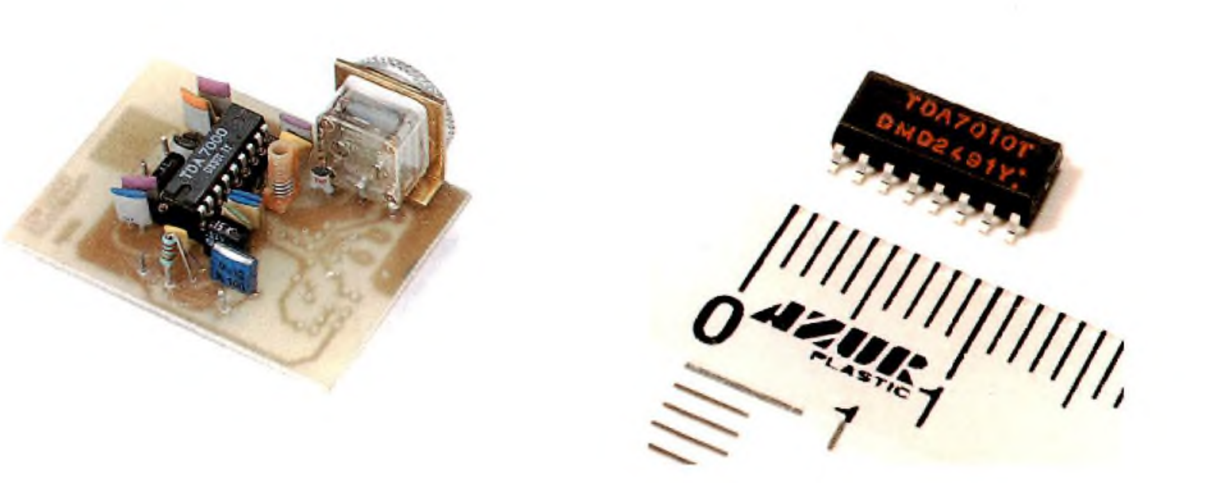
A complete f.m. radio on a chip

W. H. A. VAN DOOREMOLEN and M. HUFSCHMIDT

Until now, the almost total integration of an f.m. radio has been prevented by the need for LC tuned circuits in the r.f., i.f., local-oscillator and demodulator stages. An obvious way to eliminate the coils in the i.f. and demodulator stages is to reduce the normally used intermediate frequency of 10.7 MHz to a frequency that can be tuned by active RC filters, the op-amps and resistors of which can be integrated. An i.f. of zero seems to be ideal because it eliminates spurious signals such as repeat spots and image response, but it would not allow the i.f. signal to be limited prior to demodulation, resulting in poor S/N ratio and no a.m. suppression. With an i.f. of 70 kHz, these problems are overcome and the image frequency occurs about halfway between the desired signal and the centre of the adjacent channel. However, the i.f. image signal must be suppressed and, in common with conventional f.m. radios, there is also a need to suppress interstation noise and noise when tuned to a weak signal. Spurious responses above and below the centre frequency of the desired station (side tunings), and harmonic distortion in the event of very inaccurate tuning must also be eliminated.

We have now developed a mono f.m. reception system which is suitable for almost total integration. It uses an active 70 kHz i.f. filter and a unique correlation muting circuit for suppressing spurious signals such as side responses caused by the flanks of the demodulator S-curve. With such a low



A laboratory model of the TDA7000 in a complete f.m. radio. Also shown is the TDA7010T in the SO package against a cm scale.

i.f., distortion would occur with the ±75 kHz i.f. swing due to received signals with maximum modulation. The maximum i.f. swing is therefore compressed to ±15 kHz by controlling the local-oscillator in a frequency locked loop (FLL). The combined action of the muting circuit and the FLL also suppresses image response.

The new circuit is the TDA7000 which integrates a mono f.m. radio all the way from the aerial input to the audio output. External to the IC are only one tunable LC circuit for the local-oscillator, a few inexpensive ceramic plate capacitors and one resistor. The TDA7000 dramatically reduces assembly and post-production alignment costs because only the oscillator circuit needs adjustment during manufacture to set the limits of the tuned frequency band. The complete f.m. radio can be made small enough to fit inside a calculator, cigarette lighter, key-ring fob or even a slim watch. The TDA7000 can also be used as a receiver in equipment such as cordless telephones, CB radios, radio-controlled models, paging systems, the sound channel of a tv set or other f.m. demodulating systems.

Using the TDA7000 results in significant improvements for all classes of f.m. radio. For simpler portables, the small size, lack of i.f. coils, easy assembly and low power consumption are not the only attractive features. The unique correlation muting system and the FLL make it very easy to tune, even when using a tiny tuning knob. For higher-performance portables and clock radios, variable-capacitance diode tuning and station presetting facilities are often required. These are easily provided with the TDA7000 because there are no variable tuned circuits in the r.f. signal

