AN ADVANCED LOW POWER RADIO 1 CHIP IC

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1. ABSTRACT

A low-power single chip FM/AM radio IC capable of extending the battery life of a radio has been developed. Decreasing the current consumption is realized solely by new circuit design techniques without making changes to the conventional processes in IC fabrication. Characteristics of this IC is not degraded even though the current consumption is decreased, but instead, operating time has been improved to be four or five times than that of the conventional radio. [1]

2. INTRODUCTION

Since the realization of a single chip FM/AM radio IC [1] in 1983, radio ICs have continued to developed and advanced with the aim of reducing use of external components, cost, and current consumption. In 1986, an AM radio IC which operates at a current of only 400μA was developed. And then in 1992, a single chip FM stereo / AM radio IC [2] which includes IF (Intermediate Frequency) filters that operates at a supply voltage of 0.95 V was realized. Just like this, radio ICs have been developed for many different purposes such as low-voltage operation or low-current consumption. But the IC that will be described here was developed so that both the AM radio and FM radio have low-current consumption.

Portable pocket radios are small and thin that they require miniature battery like button type one. Naturally, radio ICs which is used for such radios must be low-power consuming to have sufficient operating time.

The current consumption is decreased by sharing current technique. Because this IC must operate by two dry batteries, the minimum operating voltage is 1.8 V. New sharing-current circuits can operate at low voltage.

This paper deals with a degradation of a bipolar transistor characteristic due to low current at first, then particular problem of a radio IC, the solution and new circuits, and characteristics of this IC at last.

3. DEGRADATION OF TRANSISTOR CHARACTERISTICS DUE TO LOW CURRENT OPERATION

Generally when it comes to bipolar transistor, a decrease in current results in a decrease of transition frequency f_T and an increase of equivalent input noise. Specially for high-frequency analog IC such as radio IC, the following problems occur due to low-current operation.

a) decrease of gain-bandwidth product
b) increase of equivalent input noise
c) degradation of interference characteristics (inter modulation, blocking, pull-in)
d) increase of distortion

Hereafter, we will refer to equivalent input noise as NOISE for simplicity as distinguished from the noise generally used. A decrease in current causes a decrease of gain-bandwidth product due to a decrease of f_T. Moreover, a decrease of gm makes a shot noise dominant resulting in an increase of NOISE. Due to today's advanced processes in IC fabrication, transistor has become small, and even in low current, high f_T transistor can be made. However, shot noise that occurs related to current can not be made small.

Since collector current of a bipolar transistor is an exponential function of base-emitter voltage, the intercept point of a single transistor is known to be 94dB μV (see Fig. 3.1).

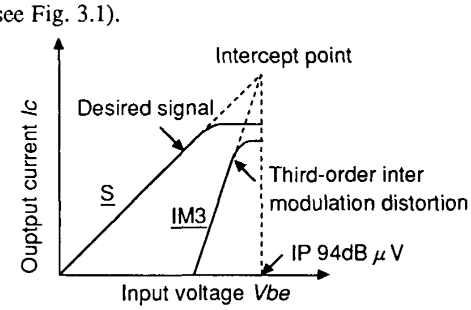

Fig. 3.1 Input voltage *Vbe* versus output current *Ic*

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That means maximum input signal level must be limited. Therefore, to increase the dynamic range related to transistor, current must be increased and NOISE level must be reduced.

3.1 INTERCEPT POINT OF BIPOLAR TRANSISTOR

Intercept point as shown in Fig. 3.1 can be calculated as follows.

The relationship of base-emitter voltage Vbe and collector current Ic is,

$$Ic = Is \times \exp(Vbe/Vt)$$

where Vt = kT/q, k is Boltzmann's constant, and q is the electric charge. At room temperature Vt = 26mV.

The transconductance is defined as

$$gm = dIc/dVbe$$

and then

$$d^3Ic/dVbe^3 = d^2gm/dVbe^2 = Ic/Vt^3 \qquad -(1)$$

The total collector current Ic can be expanded in a power series

$$Ic = Ic + gm \times Vbe + 1/2! \times dgm/dVbe \times Vbe^2 + 1/3! \times d^2gm/dVbe^2 \times Vbe^3 + \cdots \qquad -(2)$$

When two signals ($\alpha \sin \chi t$) and ($\beta \sin \psi t$) are added to this transistor, substituting $Vbe = \alpha \sin \chi t + \beta \sin \psi t$ in (2),

the third harmonic distortion signal Ic_3 occurs,

$$Ic_3 = \alpha\ \beta^2 / 8 \times d^2gm/dVbe^2 \times \sin(2\psi - \chi)t$$
$$= \alpha\ \beta^2 / 8 \times Ic/Vt^3 \times \sin(2\psi - \chi)t \quad -(3)$$
$$(\because d^2gm/dVbe^2 = Ic/Vt^3)$$

When a desired input signal ($\gamma \sin \omega t$) is added to this transistor,

$$Ic_1 = gm \times \gamma \sin \omega t \qquad -(4)$$

An input signal level at intercept point is derived from an assumption that desired output current level is equal to the third order inter modulation distortion level.

