RCA Application Note

AN-3453

An FM Tuner Using an RCA-40468 MOS-Transistor RF Amplifier

by

H. M. Kleinman and C. H. Lee

Previous work with field-effect transistors in general, and MOS field-effect transistors in particular, has demonstrated the superior signal-handling capability of this type of device.[1-3] This Note describes an FM tuner that incorporates an MOS field-effect transistor as the rf amplifier, and shows how the MOS transistor is instrumental in minimizing the spurious responses normally found in FM receivers.

Spurious responses result when harmonics of an unwanted incoming signal mix with harmonics of the local-oscillator signal to produce a difference frequency which falls within the if passband of the receiver.* When these harmonics of unwanted signals are created in the rf amplifier, they may be removed by improved filtering between the rf amplifier and the mixer. When used as an rf amplifier, the MOS transistor produces an output signal that contains low levels of the harmonics of unwanted signals. As a result, the need for a double-tuned rf interstage transformer is reduced and acceptable performance can generally be achieved with single-tuned circuits in both the antenna and rf interstage sections.

The FM tuner described in this Note utilizes an RCA-40468 MOS rf amplifier, an RCA-40478 bipolar mixer, and an RCA-40244 bipolar oscillator. The rf-stage gain of 12.7 dB and mixer gain of 21.8 dB yield a total tuner gain of 34.5 dB. A three-stage if-amplifier strip that uses RCA-40482 bipolar transistors and exhibits 94 dB of gain completes the FM tuner.

* In a receiver tuned to 100 MHz, the local oscillator is tuned to 110.7 MHz. The second harmonic of the local oscillator occurs at 221.4 MHz. A signal at a frequency of 210.7 MHz can beat with the 221.4-MHz signal to form the 10.7-MHz intermediate frequency. This 210.7-MHz frequency is the second harmonic of 105.35 MHz, which is above the desired channel by half the intermediate frequency.

Table I summarizes the performance of the system. The figure shown for if rejection was achieved when the tuner section was tested with a fully shielded, remotely located if-amplifier strip. When the final tuner was assembled, only partial shielding was used around the if amplifier. This partial shielding, coupled with the close proximity of tuner and if amplifier, reduced the if rejection to 77 dB.

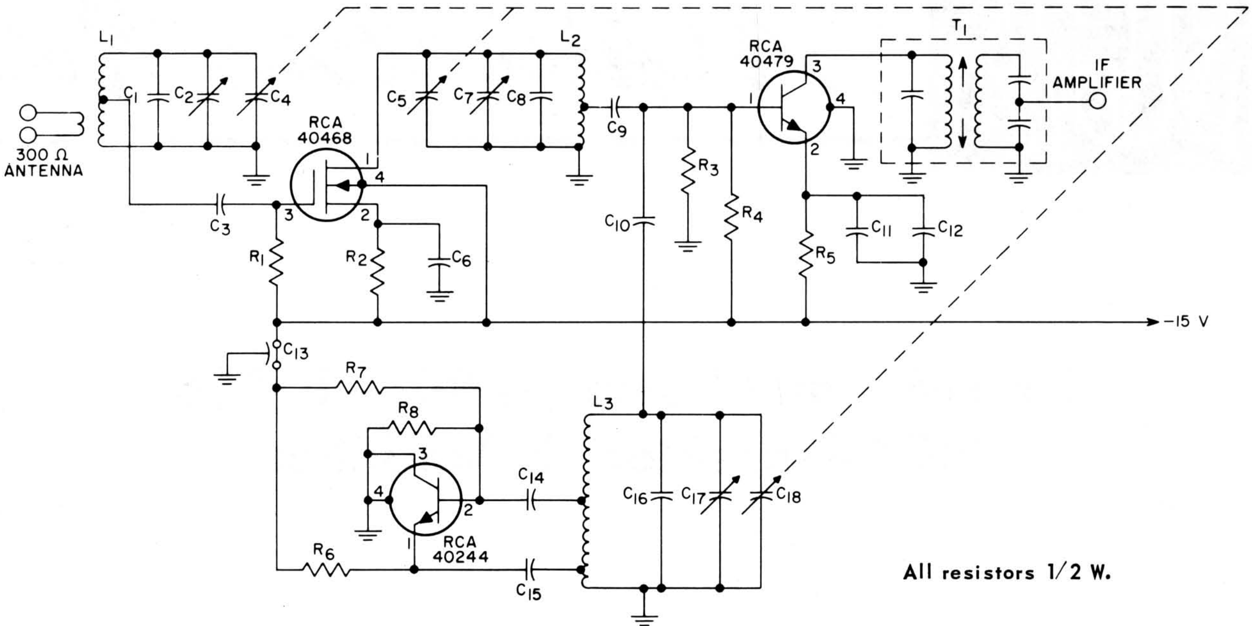
Carrier Frequency	100	MHz
Modulation	400 Hz, 22.5 kHz deviation	
Sensitivity:*		
For 20-dB signal-to-noise ratio	1.4	μV
For 30-dB signal-to-noise ratio	2.2	μV
For -3-dB limiting point (with 94-dB if strip)	1.6	μV
Image Rejection◆	72	dB
IF Rejection◆	91	dB
Half-IF Rejection◆	96	dB
Rejection of Other Spurious Responses◆ (with 0.2 volt at antenna terminals)	>100	dB