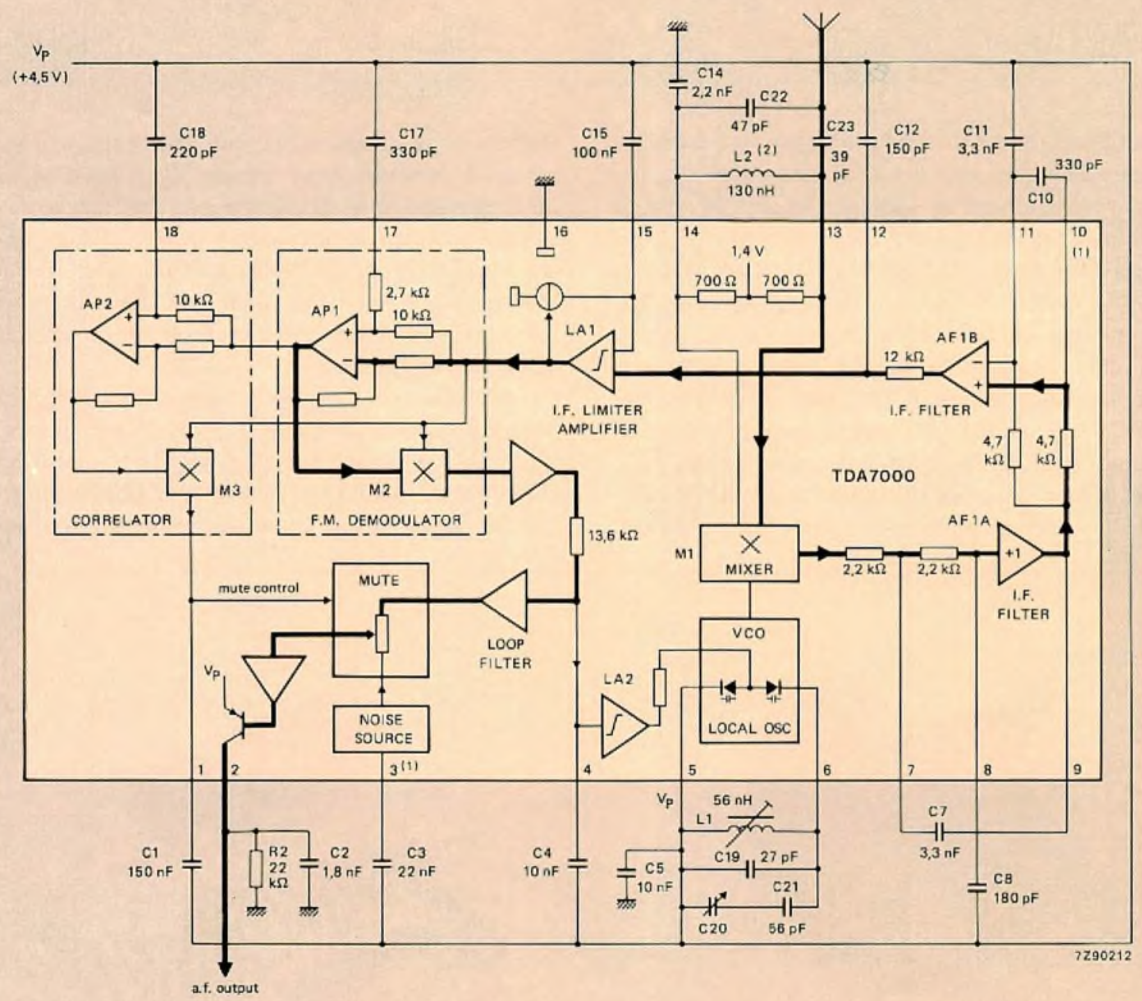


Fig.1 The TDA7000 as a variable capacitor tuned f.m. broadcast receiver

1) These pins are not used in the SO package version (TDA7010T)
AP = All-Pass filter.

2) L_2 is printed on the experimental PCB (Fig.12).
L_1 = Toko MC108 No.514 HNE 150013S13.
C_{20} = Toko No.2A-15BT-R01.

path. Only the local-oscillator needs to be tuned, so tracking and distortion problems are eliminated.

The TDA7000 is available in either an 18-lead plastic DIL package (TDA7000), or in a 16-pin SO package (TDA7010T). Future developments will include reducing the present supply voltage (4.5 V typ.), and the introduction of f.m. stereo and a.m./f.m. versions.

BRIEF DATA

typical supply voltage	V_P	4.5 V
typical supply current	I_P	8 mA
r.f. input frequency range	f_{rf}	1.5 to 110 MHz
sensitivity for −3 dB limiting e.m.f. with Z_S = 75 Ω, mute disabled	$V_{rf\text{-}3\,dB}$	1.5 μV
maximum signal input for THD < 10%, Δf = ±75 kHz e.m.f. with Z_S = 75 Ω	V_{rf}	200 mV
audio output (r.m.s.) with R_L = 22 kΩ, Δf = ±22.5 kHz	V_o	75 mV

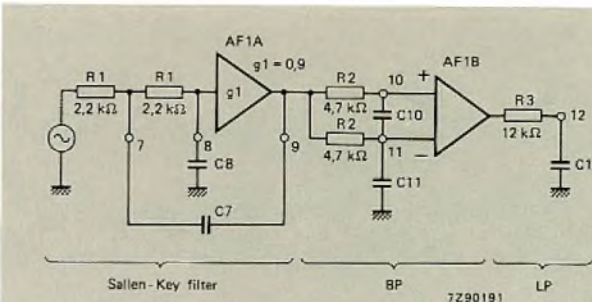
CIRCUIT DESCRIPTION

As shown in Fig.1, the TDA7000 consists of a local-oscillator and a mixer, a two-stage active i.f. filter followed by an i.f. limiter/amplifier, a quadrature f.m. demodulator, and an audio muting circuit controlled by an i.f. waveform correlator. The conversion gain of the mixer, together with the high gain of the i.f. limiter/amplifier, provides a.v.c. action and effective suppression of a.m. signals. The r.f. input to the TDA7000 for −3 dB limiting is 1.5 μV. In a conventional portable radio, limiting at such a low r.f. input level would cause instability because higher harmonics of the clipped i.f. signal would be radiated to the aerial. With the low i.f. used with the TDA7000, the radiation is negligible.

To prevent distortion with the low i.f. used with the TDA7000, it is necessary to restrict the i.f. deviation due to heavily modulated r.f. signals to ±15 kHz. This is achieved with a frequency-locked loop (FLL) in which the output from the f.m. demodulator shifts the local-oscillator frequency in inverse proportion to the i.f. deviation due to modulation.

Active i.f. filter

The first section of the i.f. filter (AF1A) is a second-order low-pass Sallen-Key circuit with its cut-off frequency determined by internal 2.2 kΩ resistors and external capacitors C_7 and C_8. The second section (AF1B) consists of a first-order bandpass filter with the lower limit of the passband determined by an internal 4.7 kΩ resistor and external capacitor C_{11}. The upper limit of the passband is determined by an internal 4.7 kΩ resistor and external capacitor C_{10}. The final section of the i.f. filter consists of a first-order low-pass network comprising an internal 12 kΩ resistor and external capacitor C_{12}. The overall i.f. filter therefore consists of a fourth-order low-pass section and a first-order high-pass section. Design equations for the filter are given in Fig.2. Figure 3 shows the measured response for the filter.