From equations (3), and (4), assuming $Ic_1 = Ic_3$

$$\alpha\ \beta^2 / 8 \times Ic/Vt^3 \times \sin(2\psi - \chi)t = gm \times \gamma \sin \omega t$$

and assuming $\alpha = \beta = \gamma$, $2\psi - \chi = \omega$,

$$\gamma^2 = 8 \times Vt^2$$
$$\gamma = 73.5\text{mvp}\ (94.3\text{dB}\mu\text{V})$$

Therefore the intercept point input voltage level is 94.3dBμV, which is constant for any collector direct bias current as shown in Fig.3.1.

3.2 NOISE OF BIPOLAR TRANSISTOR

Consider a bipolar transistor small signal equivalent circuit with noise sources. A noise source consists mainly of shot noise relating to a direct-current flow, thermal noise from base resistance, and flicker noise which rises with lowering of frequency.

A bipolar transistor small-signal equivalent circuit with noise generators is shown in Fig.3.2. vn^2, in^2 are input equivalent noise generators.

These noise sources are expressed using the next equations,

$$vn^2/\Delta f = 4kT \times (Rb + 1 / (2gm))$$
$$in^2/\Delta f = 2q \times (Ib + K \times Ib^a / f + Ic / \beta^2)$$

where Rb is base resistor, Ib is base current, K is constant for a particular device, Ic is collector current, β is forward current gain, f is frequency, and a is a constant in the range of 0.5 to 2. [3]

The noise figure of an amplifier is the ratio of the sum of these noises and thermal noise of source impedance. When a source impedance is low, current generator in^2 is negligible. The voltage source vn^2 consists of thermal noise 4kTRb produced by base resistance, and 4kT × 1 / (2gm) which is NOISE of the collector current shot noise. As current is decreased, noise 4kT × 1 / (2gm) becomes dominant and a noise figure is degraded.

This shot noise is inherent in a diode and a transistor. It can not be decreased even if an advanced processes in IC fabrication is used.

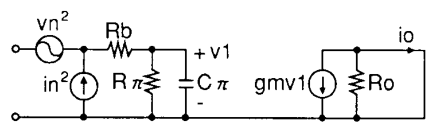


Fig.3.2 Bipolar transistor small-signal equivalent circuit with noise generators

4. PROBLEM IN RADIO IC DUE TO LOW CURRENT

Since such degradation of bipolar transistor characteristics influence a radio performance very much, some circuits in radio IC need relatively large current.

Fig.4.1 is a block diagram of a superheterodyne radio. Received signals from antenna are converted to IF (Intermediate Frequency) signal at mixer, then a desired signal is selected at filter, amplified at IF amplifier. Therefore, RF amplifier's NOISE must be lower than the signal level from the antenna. IF amplifier must be low noise to make a front-end gain low. And a current of an AF amplifier can not be reduced to avoid cross-over distortion. In this way RF, LO, IF, and AF need a relatively large current to avoid a degradation of radio characteristics.

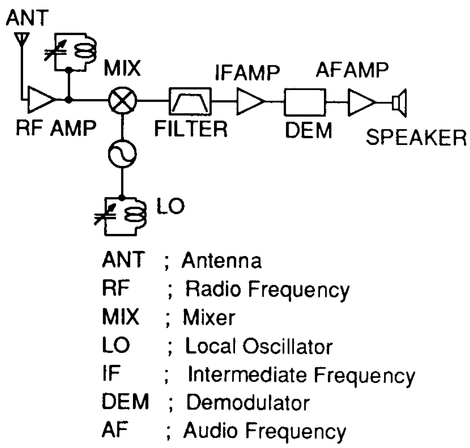


Fig. 4.1 Superhetrodyne radio

4.1 RF AMPLIFIER AND MIXER

At FM front-end of a radio a high frequency signal about 100MHz is amplified. As a current of amplifier is decreased, high frequency characteristic of a transistor is degraded and gain of the amplifier is decreased. And due to an increase of a NOISE generated from a transistor the noise figure is degraded.

