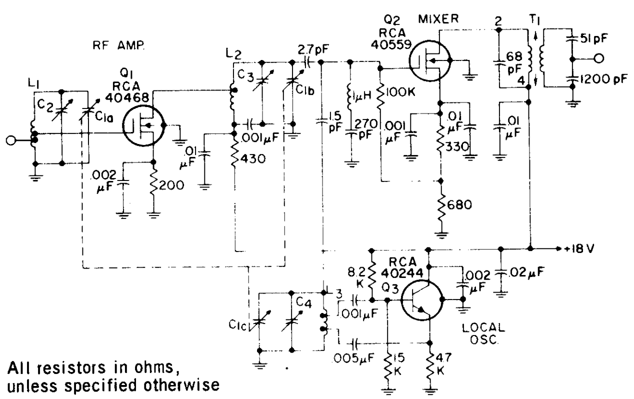
With MOS field-effect transistors, as contrasted with either bipolar transistors or junction-gate field-effect transistors, there is no loading of the input signal, nor drastic change of input capacitance even under extreme overdrive conditions.

In junction-gate field-effect transistors, a large incoming signal can have sufficiently high positive swing to drive the gate into conduction by a momentary forward bias; power is then drawn from the input signal in the same way as if a resistance were placed across the input circuit. In bipolar transistors, there is a gradual change of both input impedance and input capacitance as a function of large signal excursions. These changes are undesirable because they can result in detuning of tuned circuits and widening of the input selectivity curve.

FM Tuner Design

The FM tuner shown in Fig.1 uses single-gate MOS field-effect transistors in the rf-amplifier and mixer stages and a bipolar transistor as the local oscillator. The rf-amplifier transistor RCA-40468 operates in the common-source configuration with a stage gain of 12.7 dB. The mixer transistor RCA-40559 also operates in the common-source configuration, with both the rf and local-oscillator signals applied to the gate terminal. The bipolar oscillator transistor RCA-40244 operates in the common-collector mode. The conversion power gain from the mixer stage is 17.5 dB; the total gain of the tuner is 30.2 dB.

Performance of the FM tuner was evaluated by use of the bipolar-transistor if amplifier shown in Fig.2. The 10.7-MHz if output from the tuner is coupled to the first if-amplifier stage by means of a double-tuned transformer T_1. The if amplifier employs two 40245 and one 40246 bipolar transistors, each operating in a neutralized common-emitter configuration at a collector current of 3.5 milliamperes. The over-all gain of the if amplifier is 88 dB. A detailed analysis of a similar if amplifier is covered in an earlier publication.[5]



C_{1a}, C_{1b}, C_{1c} - 3-gang tuning capacitor, TRW 5-plate Model V2133 with trimmers stripped off.

C_2, C_3, C_4 - Arco 402 trimmer, maximum value 10 pF

L_1 - No.18 bare copper wire, 5 turns on 19/64" form, coil length 1/2", with IRN .250" x .250" Arnold slug. Q_o = 164. Antenna tap at 0.8 of a turn, output tap at 1.4 turns.

L_2 - No.18 bare copper wire, 5 turns on 15/64" form, coil length 3/8", with 0.181" x 0.375" Arnold slug. Q_o = 104.

L_3 - No.18 bare copper wire, 5 turns, air core with 3/8" O.D., coil length 1/2". Emitter tap on 1-1/2 turns. Feedback tap on 2 turns. Q = 164.

T_1 - Double tuned, 90 per cent of critical coupling. Primary unloaded uncoupled Q = 137 with 68-pF tuning capacitance, secondary unloaded uncoupled Q = 76 with 47-pF tuning capacitance. Secondary has a turns ratio of 26.2 to 1.0. Primary, No.32 enamel wire, 15 turns, space wound at 60 TPI, 0.250" x 0.500" TH slug. Secondary, No.36 enamel wire, 18 turns, close wound, 0.250" x 0.250" TH slug. Both coils on 9/32" form without shield.

Fig.1 - Circuit diagram of FM tuner using MOS transistors for the rf amplifier and mixer stages.