Sallen-Key circuit

$$A_{SK} = \frac{g}{1 + j\omega a - \omega^2 b} \quad \text{with } a = 2R_1C_8,\ b = R_1^2C_7C_8$$

$$\text{With } f_0 = \frac{1}{2\pi R_1\sqrt{(C_7C_8)}} \text{ and } Q = \frac{\sqrt{b}}{a} = 0.5\sqrt{\frac{C_7}{C_8}}$$

$$A_{SK} = \frac{g}{1 + \left(j\frac{\omega}{\omega_0} \times \frac{1}{Q}\right) - \frac{\omega^2}{\omega_0^2}}$$

For C_7 = 3.3 nF, C_8 = 180 pF; Q = 2.1 and f_0 = 94 kHz

Bandpass circuit

$$A_{BP} = \frac{1}{1 + j\omega C_{10}R_2} \times \frac{j\omega C_{11}R_2}{1 + j\omega C_{11}R_2 + \frac{j\omega C_{10}R_2}{1 + j\omega C_{10}R_2}}$$

$$\text{for } f_{LP} = \frac{1}{2\pi R_2C_{10}} \text{ and } f_{HP} = \frac{1}{2\pi R_2C_{11}}$$

$$A_{BP} = \frac{f_{LP}}{f_{HP}} \times \frac{1}{\left(1 + j\frac{f}{f_{HP}}\right)\left(1 - j\frac{f_{LP}}{f}\right) + 1}$$

For C_{10} = 330 pF, C_{11} = 3.3 nF; f_{LP} = 103 kHz, f_{HP} = 10.3 kHz

Low-pass circuit

$$A_{LP} = \frac{1}{1 + j\omega C_{12}R_3}$$

$$\text{for } f_{LP} = \frac{1}{2\pi C_{12}R_3}$$

$$A_{LP} = \frac{1}{1 + j\frac{\omega}{\omega_{LP}}}$$

For C_{12} = 150 pF; f_{LP} = 88.4 kHz.

Fig.2 I.F. filter of the TDA7000

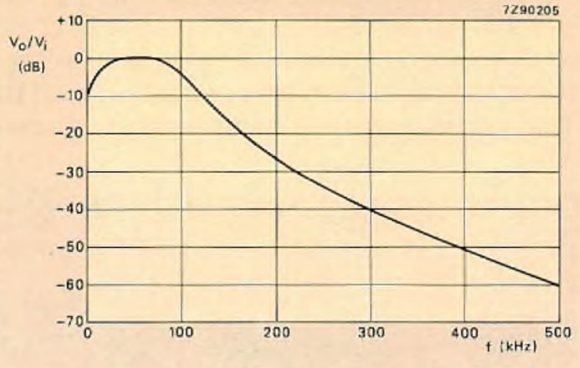
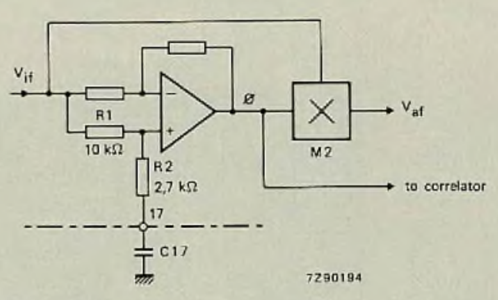


Fig.3 Measured response of the i.f. filter

F.M. demodulator

The quadrature f.m. demodulator M2 converts the i.f. variations due to modulation into an audio frequency voltage. It has a conversion gain of −3.6 V/MHz and requires phase quadrature inputs from the i.f. limiter/amplifier. As shown in Fig.4, the 90° phase shift is provided by an active all-pass filter which has about unity gain at all frequencies but can provide a variable phase shift, dependent on the value of external capacitor C_{17}.



With $R_2 = 0$,

$\phi = -2 \tan^{-1} \omega R_1 C_{17}$

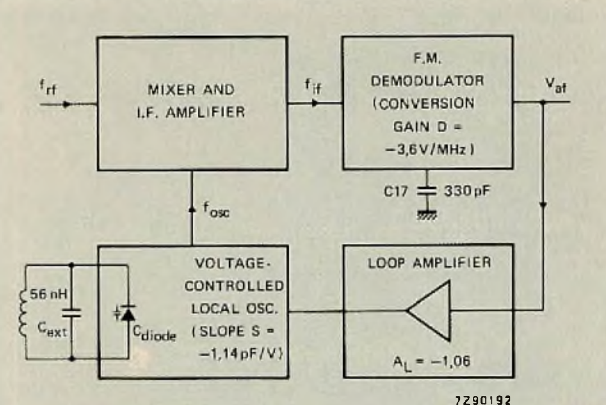
for $\phi = -90°$, $C_{17} = \frac{1}{\omega R_1}$, = 227 pF for f_{if} = 70 kHz.

To improve the performance of the all-pass filter with the amplitude limited i.f. waveform, R_2 has been added. Since this influences the phase angle, the value of C_{17} must be increased by 50% i.e. to 330 pF for f_{if} = 70 kHz.

Fig.4 F.M. demodulator phase shift circuit (all-pass filter)

I.F. swing compression with the FLL

With a nominal i.f. as low as 70 kHz, severe harmonic distortion of the audio output would occur with an i.f. deviation of ±75 kHz due to full modulation of a received f.m. broadcast signal. The FLL of the TDA7000 is therefore used to compress the i.f. swing by using the audio output from the f.m. demodulator to shift the local-oscillator frequency in opposition to the i.f. deviation. The principle is illustrated in Fig.5, which shows that an i.f. deviation of 75 kHz is compressed to about 15 kHz. The THD is thus limited to 0.7% with ±22.5 kHz modulation, and to 2.3% with ±75 kHz modulation.



$C_o = C_{ext} + C_{stray} + C_{diode}$ with open loop = 49 pF at f_o = 96 MHz

feedback factor $\beta = \frac{A_L S f_o}{2C_o}$

open loop conversion gain = D = −3.6 V/MHz

closed loop conversion gain = $\frac{D}{1 + D\beta}$ = 0.68 V/MHz for f_o = 96 MHz

modulation compression factor $K = \frac{\text{open loop gain}}{\text{closed loop gain}} = \frac{3.6 \text{ V/MHz}}{0.684 \text{ V/MHz}} \approx 5$

$$\Delta f_{osc} = \Delta f_{rf} \left(1 - \frac{1}{K}\right)$$

$$\Delta f_{if} = \frac{\Delta f_{rf}}{K}$$

for Δf_{rf} = 75 kHz, Δf_{osc} = 60.74 kHz, $\Delta f_{if} \approx$ 15 kHz

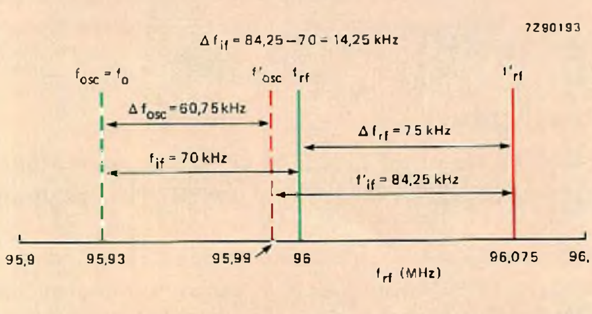


Fig.5 I.F. swing compression with the FLL

Correlation muting system with open FLL

A well-known difference between f.m. and a.m. is that, for f.m., each station is received in at least three tuning positions. Fig.6 shows the frequency spectrum of the output from the demodulator of a typical portable f.m. radio receiving an r.f. carrier frequency-modulated with a tone of constant frequency and amplitude. In addition to the audio response at the correct tuning point in the centre of Fig.6, there are two side responses due to the flanks of the demodulator S-curve. Because the flanks of the S-curve are non-linear the side responses have increased harmonic distortion. In Fig.6, the frequency and intensity of the side responses are functions of the signal strength, and they are separated from the correct tuning point by amplitude minima. However, in practice, the amplitude minima are not well defined because the modulation frequency and index are not constant and moreover, the side responses of adjacent channels often overlap.