* Measured at antenna terminals (300-ohm nominal impedance).
◆ Relative to 2 μV.

Table I - Over-all Tuner Performance

Circuit Considerations

The rf section of the tuner is shown in Fig.1, and the if strip in Fig.2. The if strip, which is described more fully elsewhere,[4] utilizes three 40482 bipolar transistors that operate at collector currents of 3.5



R_1	= 100 KΩ	C_1, C_8, C_{16}	= 16 pF
R_2	= 220 KΩ	C_2, C_7	= 2-12 pF, Trimmer
R_3, R_4	= 47 KΩ	C_3, C_6	= 0.002 μF
R_5	= 4.7 KΩ	C_4, C_5, C_{18}	= 5.5-22.5 pF, ganged tuning capacitor
R_6	= 8.2 KΩ	C_9	= 5000 pF
R_7	= 120 KΩ	C_{10}	= 2.7 pF
R_8	= 22 KΩ	C_{11}	= 0.01 μF
		C_{12}, C_{14}, C_{15}	= 1000 pF
		C_{13}	= 1000 pF feedthrough type
		C_{17}	= 2-10 pF, Trimmer

L_1 = #18 bare copper wire, 4 turns, 1/4" I.D., 7/16" winding length, Q_o at 100 MHz = 130.
Tunes with 34 pF capacitance at 100 MHz.
Antenna Link approximately 1 turn from ground end.
Gate Tap approximately 1-1/2 turns from ground end.

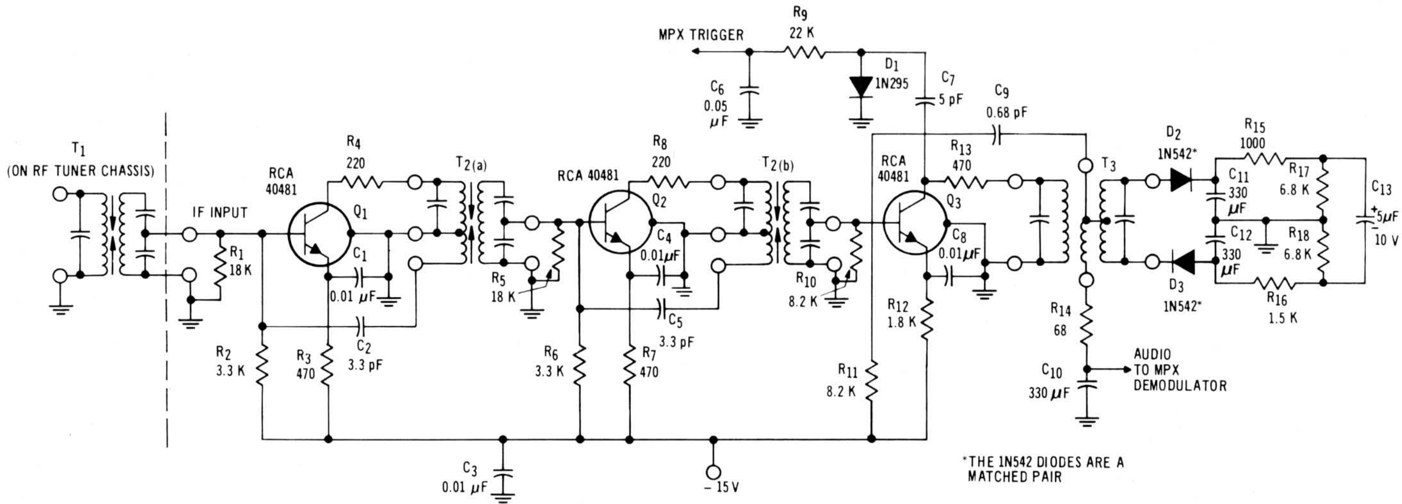
L_2 = #18 bare copper wire, 4 turns, 1/4" I.D., 7/16" winding length, Q_o at 100 MHz = 120.
Tunes with 34 pF capacitance at 100 MHz.
Base Tap approximately 3/4-turn.