As shown in Fig.4.2, generally an impedance of FM antenna is about 75Ω, the impedance steps up at BPF (Band Pass Filter) attached to FM RF amplifier input, and then output impedance of the filter is 150~300 Ω, which is reasonable to realize a good interference performance. To make noise figure low in spite of such low input source impedance, relatively large current is needed at FM RF amplifier.

Taking into account FM interference characteristic, many tunable filters are needed in RF circuit preceding the mixer. But to achieve such circuit, peripheral components increase and currents increase. This IC is used for a pocket portable radio, therefore RF circuit selectivity is adequate using a broad band BPF and a single tunable filter as shown in Fig.4.2. An image interference characteristic is adequate by these two filters, but these filters are not effective to inter modulation and cross modulation interference. Therefore these interference are decided by voltage gain of RF amplifier and mixer interference characteristic. RF circuit must be designed taking into account such interferences.

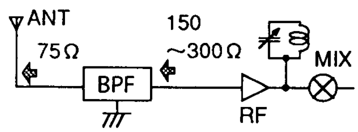


Fig. 4.2 FM front-end configuration

4.2 LOCAL OSCILLATOR CIRCUIT

At this circuit, an oscillation level become low if current decrease. Because of this, the oscillator signal pull-in, caused by an external interference signal, occur. And then the oscillator become unstable or stop. Therefore large current is needed in the circuit.

Moreover, an oscillator C/N (Carrier to Noise ratio) influence demodulated FM signal S/N (Signal to Noise ratio). Since C/N depends on noise level of transistors, the oscillator current must be large.

4.3 IF CIRCUIT

Intermediate Frequency (IF) circuit is the highest gain amplifier in a radio. Front-end gain will be low if noise figure of IF circuit is low. It is effective to decrease a front-end current. And in order to make a total noise figure of IF circuit low, the first IF amplifier must be low NOISE and high gain.

Because a gain of FM IF circuit is high, and high frequency (10.7MHz) signal is amplified by the circuit, FM IF circuit is multiple stages amplifiers. In multiple stages amplifiers, gain of a single amplifier is a product of a current and a load resistance. But at high frequency operation, the gain dose not increase even if a load resistance is increased, because a capacitance parallel with a load resistance is not negligible.

Therefore in order to realize high gain FM IF circuit, the current of this circuit becomes large.

4.4 AF CIRCUIT

In AF circuit, due to low current operation, the gain decreases, cross-over distortion increases. Because value of negative feed back in low-gain amplifier is low, distortion will increase. Moreover, the amplifier will not drive low impedance like a dynamic speaker if the current is low.

5. SOLUTION AND NEW CIRCUITS

In order to reduce consumption current, sharing-current technique is used in this radio IC. When two circuits are biased independently as shown in Fig.5.1 and a regulator is a conventional series regulator, a consumption current is I1+I2. But when circuit1 is connected in series with circuit 2 as shown in Fig.5.2, A current I1 flows circuit2 also and a consumption current is only I1 or I2 smaller than I1 + I2. In addition, since the Regulator line impedance is very low, interference between two circuits is very small.

This IC operates by two dry batteries. So in order to realize new circuit as shown in Fig. 5.2, Both circuit 1 and circuit 2 must operate at a low supply voltage under 1.1volt, and the regulator must drive both direction current.

As shown in Fig.5.3, output current of this regulator flows in both direction. When a load current IL is negative, transistor Q1 will turn on, when the current is positive Q2 will turn on.

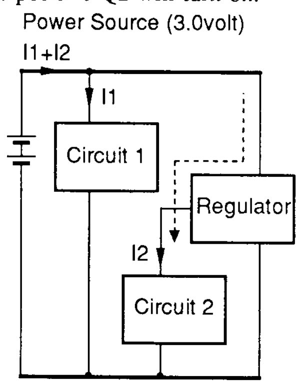


Fig. 5.1 Conventional circuits

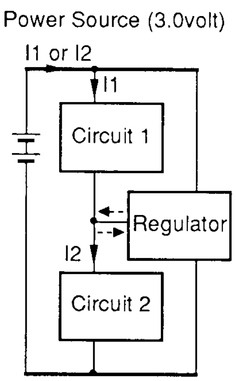


Fig. 5.2 New circuits

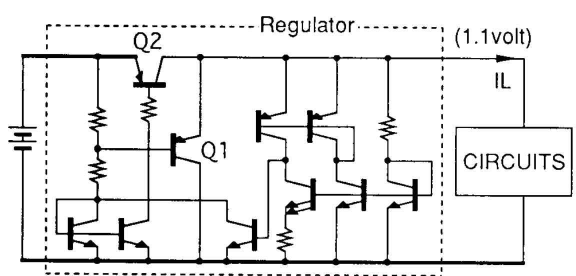


Fig. 5.3 Regulator

In addition, a sum of currents of multiple stages amplifiers such as FM IF amplifier is minimum when the number of stages is optimum. The optimum number of stages can be calculated as follows, assuming that both total gain and load resistances are constant.