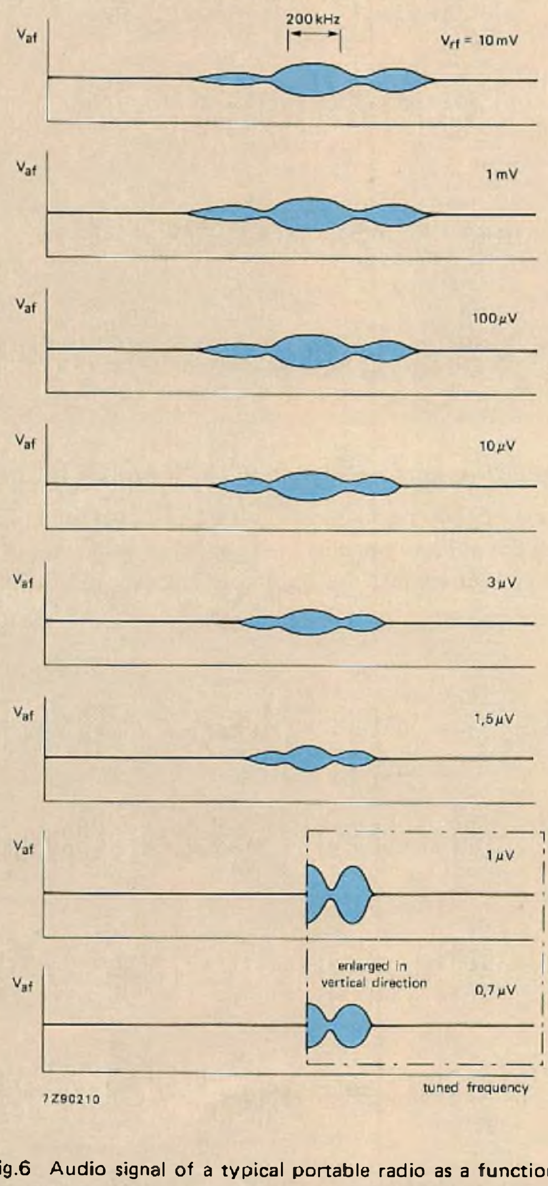


Fig.6 Audio signal of a typical portable radio as a function of tuned frequency with r.f. input as a parameter. The modulation frequency and amplitude are both constant

High performance f.m. radios incorporate squelch systems such as signal-strength-dependent muting and tuning-deviation-dependent muting (Ref.1) to suppress side responses. They also have a tuning meter to facilitate correct tuning. Although the TDA7000 is mainly intended for use in portables and clock radios, it incorporates a very effective new correlation muting system which suppresses interstation noise and spurious responses due to detuning to the flanks of the demodulator S-curve. The muting system is controlled by a circuit which determines the correlation between the waveform of the i.f. signal and an inverted version of it which is delayed (phase shifted) by half the period of the nominal i.f. (180°). A noise generator works in conjunction with the muting system to give an audible indication of incorrect tuning.

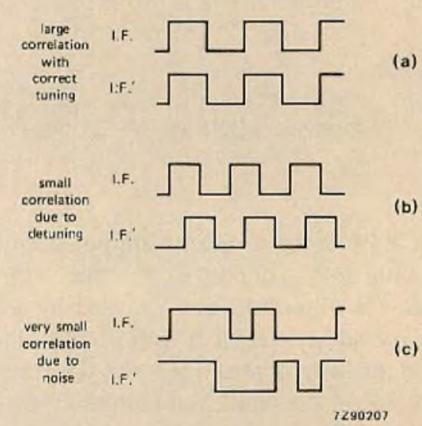
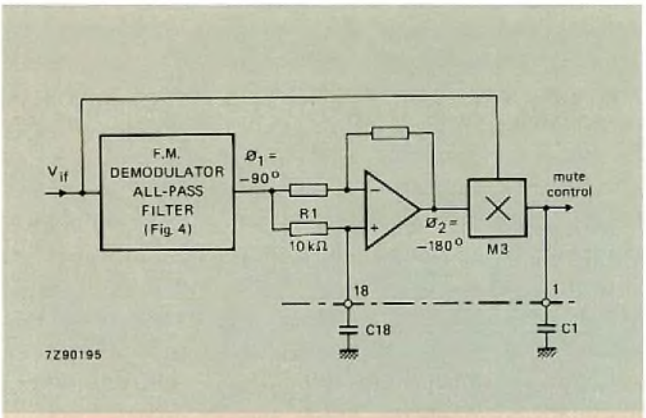


Fig.7 Function of the correlation muting system

Figure 7 illustrates the function of the muting system. Signal IF′ is derived by delaying the i.f. signal by half the period of the nominal i.f. and inverting it. With correct tuning as shown in Fig.7(a), the waveform of the two signals are identical resulting in large correlation. In this situation, the audio signal is not muted. With detuning as shown in Fig.7(b), signal IF′ is phase-shifted with respect to the i.f. signal. The correlation between the two waveforms is therefore small and the audio output is muted. Figure 7(c) shows that, because of the low Q of the i.f. filter, noise causes considerable fluctuations of the period of the i.f. signal waveform. There is then small correlation between the two waveforms and the audio is muted. The correlation muting system thus suppresses noise and side responses due to detuning to the flanks of the demodulator S-curve. Since the mute threshold is much lower than that obtained with most other currently used muting systems, this muting system is ideal for portable radios which must often receive signals with a level only slightly above the input noise.