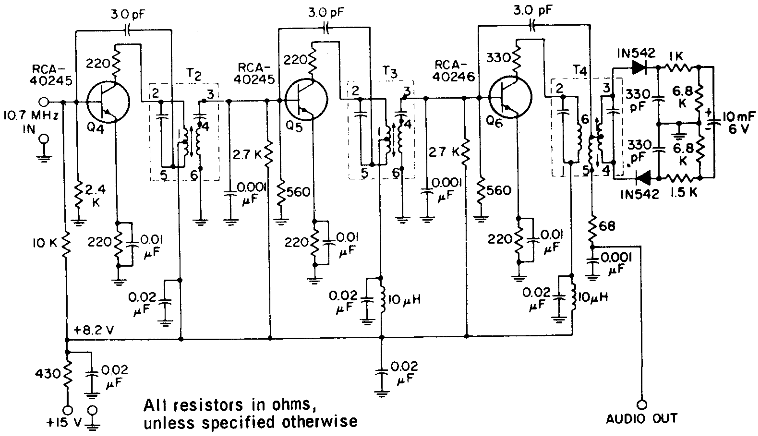


Fig.2 - Three-stage if amplifier using bipolar transistors.

Table I summarizes the performance of the MOS tuner. Spurious response was evaluated with a generator output of 350 millivolts.

OVER-ALL TUNER PERFORMANCE

Carrier Frequency	100	MHz
Modulation Frequency	400	Hz
Deviation (except IHFM)	22.5	kHz
Sensitivity:		
IHFM	1.75	μV
20-dB Quieting	1.5	μV
30-dB Quieting	1.75	μV
3-dB Limiting	2.5	μV
Image Rejection	62	dB
IF Rejection	96	dB
Half-IF Rejection	92	dB
Spurious Response across VHF band with $e_{gen.}$ = 0.35 volt	NONE	

Table I - Over-all performance characteristics of FM tuner.

RF-Circuit Considerations

The RCA-40468 MOS transistor used in the rf amplifier stage has a maximum available gain of 24 dB. Because the design criteria required a total mismatch plus insertion loss of 11.3 dB, the net gain for the stage is 12.7 dB. Although the design procedure used for these calculations has been discussed previously,[1,6] some of the considerations for optimizing performance warrant additional comment.

In the design of an rf stage for FM performance, the stage gain should be a compromise between optimum receiver sensitivity and spurious response rejection. In other words, the rf gain capability should be large to minimize the effects of noise from the mixer, and yet be limited to prevent a very large undesired incoming signal located on the skirt of the selectivity curve from driving the mixer beyond its dynamic range. Good FM tuner performance is achieved by selection of the proper rf-stage gain and step-down to the mixer input.

The rf input coil L_1 is tapped down to provide the smallest practical input swing to the gate of the rf-amplifier transistor for increased dynamic range. This tap-down is a compromise between optimizing for dynamic range and noise. When the degree of mismatch has been established, the drain-circuit load L_2 is determined from stage-gain and bandwidth requirements. Table II shows the device parameters used for the design of the rf stage.

The 40468 MOS transistor has a typical feedback capacitance of 0.12 picofarad, with a maximum value of 0.2 picofarad. This small value of C_{rss} minimizes oscillator radiation feedback through the device, and also makes it unnecessary to add neutralization components to the rf stage to achieve adequate gain.

Mixer-Circuit Considerations

The mixer circuit shown in Fig.1 is designed for operation into an 8000-ohm load. A load up to 12,000 ohms is permissible and provides a gain increase of about 1 dB from the mixer. The input circuit is tapped down by a 2.7-picofarad capacitor in series with the device input capacitance to improve dynamic range. These mismatch losses result in a stage gain of 17.5 dB, as compared to the maximum available gain of 21.5 dB shown in the published data for the 40559 transistor.

The trap consisting of a 1-microhenry inductor and 270-picofarad capacitor is designed to bypass any 10.7-MHz component that may appear at the input to the mixer. A 1.5-picofarad capacitor couples the oscillator signal to the mixer gate. Because the capacitor is small, interaction with the oscillator tuned circuit is minimized and good oscillator stability is maintained. The injection level at the gate of the mixer is 700 millivolts rms.

The biasing arrangement for the mixer stage is particularly important: substrate bias is used to provide the optimum combination of mixing and spurious-response rejection. Fig.3 shows the shift of the transfer characteristic as a function of negative substrate bias E_{bs} for the RCA-40559 mixer transistor.