L_3 = #18 bare copper wire, 4 turns, 7/32" I.D., 7/16" winding length, Q_o at 100 MHz =120.
Tunes with 34 pF capacitance at 100 MHz.
Emitter Tap approximately 1-1/2 turns from ground end.
Base Tap approximately 2 turns from ground end.

Fig.1 - Typical FM receiver front end using RCA-40468 MOS field-effect transistor.

milliamperes in neutralized configurations and provide an over-all if gain of 94 dB.

The rf section provides a total gain of 34.5 dB, which includes 12.7 dB in the rf stage and 21.8 dB in the mixer. The mixer and oscillator were designed according to principles established previously,[5,6] and details of their design are not discussed. The common-collector oscillator provides an extremely clean oscillator waveform. In addition, the low injection level at the mixer base, 25 to 30 millivolts, coupled with the design of the preceding circuits, limits the maximum possible signal at the mixer base and minimizes the generation of spurious responses in that stage.



T1	TRW-EO-21124-RA
T2(a), T2(b)	TRW-EO-21125-R1
T3	TRW-EO-23023

All resistors 1/4 watt
0.01- and 0.05-μF capacitors, 50-V ceramic disks
330-pF capacitors, 1-kV disks

Fig.2 - Typical if-amplifier strip.

RF-Stage Design

The 40468 rf stage is designed to achieve the published maximum usable stable gain of 14 dB at a nominal operating point of 5 milliamperes. Additional losses of 1.3 dB reduce the actual gain in the tuner to 12.7 dB. Details of the rf-stage design are given in the Appendix.

Selection of the appropriate source and load impedances for the rf stage is based on the fact that a low spurious response requires the gate of the 40468 to be tapped as far down on the antenna coil as gain and noise considerations permit. This arrangement applies the smallest possible voltage swing to the gate and makes optimum use of the available dynamic range. (In a bipolar tuner designed to optimize the rejection of spurious responses, the tap point on the antenna coil was approximately 25 ohms.)

For low spurious response, therefore, the entire rf coil is used as the load for the 40468. The interstage coil presents a load impedance to the rf stage of 3800 ohms, which nearly matches the 4200-ohm output impedance of the 40468. Although this arrangement loads the interstage coil and causes a degradation of selectivity of the front end, it is an acceptable compromise in this case because the antenna coil is not loaded by the gate of the MOS transistor.

As indicated by the calculations in the Appendix, this approach yields a source impedance of approximately 200 ohms for the 4500-ohm input impedance of the gate of the 40468.

Tuner Performance

Performance of the tuner with respect to sensitivity limiting, if rejection, and image rejection compares favorably with that of tuners using high-performance bipolar transistors. Figs.3, 4, and 5 show typical performance characteristics of the receiver. Receiver performance, particularly as regards spurious-response-rejection figures, is highly dependent on such factors as physical layout, power-supply decoupling, and care in construction. The use of a negative supply voltage facilitates the grounding of tuned circuits and the decoupling of the supply.