$$\phi_2 = -2\tan^{-1}\omega R_1 C_{18}$$

$$\text{for } \phi_2 = -90^\circ \; C_{18} = \frac{1}{\omega R_1}$$

for f_{if} = 70 kHz, C_{18} = 227 pF

Fig.8 Correlator of the TDA7000

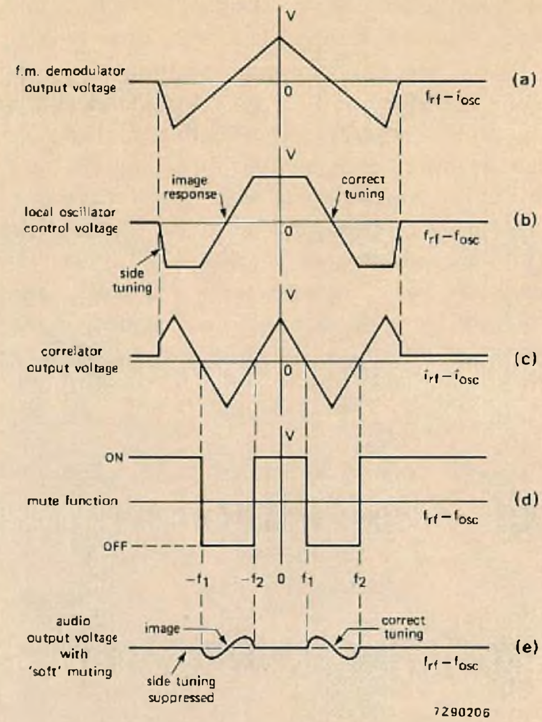


Fig.9 Operation of the correlation muting system with open-loop FLL

As shown in Fig.8, the correlation muting circuit consists of all-pass filter AP2 connected in series with f.m. demodulator all-pass filter AP1 and adjusted by an external capacitor to provide a total phase shift of 180°. The output from AP2 is applied to mixer M3 which determines the correlation between the undelayed limited i.f. signal at one of its inputs and the delayed and inverted version of it at its other input. The output from mixer M3 controls a muting circuit which feeds the demodulated audio signal to the output when the correlation is high, or feeds the output from a noise source to the output to give an audible indication of incorrect tuning when the correlation is low. The switching of the muting circuit is progressive (soft muting) to prevent the generation of annoying audio transients. The output from mixer M3 is available externally at pin 1 and can also be used to drive a detuning indicator.

Figure 9 shows that there are two regions where the demodulated audio signal is fed to the output because the muting is inactive. One region is centred on the correct tuning point f_L. The other is centred on the image frequency $-f_L$. The image response is therefore not suppressed by the muting system when the frequency-locked loop is open. When the loop is closed, the time-constant of the muting system, which is determined by external capacitor C_1, prevents the image response being passed to the audio output. This is described under the next heading.

Correlation muting system with closed FLL

The closed-loop response of the FLL is shown in Fig.10, in which the point of origin is the nominal i.f. ($f_{rf} - f_{osc} = f_L$). With correct tuning, the muting is inactive and the audio

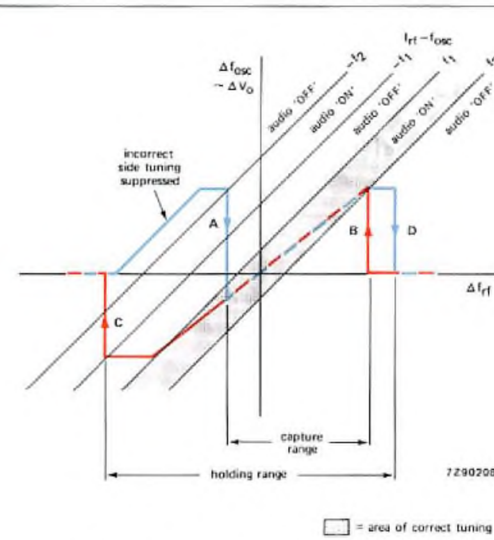


Fig.10 Closed-loop response of the FLL. The slope of the correct tuning line is such that a 75 kHz deviation of f_{rf} causes a 15 kHz deviation of $f_{rf} - f_{osc}$

signal is fed to the output. Spurious responses due to the flanks of the demodulator S-curve which occur outside the i.f. band $-f_2$ to f_2 are suppressed because the muting is active. Fast transients of the audio signal due to locking of the loop (A and B), and to loss of lock (C and D) are suppressed in two ways.

Lock and loss of lock transients B and D occur when the i.f. is greater than f_2 and are therefore suppressed because the muting is active. The situation is different during loss of lock transient C because the muting is only active for the last part of the transient. To completely suppress this transient, capacitor C_1 in Fig.1 holds the muting control line positive (muting active) during the short interval whilst the i.f. traverses from $-f_1$ to $-f_2$. The same applies for lock transient A during the short interval whilst the i.f. traverses from $-f_2$ to $-f_1$. Since the image response occurs halfway between $-f_1$ and $-f_2$, it is also suppressed.

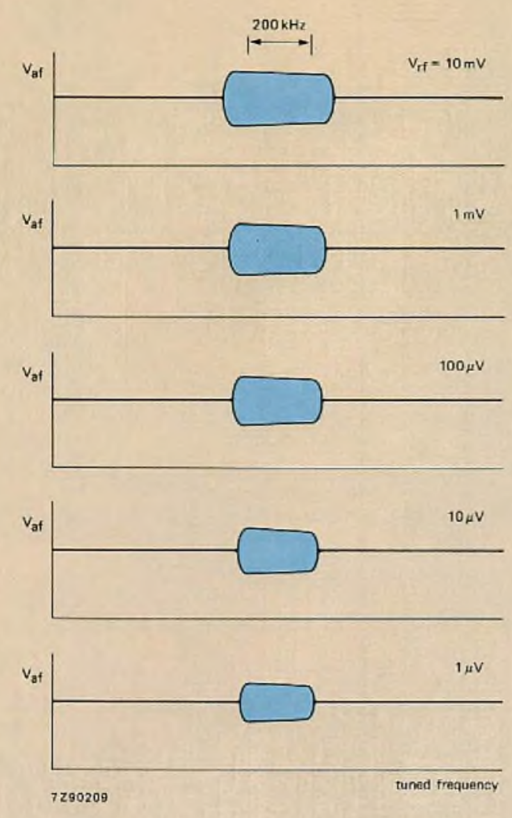


Fig.11 Audio signal of the TDA7000 as a function of the tuned frequency with r.f. input as a parameter. The modulation frequency and amplitude are both constant

Figure 11 shows the audio output from the TDA7000 radio as a function of tuned frequency with aerial signal level as a parameter. Compared with the similar diagram for a typical conventional portable radio (Fig.6), there are three important improvements:

- There are no side responses due to the flanks of the demodulator S-curve. This is due to the action of the correlation muting system (soft mute) which combines the function of a detuning-dependent muting system with that of a signal-strength-dependent muting system
- The correct tuning frequency band is wide, even with weak aerial signals. This is due to the a.f.c. action of the FLL which reduces a large variation of aerial input frequency (equivalent to detuning) to a small variation of the i.f. There is no audio distortion when the radio is slightly detuned
- Although the soft muting system remains operative with low-level aerial signals, there is no degradation of the audio signal under these conditions. This is due to the high gain of the i.f. limiter/amplifier which provides -3 dB limiting of the i.f. signal with an aerial input level of 1.5 µV. However, the soft muting action does reduce the audio output level with low level aerial signals.