As shown in Fig. 5.4, a single stage amplifier's gain Go is

$$Go = RL \times Io / Vt$$

where $Vt = kT / q$

total gain G of the multiple stages amplifier is

$$G = Go^n = (RL \times Io / Vt)^n \qquad -(1)$$

where n is a number of stages

and total current I of n stages amplifiers is given

$$I = 2 \times Io \times n \qquad -(2)$$

Combining (1) and (2)

$$I = 2n \times Vt \times G^{1/n} / RL$$

The relationship of n and I is shown in Fig. 5.5, total current I is the smallest at the optimum number of stages.

At this point, assuming $dI/dn = 0$,

$$\ln Go = 1$$
$$Go = 2.72$$
$$= 8.7\text{dB}$$

For example, when G = 87dB, optimum number of n is 10 (∵ 87dB / 8.7dB = 10).

The characteristic of n stages versus total current I is shown in Fig. 5.5 when G = 87dB RL = 5kΩ. [4]

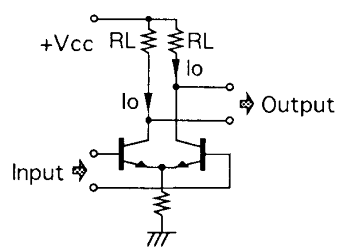


Fig. 5.4 Single-stage amplifier

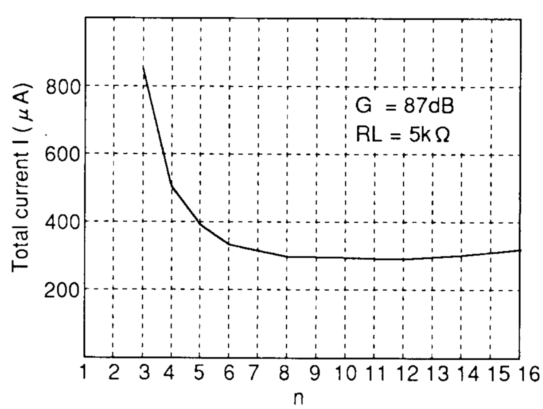


Fig. 5.5 n stages versus total current I

5.1 FM FRONT END

In FM front end, RF amplifier and local oscillator share currents to reduce a consumption current. As shown in Fig.5.6, the RF amplifier is a cascode configuration which consists of transistor Q1 and Q2, and local oscillator is a Colpitts circuit configuration.

In order to decrease currents, mixer circuit is not a double-balanced type, but it is a single-balanced type. Since new circuit's isolation from mixer to local oscillator is improved, a buffer amplifier between the mixer and the local oscillator is not needed.

In order to avoid degradation of interference characteristics of low consumption power, broad band AGC (Automatic Gain Control) is applied in this IC. FM mixer output circuit is shown in Fig. 5.8 . The signal at a collector of a transistor Q1 is detected, and a external capacitor CA is charged by the detected signal. And then the RF amplifier gain is controlled by this capacitor voltage. Therefore mixer input signal level is limited.

Q1 is a emitter-follower amplifier which drive a ceramic filter impedance about 300~330Ω. A large current was needed to drive this low impedance using a class A amplifier in a conventional IC. But this new circuit is a class AB Shunt-Regulated-Push-Pull configuration made up of Q1 and Q2 to decrease currents.

As a result, the image interference response is more than 40dB, spurious response is more than 60dB, and the inter modulation ratio is more than 60dBμV as shown in Fig. 5.7 , so good performance can be achieved for pocket portable radio.