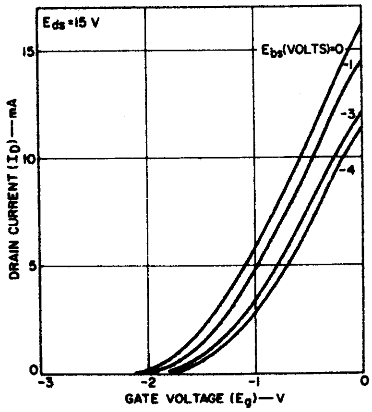


Fig.3 - Transfer characteristics of the RCA-40559 MOS field-effect transistor for several values of substrate bias.

The transconductance, which is the first derivative of the transfer characteristic, also varies as a function of substrate bias, as shown in Fig.4. As stated previously, mixing is accomplished by means of the quadratic term of Eq.(1); higher-order terms contribute only to undesired responses. For ideal mixing, therefore, the transconductance curve should approach a straight line. As the transconductance curve becomes linear, higher-order derivatives (i.e., above the second) reduce to zero and the conversion transconductance increases. Fig.4 shows that the transconductance curve is most linear at

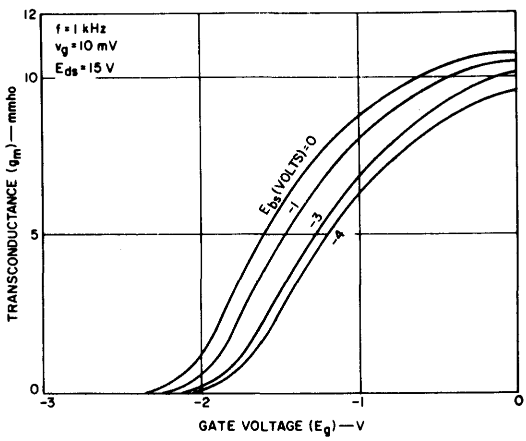


Fig.4 - Transconductance of the RCA-40559 as a function of gate bias with the substrate voltage as the parameter.

a substrate bias of -3 volts. Fig.5 shows the relative conversion gain of the RCA-40559 mixer stage as a function of the oscillator injection level at substrate bias of zero and -3 volts. It can be seen that the conversion transconductance also increases with the oscillator injection level.

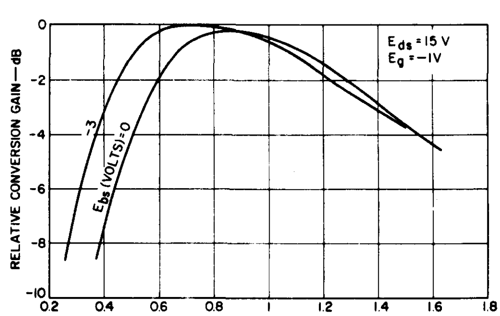


Fig.5 - Conversion transconductance as a function of oscillator injection level.

Table II shows the MOS device characteristics measured under circuit conditions. Reasonable verification of the measured conversion transconductance was obtained by calculation of the conversion transconductance for gate voltages ranging from zero to -2.1 volts. Details of these measurements are given in the Appendix.

Parameter	Units	RF Amplifier RCA-40468	Mixer RCA-40559
C_{rss}	pF	0.12	0.12
R_{in}	KΩ	4.5	6 (100 MHz)
C_{in}	pF	5.5	5.0
R_o	KΩ	4.2	12 (10.7 MHz)
C_o	pF	1.4	1.5
y_{21}	mmho	7.5	2.8
MAG	dB	24.2	21.5
MUG (unneutralized)	dB	14	-
G_p (in tuner)	dB	12.7	17.5

Table II - Device parameters for RCA-40468 and 40559 MOS field-effect transistors.

On the basis of these results, the optimum operating conditions for the mixer circuit were empirically established at an effective gate bias of -1 volt and an effective substrate bias of -3 volts to provide a typical drain current of 3 milliamperes.

Oscillator-Circuit Considerations

The common-collector oscillator circuit shown in Fig.1 generates an extremely clean output waveform.[7] The absence of harmonics in the oscillator signal is an important factor in good tuner design. The oscillator signal is coupled to the mixer gate by means of a 1.5-picofarad capacitor which isolates the tuned circuit of the oscillator from the input circuit of the mixer and thus minimizes the possibility of oscillator instabilities as a result of "pulling".

Over-all Tuner Performance

The performance of the single-gate MOS tuner with respect to sensitivity, limiting, and particularly spurious response exceeds that obtained with the best bipolar transistors. In general, spurious-response performance can be degraded by inadequate circuit layout and wiring practices. For this reason, care should be exercised in arranging the physical layout of the tuner, and power-supply decoupling should be used.