RECEIVER CIRCUITS

Circuits with variable capacitor tuning

The circuit diagram of the complete mono f.m. radio shown in the frontispiece is given in Fig.1. An experimental printed-wiring board layout is given in Fig.12. Special attention has been paid to supply lines and the positioning of large-signal decoupling capacitors.

The functions of the peripheral components of Fig.1 not already described are as follows:

C_1:

Determines the time constant required to ensure muting of audio transients due to the operation of the FLL.

C_2:

Together with R_2 determines the time-constant for audio de-emphasis (e.g. $R_2C_2 = 40\mu s$).

C_3:

The output level from the noise generator during muting increases with increasing value of C_3. If silent mute is required, C_3 can be omitted.

C_4:

Capacitor for the FLL filter. It eliminates i.f. harmonics at the output of the f.m. demodulator. It also determines the time-constant for locking the FLL and influences the frequency response.

C_5:

Supply decoupling capacitor which must be connected as close as possible to pin 5 of the TDA7000.

C_7 to C_{12}, C_{17} and C_{18}:
Filter and demodulator capacitors. The values shown are for an i.f. of 70 kHz. For other intermediate frequencies, the values of these capacitors must be changed in inverse proportion to the i.f. change.

C_{14}:
Decouples the reverse r.f. input. It must be connected to the common return via a good quality short connection to ensure a low-impedance path. Inductive or capacitive coupling between C_{14} and the local-oscillator circuit or i.f. output components must be avoided.

C_{15}:
Decouples the d.c. feedback for i.f. limiter/amplifier LA1.

C_{19} and C_{21}:
Local-oscillator tuning capacitors. Their values depend on the required tuning range and on the value of tuning capacitor C_{20}.

C_{22}, C_{23}, L_1, L_2:
The values given are for an r.f. bandpass filter with Q = 4 for the European and U.S.A. domestic f.m. broadcast band (87.5 MHz to 108 MHz). For reception of the Japanese f.m. broadcast band (76 MHz to 91 MHz), L_1 must be increased to 78 nH and L_2 must be increased to 150 nH. If stopband attenuation for high level a.m. or tv signals is not required, L_2 and C_{22} can be omitted and C_{23} changed to 220 pF.

R_2:
The load for the audio output current source. It determines the audio output level, but its value must not exceed 22 kΩ for V_p = 4.5 V, or 47 kΩ for V_p = 9 V.

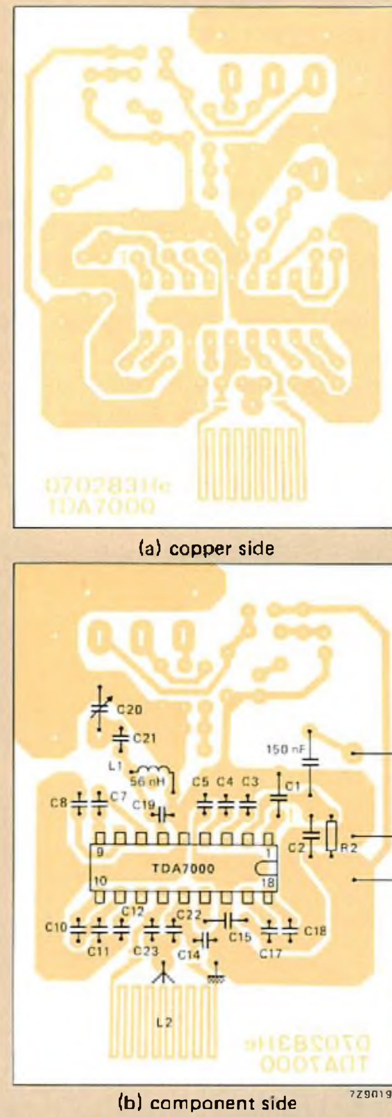


Fig.12 Experimental printed-wiring board for the circuit of Fig.1

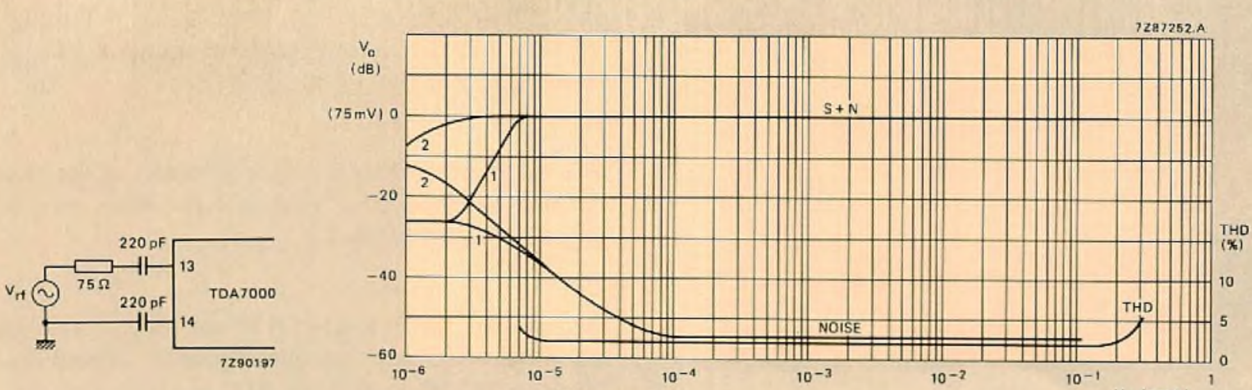


Fig.13 Audio output as a function of input e.m.f. The curves numbered 1 were measured with the muting system active. The curves numbered 2 were measured with the muting system disabled by injecting about 20 µA into pin 1 of the TDA7000. The input frequency was 96 MHz modulated with 1 kHz with a deviation of ±22.5 kHz for the output level curves, and ±75 kHz for the distortion curve