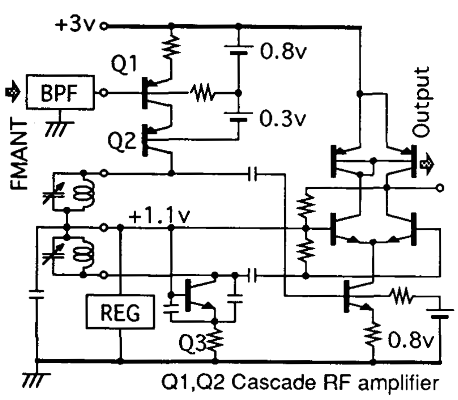


Fig.5.6 FM RF amplifier
FM Local oscillator

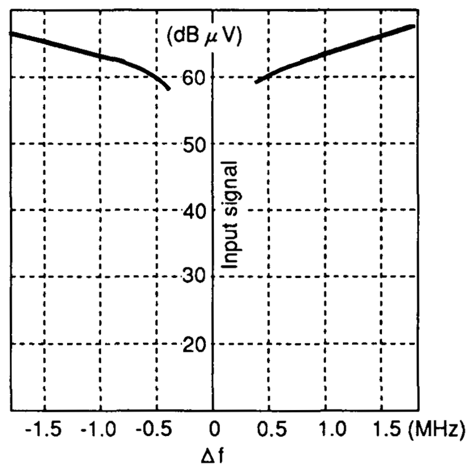


Fig. 5.7 FM inter modulation interferance characteristic

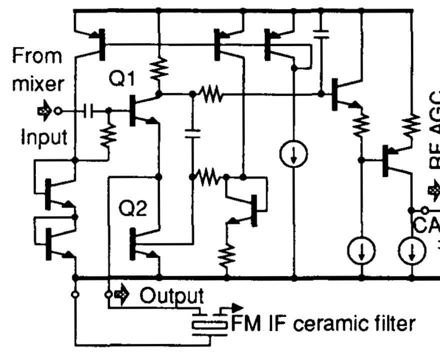


Fig. 5.8 FM mixer output
FM IF post amplifier

5.2 FM IF CIRCUIT

The current of the first amplifier in FM IF circuit is large, since noise figure of the circuit must be low. The direct bias current of the first amplifier flows through the second, the third, the fourth amplifiers. And in effect, four amplifiers can operate by a current of only single amplifier.

This new configuration of FM IF circuit is shown as Fig. 5.9. A direct bias current of this circuit consists of a current Ib, and alternating signal paths are indicated by the dotted lines.

As a result, FM IF circuit operates at 10.7MHz, its voltage gain is 60dB, its consumption current is 100 μA. The voltage gain versus frequency characteristic is shown in Fig. 5.10.

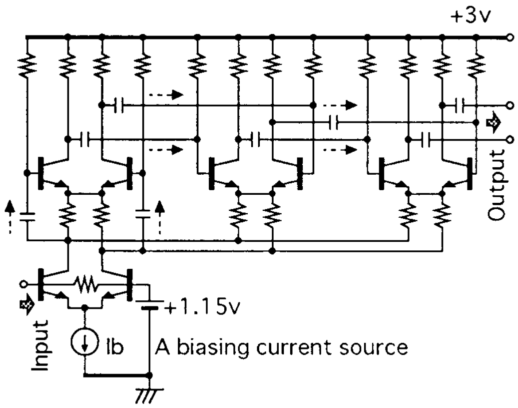


Fig.5.9 FM IF amplifier

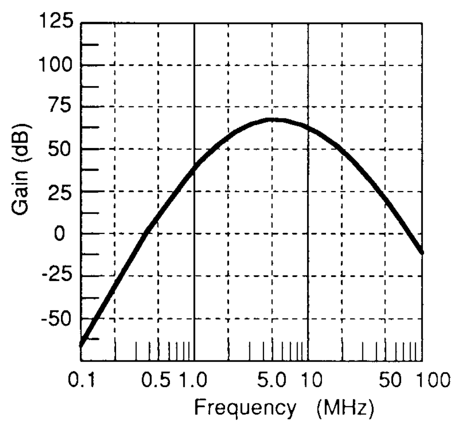


Fig. 5.10 FM IF amplifier gain

5.3 AM CIRCUITS

As shown in Fig. 5.11 , AM IF circuit and AM RF · AM LOCAL circuit share currents. AM RF circuit and AM LOCAL circuit are biased by a voltage regulator, and AM IF circuit is biased by a power supply voltage.

AM RF circuit and AM LOCAL circuit are shown in Fig. 5.12. AM RF circuit consists of differential input transistors Q1 and Q2, and operates at a low supply voltage of 1.1volt. AM LOCAL circuit is a positive feedback type oscillator which consists of Q3 and Q4.

AM IF circuit consists of three stages amplifiers as shown in Fig. 5.12. The second and the third amplifiers consist of PNP transistors (Q7,Q8,Q9,Q10). The gain of the circuit is controlled by the bias current of each differential amplifier.