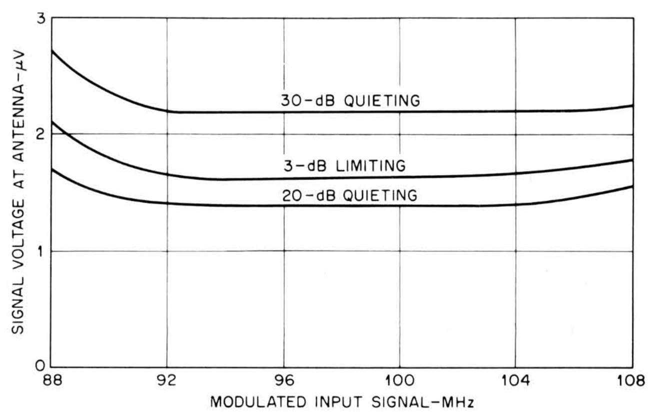


Fig.3 - Sensitivity curves for FM receiver using circuits of Figs.1 and 2.

The elimination of spurious response was the primary goal in this design. Generally, a circuit that has a low spurious response is difficult to reproduce. In some systems, the performance of such a circuit depends on the exact operating points of the transistors used; when the rf-amplifier transistor in Fig.1 was repeatedly changed, performance of the tuner remained essentially the same. The best correlation was found with the operating current of the transistor in the circuit. Fig.6 shows the change in the rejection of the "half-if" spurious response as a function of drain current for a

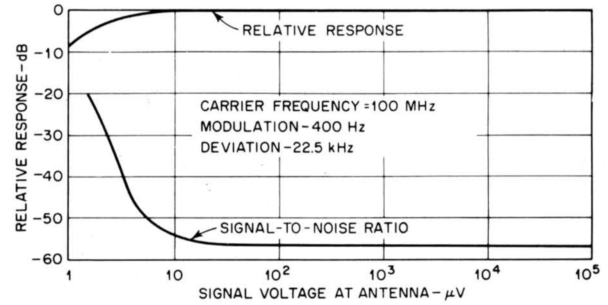


Fig.4 - Relative response as a function of signal voltage measured at antenna terminals.

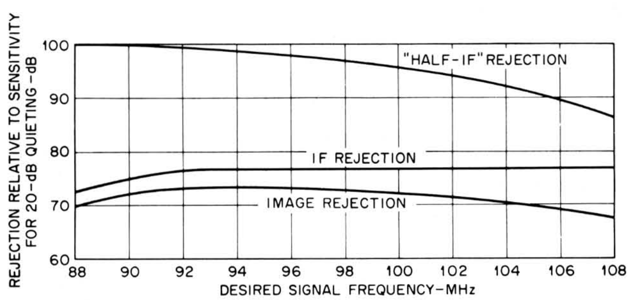


Fig.5 - Spurious-response rejection as a function of frequency.

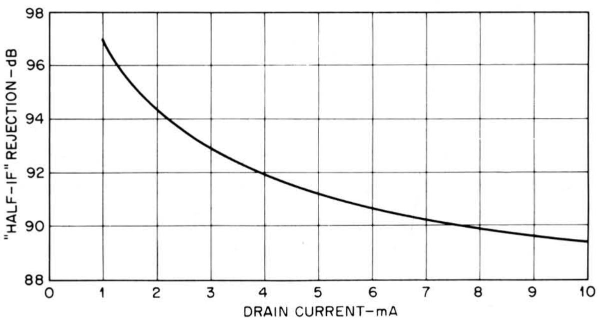


Fig.6 - Half-if rejection as a function of operating point.

typical 40468. For the normal spread of operating current in this circuit of 3.5 to 7 milliamperes, the variation in rejection is shown to be about ± 1 dB.

Fig.7 shows the variation of 20-dB quieting sensitivity as a function of drain current, and indicates why the 5-milliampere nominal operating point was chosen. Below 3 milliamperes, the sensitivity of the receiver degrades very rapidly. However, at 5 milliamperes the actual spread of 3.5 to 7 milliamperes causes a negligible change in performance.

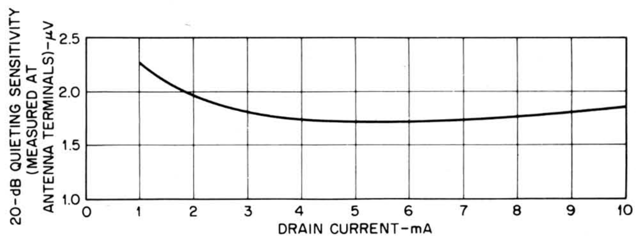


Fig.7 - 20-dB quieting sensitivity as a function of operating point.