Performance of the circuit

unless otherwise specified, V_P = 4.5 V, T_{amb} = 25 °C, f_{rf} = 96 MHz, V_{rf} = 0.2 mV e.m.f. from a 75 Ω source, modulated with Δf = ±22.5 kHz, f_m = 1 kHz. Noise voltage measured unweighted over the bandwidth 300 Hz to 20 kHz

parameter	symbol	typ.	max.	unit
sensitivity (e.m.f. voltage) for −3 dB limiting:				
muting disabled	EMF	1.5	–	μV
for −3 dB muting	EMF	6	–	μV
for (S+N)/N = 26 dB	EMF	5.5	–	μV
signal handling (e.m.f. voltage) for THD < 10%; Δf = ±75 kHz	EMF	200	–	mV
signal-to-noise ratio (see Fig.13)	(S+N)/N	60	–	dB
total harmonic distortion (see Fig.13)				
at Δf = ±22.5 kHz	THD	0.7	–	%
at Δf = ±75 kHz	THD	2.3	–	%
a.m. suppression (ratio of the a.m. output signal referred to the f.m. output signal) f.m. signal: f_m = 1 kHz; Δf = ±75 kHz a.m. signal: f_m = 1 kHz; m = 80%	AMS	50	–	dB
ripple rejection (ΔV_P = 100 mV; f = 1 kHz)	RR	10	–	dB
oscillator voltage (r.m.s. value) at pin 6	$V_{6\text{-}5(rms)}$	250	–	mV
variation of oscillator frequency with supply voltage (ΔV_P = 1 V)	Δf_{osc}	60	–	kHz/V
selectivity	S_{+300}	45	–	dB
	S_{-300}	35	–	dB
a.f.c. range	Δf_{rf}	±300	–	kHz
audio bandwidth at ΔV_o = 3 dB measured with pre-emphasis (t = 50 μs)	B	10	–	kHz
a.f. output voltage (r.m.s. value) at R_L = 22 kΩ	$V_{o(rms)}$	75	–	mV
load resistance for audio output current source				
at V_P = 4.5 V	R_L	–	22	kΩ
at V_P = 9.0 V	R_L	–	47	kΩ

Circuit with variable-capacitance diode tuning

Since it is only necessary to tune the local-oscillator coil, it is very simple to modify the circuit of Fig.1 for variable-capacitance diode tuning. The modifications are shown in Fig.14. A circuit board layout for the modified receiver and a photograph of a complete laboratory model are shown in Fig.15.

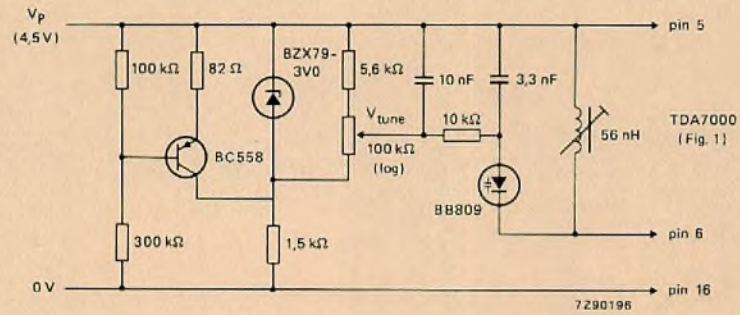


Fig.14 Variable-capacitance diode tuning for the local-oscillator. Additonal measures must be taken to ensure temperature stability

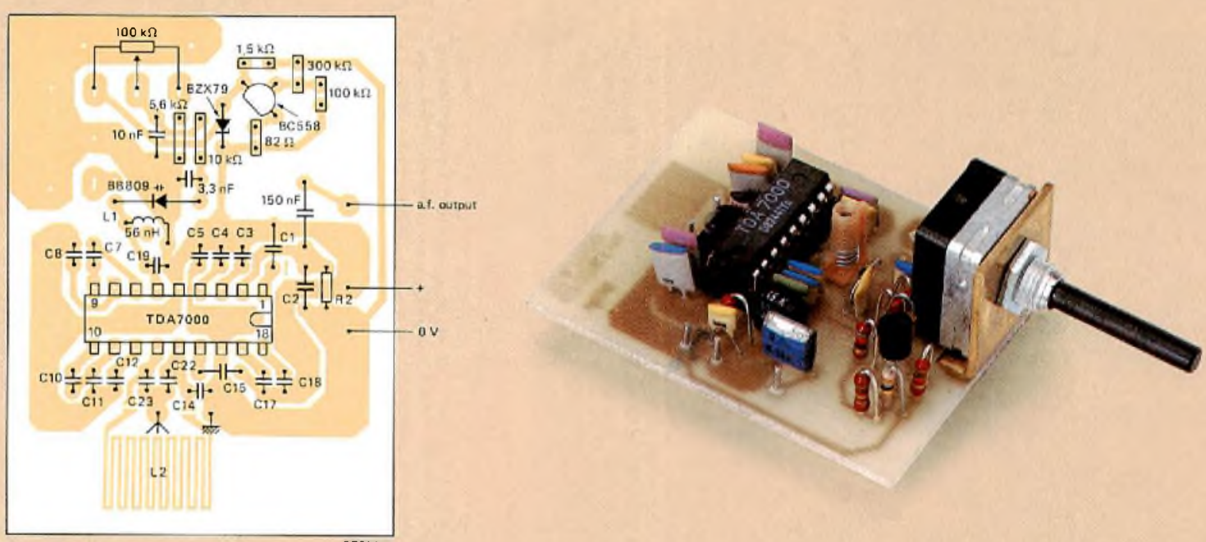


Fig.15 Circuit board layout and complete model of a TDA7000 radio with variable-capacitance diode tuning. This is the same pcb as shown in Fig.12

Narrow-band f.m. receiver

The TDA7000 can also be used for reception of narrow-band f.m. signals. In this case, the local-oscillator is crystal-controlled as shown in Fig.16 and there is therefore hardly any compression of the i.f. swing by the FLL. The deviation of the transmitted carrier frequency due to modulation must therefore be limited to prevent severe distortion of the demodulated audio signal.

The component values in Fig.16 result in an i.f. of 4.5 kHz and an i.f. bandwidth of 5 kHz (Fig.17). If the i.f. is multiplied by N, the values of capacitors C_{17} and C_{18} in the all-pass filters and the values of filter capacitors C_7, C_8, C_{10}, C_{11}, and C_{12} must be multiplied by 1/N. For improved i.f. selectivity to achieve greater adjacent channel attenuation, second-order networks can be used in place of C_{10} and C_{11}.