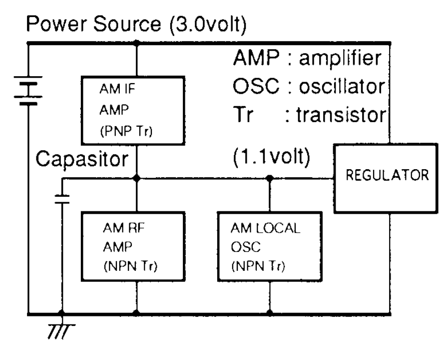


Fig. 5.11 AM circuit block

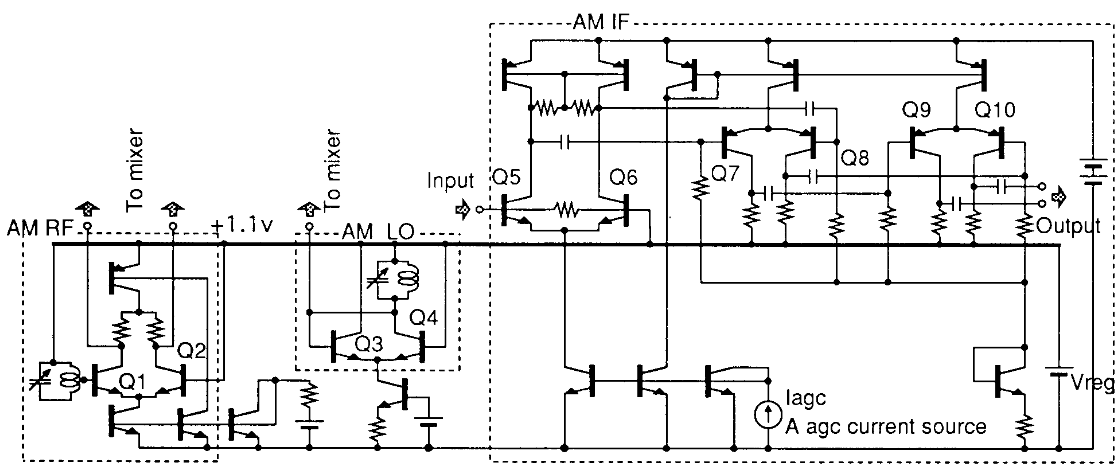


Fig. 5.12 AM RF, LO, and IF circuits

6. OVERALL CHARACTERISTICS

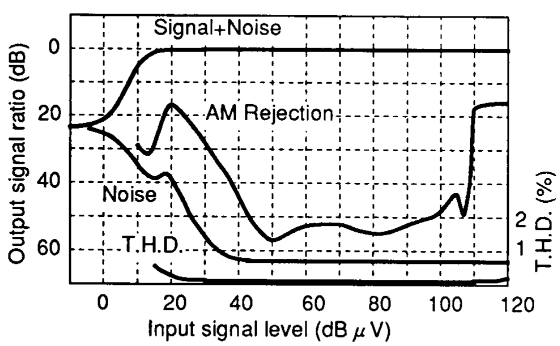
An FM I/O (Input and Output) characteristic is shown in Fig. 6.1. S/N30dB quieting sense is 10dBμ V, S/N is 60dB, T.H.D.(Total Harmonics Distortion) is under 0.2%, AM suppression ratio is about 50dB.

FM effective selectivity with a 3-elements-ceramic filter is shown in Fig. 6.2. An adjacent channel (400kHz away from center frequency) selectivity is 40dB, it is adequate for a pocket portable radio.

AM I/O characteristic is shown in Fig. 6.3, S/N is 50dB, T.H.D. is 0.5%. Noise Figure of antenna input is 2dB when a signal source impedance is 20kΩ corresponding to a ferrite bar antenna impedance.

AM selectivity is shown in Fig. 6.4. A third-order LPF (Low Pass Filter) is included after a mixer circuit in this IC. Spurious response due to harmonic response of a ceramic filter is suppressed by this LPF. AM selectivity with 2-elements ceramic filter is shown in Fig.6.4. An adjacent channel (10kHz away from center frequency) suppression is more than 20dB.

In this way in spite of the low consumption power, characteristics of this IC are same as that of an conventional IC.

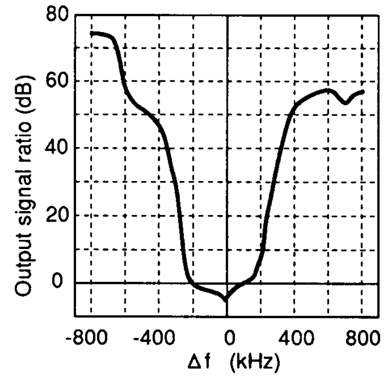


VBB = 3.0volt, Frf = 83MHz, Fmod =1kHz, Fdev = 22.5kHz

Fig. 6.1 FM I/O characteristic

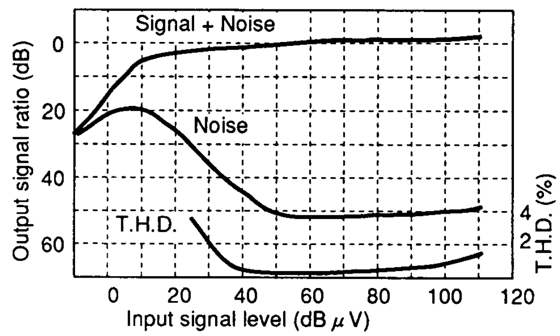
AM S/N 6dB sense	0 dBμV
FM S/N 30dB quieting sense	10 dBμV
AM T.H.D. (AM 30%)	0.5%
FM T.H.D. (Fdev=22.5kHz)	0.2%
Audio output (T.H.D=10% RL=8Ω)	115mW