Figs.6 and 7 show the measured sensitivity of the tuner of Fig.1. The quieting sensitivity, shown in Fig.6, is practically flat across the entire FM band. IHFM sensitivity and 3-dB limiting, shown in Fig.7, show the same excellent performance. The IHFM sensitivity test input voltage, as defined by the Institute of High Fidelity Manufacturers, is the minimum 100-per-cent-modulated signal input which, when applied to a receiver through the standard 300-ohm dummy antenna and an audio voltmeter connected through a 400-Hz filter, reduces a total internal receiver noise and distortion to the point where the output rises 30 dB when the 400-Hz null filter is removed from the audio voltmeter circuit. This value is expressed in microvolts.

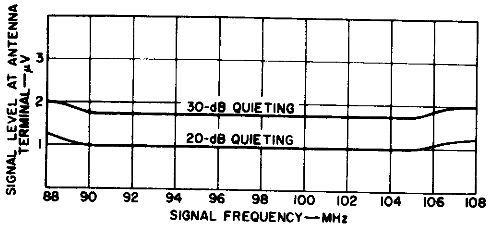


Fig.6 - Signal level for 20- and 30-dB quieting as a function of signal frequency.

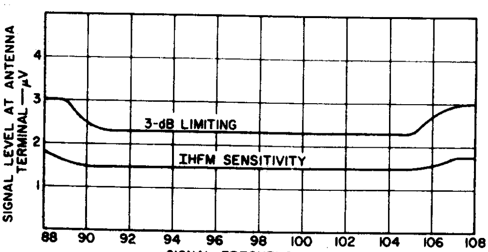


Fig.7 - Signal level for 3-dB limiting and IHFM sensitivity as a function of signal frequency.

Figs.8 and 9 provide additional performance characteristics. Fig.8 shows the gain and noise characteristics; Fig.9 shows the image and half-if rejection of the tuner. The spurious responses shown in Fig.9 were measured with a generator drive capability of 350-millivolts from 10.7 to 216 MHz.

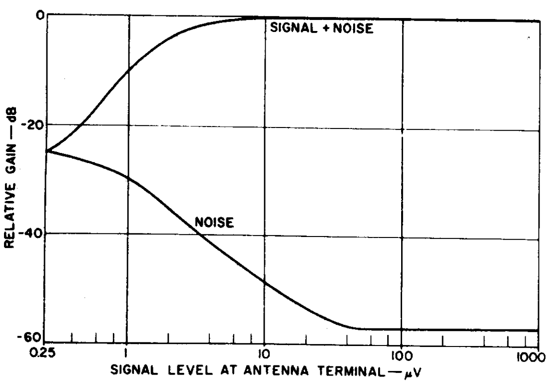


Fig.8 - Relative gain of signal and noise as a function of the signal voltage level.

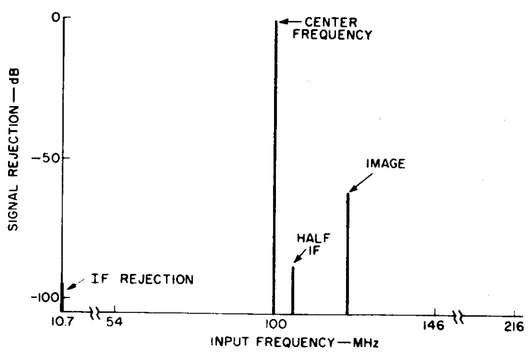


Fig.9 - Signal rejection as a function of input frequency, measured with a generator voltage of 350 millivolts.

MOS transistors covering a wide range of drain current were tested in the rf-amplifier and mixer sockets. Performance variations for image rejection and half-if rejection were within ± 1 dB of the values shown in Table I. Variations in sensitivity were less than 0.25 microvolt.

Conclusions

The RCA-40468 and 40559 MOS field-effect transistors were designed into an FM tuner. Evaluation of this tuner was made in conjunction with an FM-if amplifier that used 40245 and 40246 bipolar transistors. Over-all performance of the combination showed that the capability of MOS devices for dynamic range, sensitivity, and spurious response rejection exceeds that obtained with similar FM tuners that used bipolar transistors. Experimental work indicated that performance variations as a function of product distribution were insignificant.