Conclusions

The 40468 MOS field-effect transistor has been incorporated into an FM tuner in which all other stages are high-performance, low-capacitance bipolar types. The wider dynamic range of the MOS transistor provides significant improvements in the rejection of spurious responses over results previously achieved with bipolar rf amplifiers.

Most significantly, the performance with respect to spurious-response rejection has been repeated when devices with wide parameter variations have been used. Furthermore, the system has been duplicated with comparable results. These two factors strongly indicate that the performance advantages are real and are attributable to the characteristics of the MOS rf amplifier used rather than the result of cancellation or peculiar trapping in a single tuner.

Appendix - Design of 40468 RF-Amplifier Stage

The following parameters are important in the design of the rf-amplifier stage:

40468 parameters (at V_{DD} = 15 V, I_D = 5 mA):

input resistance R_{in}	4500	ohms
output resistance R_{out}	4200	ohms
forward transmittance y_{fs}	7500	μmhos
feedback capacitance C_{rss} (max).	0.2	pF

mixer-stage parameters:

input resistance R_{in}(mix)	550	ohms
input stability IS(mix) (from previous design)	4	

coil data:

mounted unloaded Q.	120	
tuning capacitance C_T at 100 MHz	34	pF
antenna impedance	300	ohms

Fig.8 shows the ac equivalent circuit for the rf stage. At resonance, this circuit reduces to the form

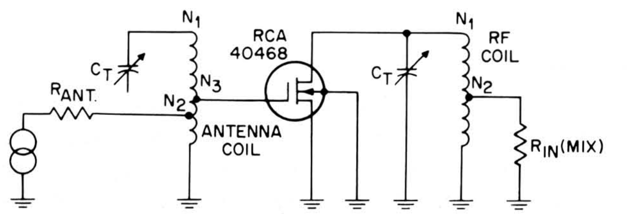


Fig.8 - AC equivalent circuit of the 40468 rf stage.

shown in Fig.9, where all impedances are referred to the gate and drain terminals of the 40468. The maximum available gain (MAG) is the gain in a conjugately matched, unilateralized circuit and is defined as follows:

$$MAG = \frac{|y_{fs}|^2 R_{in} R_{out}}{4} \quad (1)$$

For the values given above, MAG = 266 = 24.2 dB.

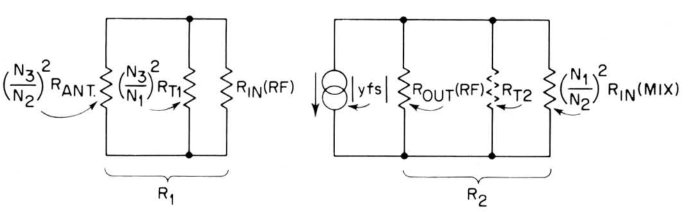


Fig.9 - Equivalent input (R_1) and output (R_2) circuit of the rf stage during resonance.

The maximum usable gain MUG is the stable gain which may be realized in a practical neutralized or unneutralized circuit. It is defined by the relationship for the unneutralized case as follows:

$$MUG = \frac{2\,|y_{fs}|}{\omega C_{rss}} \times \frac{a}{b} \quad (2)$$

where a is a skew factor smaller than unity which is used to maintain bandwidth, and b is a number equal to or greater than unity related to the number of stages (inserted to maintain bandwidth in multistage amplifiers). A skew factor of 0.2 is generally used. Because only one stage of 100-MHz gain is used in the amplifier shown in Fig.1, b = 1. For the values given, therefore, MUG is given by

$$MUG = \frac{0.4\, y_{fs}}{\omega C_{rss}} = 23.5 = 13.7 \text{ dB} \quad (3)$$

The total mismatch loss is called the stability factor S, and is equal to the difference (in dB) between MAG and MUG, as follows:

$$S = MAG - MUG = 10.5 \text{ dB, or } 11.3 \text{ times} \quad (4)$$

This value is arbitrarily divided between the input and output circuits by use of an input stability IS and an output stability OS, as follows:

$$IS = R_{in}/2R_1 \quad (5)$$

$$OS = R_{out}/2R_2 \quad (6)$$

where R_1 and R_2 are the total parallel impedances at the input terminal (gate) and the output terminal (drain), respectively. These stability terms are related to the stability factor S as follows:

$$S = IS \times OS \quad (7)$$

The division between IS and OS is made by means of some arbitrary choices. As mentioned previously, it was decided to maximize IS so that the signal level at the gate would be minimized. This choice necessitates matching or nearly matching R_{out} to its load. Therefore, the entire rf coil is used as the output load.