Table 1 Dynamic characteristics



Desired signal level = 34dBμV

Fig. 6.2 FM effective selectivity



VBB = 3.0volt, Frf = 1000kHz, Fmod = 400Hz30%

Fig. 6.3 AM I/O characteristic

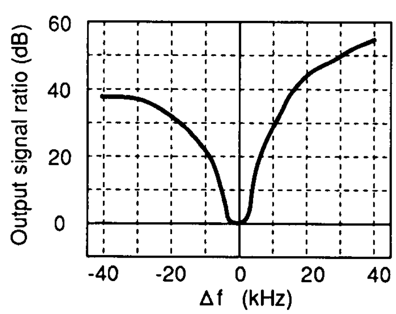


Fig. 6.4 AM selectivity

Operating voltage	1.8v~4.5v
Current consumption (FM)	1.4mA
Current consumption (AM)	0.8mA

Table 2 Static characteristics

7. CONCLUSION

Using the current-saving techniques described, a low-power single chip FM/AM radio IC with current of 1.4mA at FM mode and 0.8mA at AM mode can be achieved. The minimum operation voltage is 1.8V. The current consumption is 1/4 ~ 1/5 that of the conventional one, and in effect, battery life time is four to five times longer. Furthermore, this IC, which is a 24-pin SOP (small outline package), includes all the functions of an FM/AM radio from antenna input to audio output amplifier that can drive a speaker.

Fig. 7.1 is a microphotograph of the IC. Its chip size is 2.81mm×1.95mm. Fig. 7.2 shows the necessary peripheral components while Fig. 7.3 shows an actual card radio that uses this radio IC.

8. ACKNOWLEDGEMENTS

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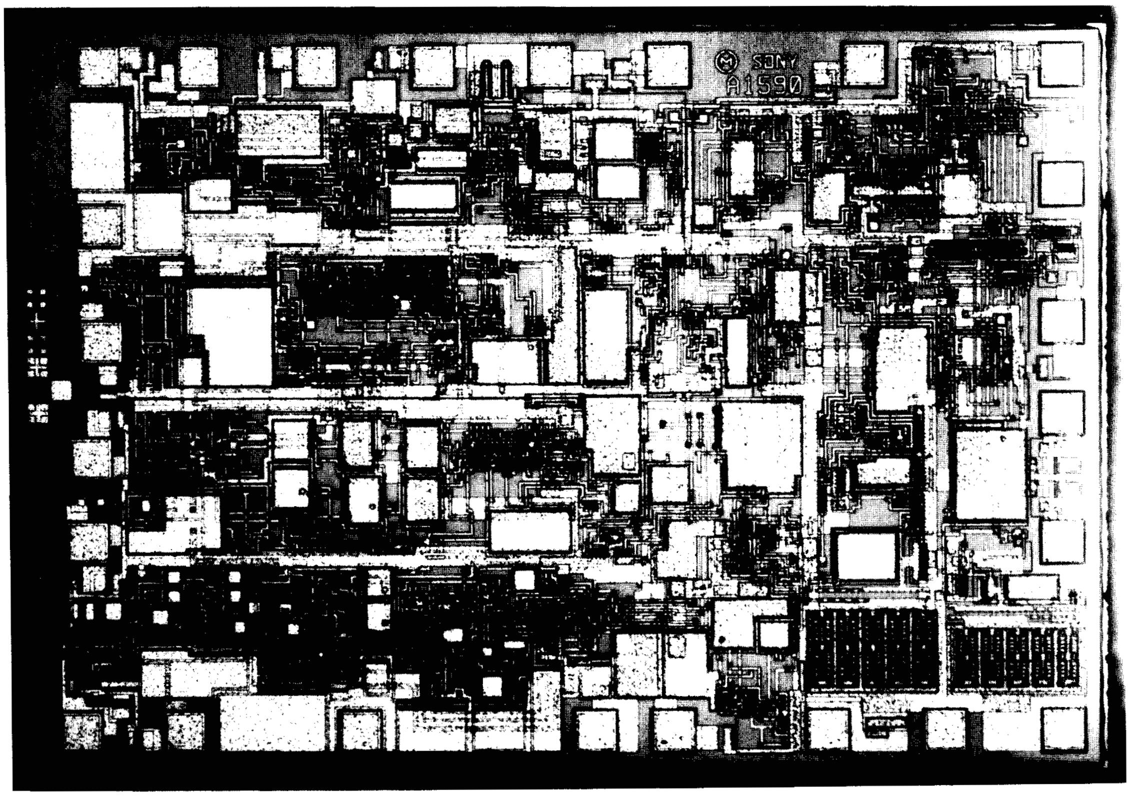