APPENDIX

Calculation of Conversion Transconductance from the Operating Characteristic

The following procedure is used to calculate the conversion transconductance of the mixer stage based on the degree of linearity of the transconductance curves of Fig.4 and the magnitude of the oscillator injection voltage. The results show that the conversion transconductance is greatest for the curve that is most linear. For the mixer circuit described in this Note, this condition occurs at a substrate bias of -3 volts.

For the curves of Fig.4, the transconductance g_m is given by the following general relation:

$$g_m = f(E_g) \qquad (2)$$

where E_g is the gate bias. For a substrate bias of -3 volts, and a gate bias between zero and -2.1 volts, the corresponding curve of transconductance is expressed as follows:

$$g_m = 12.5 - 2.14\epsilon^{-0.937E_g} \quad (3)$$

For optimum mixer performance with a minimum of spurious responses, a gate voltage of -1 volt was selected as the quiescent operating point. The Taylor series expansion for Eq.(3) for a center-point operating bias E_g of -1 volt is given by

$$g_m = 10.3 + 2.584\ e_g - 0.148\ e_g^2 + 0.75\ e_g^3 + \ldots \quad (4)$$

where e_g is the instantaneous voltage on the gate. This instantaneous gate voltage e_g can be expressed in terms of the peak oscillator signal voltage e_o, as follows:

$$e_g = -1 + e_o \sin \omega_o t \quad (5)$$

Substitution of Eq.(5) into Eq.(4) yields the following expression for transconductance:

$$g_m = 6.82 + 5.13\ e_o \sin \omega_o t - 2.39\ e_o^2 \sin^2 \omega_o t + 0.75\ e_o^3 \sin^3 \omega_o t \quad (6)$$

An expression for instantaneous drain current i_d in terms of Eq.(6) and the incoming signal e_s can then be written, as follows:

$$i_d = g_m\ e_s \sin \omega_s t \quad (7)$$

Expansion of Eq.(7) in terms of $e_o \sin \omega_o t$ and $e_s \sin \omega_s t$ and selection of those components which are effective at 10.7 MHz [i.e., sin $(\omega_o - \omega_s)t$ components] provides the following expression for drain current at the intermediate frequency:

$$i_{IF} = (2.57\ e_o + 0.28\ e_o)e_s \quad (8)$$

By definition, the conversion transconductance g_c is equal to the if current divided by the signal voltage, as follows:

$$g_c = i_{IF}/e_s \quad (9)$$

Therefore, g_c can be expressed in terms of the oscillator injection voltage e_o as follows:

$$g_c = (2.57 + 0.28)e_o \quad (10)$$

Because the magnitude of oscillator injection voltage e_o for the MOS FM tuner was selected to be 1 volt peak, the conversion transconductance is calculated to be

$$g_c = (2.57) + (0.28) = 2.85 \text{ mmhos}$$

By use of the same procedure, the conversion transconductance at a substrate bias of zero volts is calculated to be 2.29 millimhos. It is apparent that the application of a substrate bias provides an increase in conversion transconductance of more than 25 per cent.

REFERENCES

1. Kleinman, H. M., and Lee, C. H., "An FM Tuner Using an RCA-40468 MOS-Transistor RF Amplifier." RCA Application Note AN-3453, June 1967.
2. McKeon, E. F., "Cross-Modulation Effects in Single-Gate and Dual-Gate MOS Field Effect Transistors." RCA Application Note AN-3435, August 1967.
3. Fournier, R. V., Lee, C. H., and Peterson, R. T., "Performance Analysis of 3 and 4 Coil FM Tuners Using RCA High Frequency Transistors." IEEE TRANSACTIONS on Broadcast and TV Receivers, November 1965. RCA Reprint No.ST-3295.
4. Baar, L. S., Reich, S., "A Comparison of Solid-State and Electron Tube Devices for TV Receiver and IF Stages," IEEE TRANSACTIONS on Broadcast and TV Receivers, April 1967. RCA Reprint No.ST-3295.
5. Peterson, R. T., "High Quality FM and AM/FM Tuners Using New N-P-N Silicon Transistors," RCA Application Note AN-3466, June 1967.
6. Holmes, D. D., and Stanley, T. O., "Stability Considerations in Transistor IF Amplifiers," TRANSISTORS I, RCA Laboratories, Princeton, N.J., 1956.
7. Fournier, R. V., Lee, C. H., and Kuklis, J. A., "A Goal: Spurious Signal Immunity of Solid State AM/FM Tuners." IEEE TRANSACTIONS on Broadcast and TV Receivers, April 1966. RCA Reprint No.ST-3295.