In this circuit the detuning noise generator is not used. Since the circuit is mainly for reception of audio signals, the audio output must be passed through a low-pass Chebyshev filter to suppress i.f. harmonics.

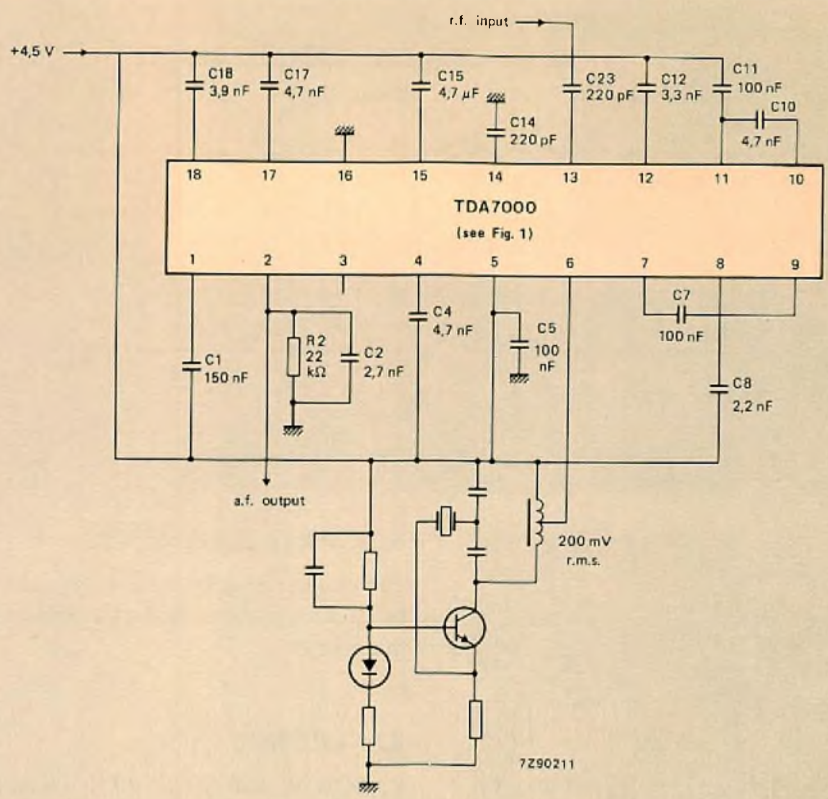


Fig.16 A narrow-band f.m. receiver with a crystal-controlled local-oscillator

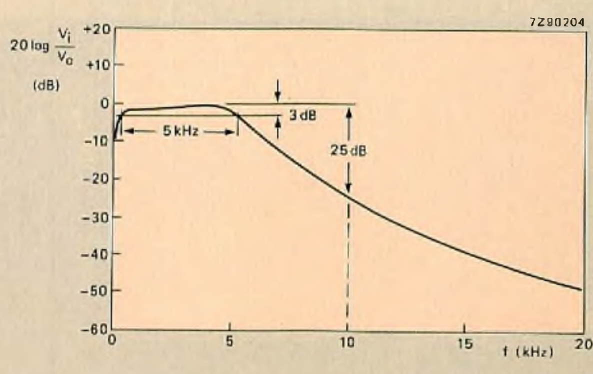


Fig.17 I.F. selectivity for the narrow-band f.m. receiver

AUDIO AMPLIFIER AND DETUNING INDICATOR CIRCUITS

Audio output stages suitable for use with the TDA7000 are shown in Fig.18 and 19. Figure 20 shows how the muting signal can be used to operate a LED to give an indication of detuning.

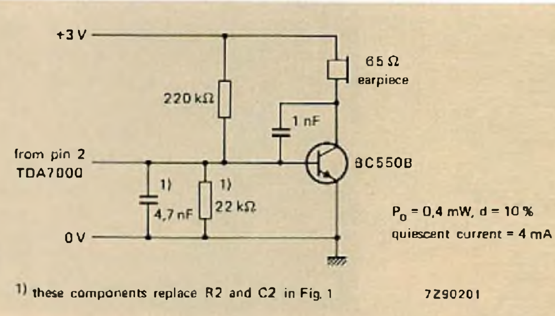


Fig.18 A 0.4 mW transistor audio output stage without volume control for driving an earpiece

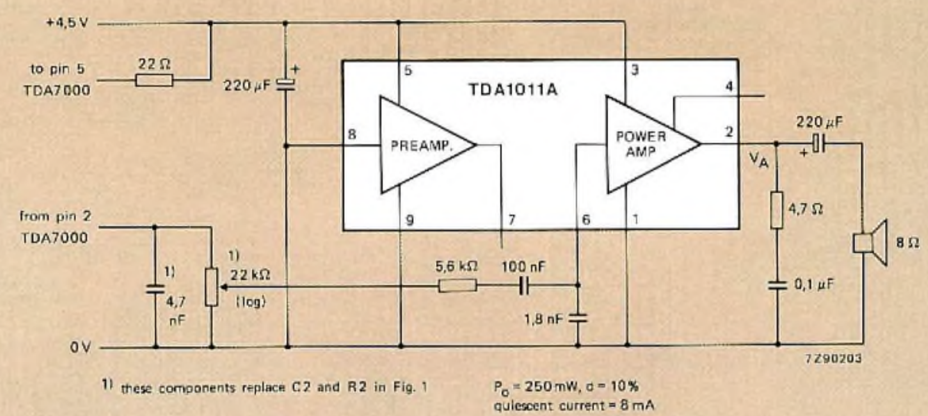


Fig.19 An integrated 250 mW audio output stage

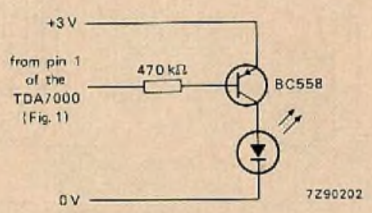


Fig.20 A detuning indicator driven by the mute signal from the TDA7000

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REFERENCE

KANOW, W. and SIEWERT, I., 'Integrated circuits for hi-fi radios and tuners', Electronic Components and Applications, Vol. 4, No. 1, November 1981, pp. 11 to 27.

The TDA7000 allows f.m. radios to be made small enough to fit inside a pencil, a cigarette lighter, or a wristwatch