Fig.7.1 Low-power one-chip radio IC

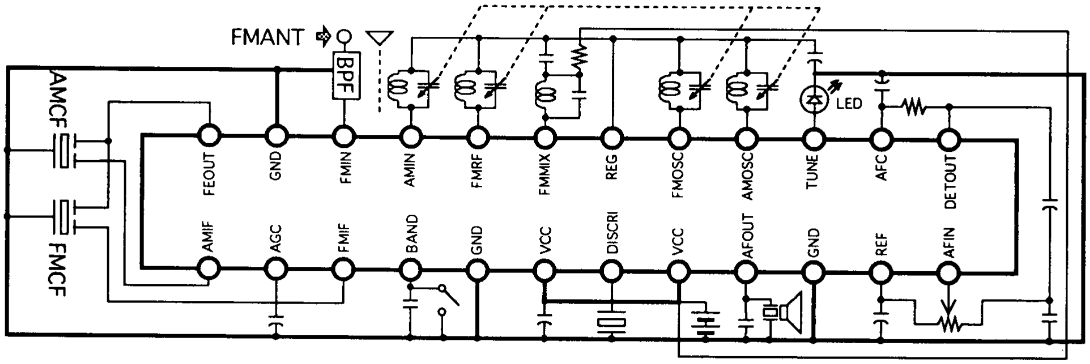

Fig. 7.2 Peripheral components for the low-power one-chip radio IC

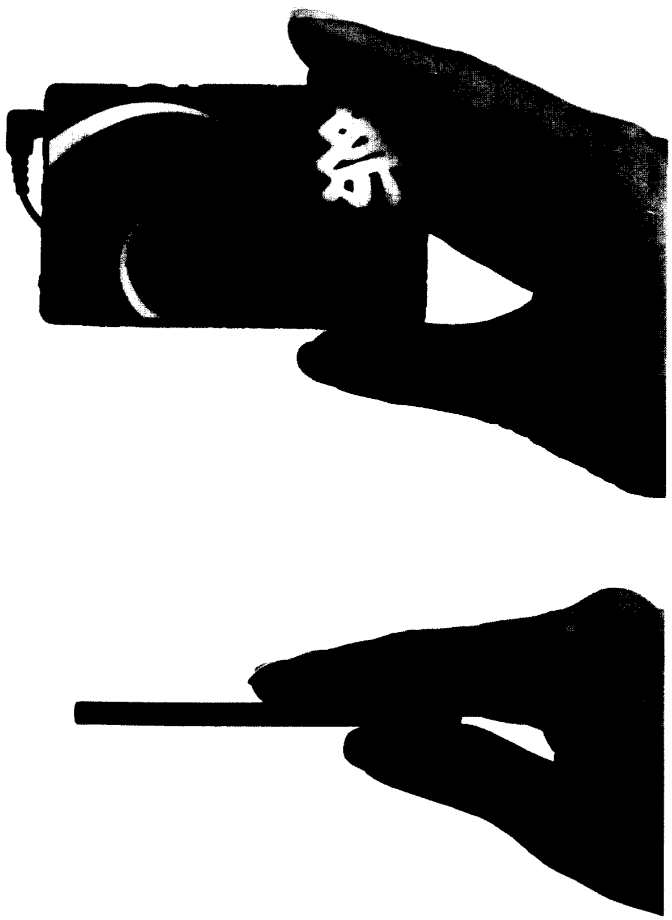

Fig. 7.3 Card radio

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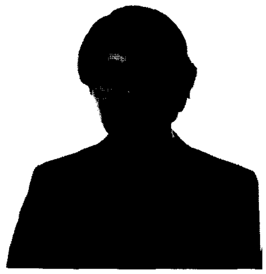
10. BIOGRAPHIES



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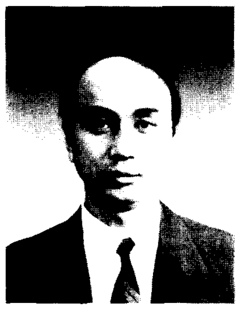

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