As indicated in Eq.(6), the value of R_2 must be determined to define OS; the value of IS can then be determined and the input circuit defined. R_2 consists of the parallel combination of R_{out}, R_{T2}, and $(N_1/N_2)^2 \times R_{in}$(mix), where R_{T2} is the tuned impedance of the rf coil and is given by

$$R_{T2} = Q_o/\omega_o C_t \quad (8)$$

The value of R_{out} is given above as 4200 ohms. The value of R_{T2} as calculated from Eq.(8) is 5600 ohms. The value of the input impedance of the mixer R_{in}(mix), obtained from the published data for the 40479, is 550 ohms. The only remaining component of R_2 to be determined is the turns ratio N_1/N_2.

In Fig.8, the rf coil L_2 represents both the input circuit of the mixer and the output circuit of the rf stage. Therefore, the stability of the mixer stage must also be considered. Because stability factors are equal to resistance ratios, the input stability of the mixer can be considered at the top of the rf coil, as follows:

$$IS(mix) = \frac{(N_1/N_2)^2 R_{in}(mix)}{2R_2} \quad (9)$$

The value of IS(mix) was specified above as 4 (from a previous design). Because R_2 is a linear function of $(N_1/N_2)^2 R_{in}(mix)$, manipulation of the data through several steps provides a value of 5.5 for (N_1/N_2) and a reflected value of 16,800 ohms for $R_{in}(mix)$.

The output stability of the rf stage can then be determined. R_2 is computed as the parallel combination of R_{out}, R_{T2}, and $(N_1/N_2)^2 R_{in}(mix)$, and is found to be 2100 ohms. The output stability OS is determined from Eq.(6), as follows:

$$OS = R_{out}/2R_2 = 4200/(2 \times 2100) = 1$$

The value of unity indicates an impedance match between R_{out} and the load.

The input stability of the rf amplifier can then be determined from Eq.(7), as follows:

$$IS = S/OS = 11.3$$

By use of this stability term, the input-circuit constants can be calculated. R_1 is determined from Eq.(5), as follows:

$$R_1 = R_{in}/2IS = 191 \text{ ohms}$$

This value is so much lower than R_{in} that it is apparent the MOS transistor does not load the antenna coil at all.

Because it is desired to match the antenna with the input circuit, the value of R_1 should be one-half the reflected antenna impedance. Therefore, the value of $(N_3/N_2)^2 R_{ANT}$ is 382 ohms, which is a very slight step up. Because two of the three component terms of R_1 are then known, the remaining term $(N_3/N_1)^2 R_{T1}$ can be determined as 456 ohms. The turns ratios are then given by

$$N_1/N_2 = 4.3$$
$$N_1/N_3 = 3.7$$

The values of circuit components obtained by means of this design method are given in the parts list for Fig.1.

References

1. F. M. Carlson and E. F. McKeon, "Small Signal RF Amplification of MOS Devices," **Proceedings of the 1966 National Electronics Conference.**
2. F. M. Carlson, "Application Considerations for the RCA-3N128 VHF MOS Field-Effect Transistor," RCA Application Note AN-3193, August 1966.
3. D. L. Leonard, "Improve FM Performance with FETS," **Electronic Design**, Vol.15 No.5, March 1967.
4. R. T. Peterson, "High-Quality FM and AM/FM Tuners Using New Silicon Transistors," RCA Application Note AN-3466, June 1967.
5. R. V. Fournier, C. H. Lee, and R. T. Peterson, "Performance Analysis of 3- and 4-Coil FM Tuners Using RCA High-Frequency Transistors," **IEEE Transactions on Broadcast and TV Receivers,** November 1965.
6. R. V. Fournier, C. H. Lee, and J. A. Kuklis, "A Goal: Spurious-Signal Immunity of Solid-State AM/FM Tuners," **IEEE Transactions on Broadcast and TV Receivers,** April 1966.