induction loop paging system

Short range paging systems are normally used in large buildings or by people with very poor hearing. The system described in this article has many more applications: it can be used as a 'wireless' connection for radio or TV sound, as a baby alarm, as a doorbell extension or even as an intercom system.

An induction loop paging system provides wireless transmission of information and can be used as a personal paging system in factories, warehouses, etc. or as a hearing aid in cinemas, theatres, etc. To be viable, the system should be very economically priced. The requirements for constructing such a system are: a (powerful) audio amplifier; a loop of wire that marks the periphery of the area to be covered; a sensitive audio amplifier for each 'participant'. The latter must be able to sufficiently amplify the energy produced in a small pick-up coil (see figure 1).

The lines of (magnetic) flux are perpendicular to the area produced and bordered by the paging system. Although this system can be used in all the above mentioned cases, an infra-red system is more commonly used. Compared with the induction loop paging system, an infra-red system has many more advantages if only a small area has to be covered, the main points being greater bandwidth and less chance of interference.

The (audio) induction loop paging system only operates in the audio frequency range and is prone to interference from television sets and thyristor or triac controlled dimmer circuits. If an induction loop paging system is required, possible interference sources in the surroundings must be taken into account. Advantages of the system are: low cost and no visible connection (direct or indirect) between the 'transmitter' and 'receiver'.

There are certain disadvantages of this type of system: not only can the neighbour's television and dimmer controls cause interference, but any attempts to minimise this interference by increasing the power output have an inverse effect as well. The magnetic field of the induction loop paging system will generate a voltage in any surrounding coils. Such a coil could be formed by an existing earth circuit in electronic equipment. This indicates that interference will be caused to stereo equipment containing magnetic or moving coil cartridges. Another 'victim' would be a tape recorder due the coil of the record head, which is connected to a very sensitive amplifier circuit. The induction loop paging system could also interfere with an electric guitar.

This means that if an induction loop paging system is to be employed on a small scale, it is necessary to ensure that the system does not cause interference to or receive interference from other systems. Therefore, some form of modulation has to be implemented.

On the one hand, the frequencies used

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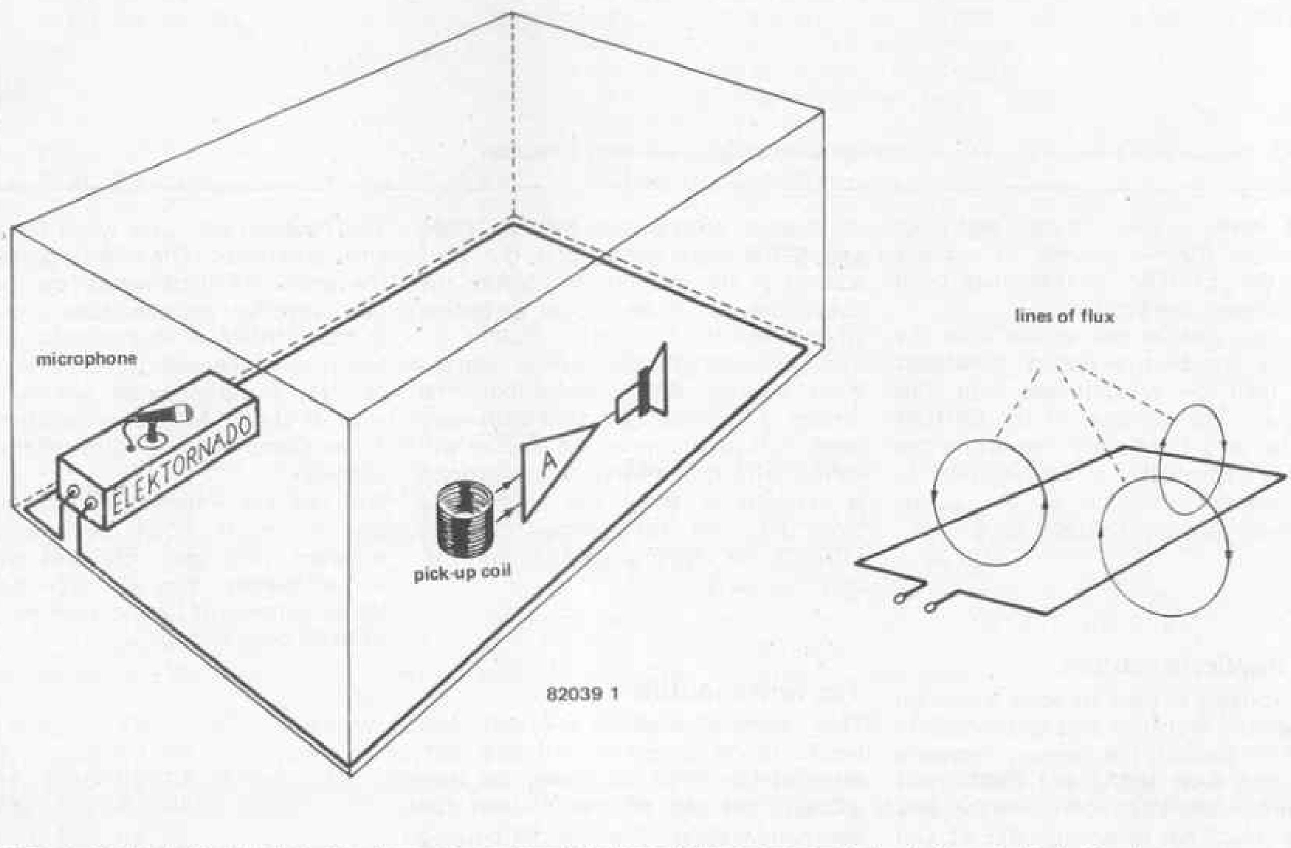

Figure 1. The basic idea behind the induction loop paging system. The lines of flux are perpendicular to the actual induction loop.

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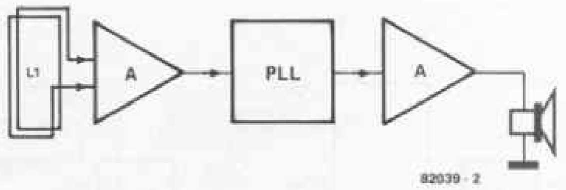

Figure 2. The receiver consists of a preamplifier, a phase-locked loop demodulator and an audio amplifier.

have to remain in the audio range, to satisfy Home Office requirements, and on the other, they must be inaudible. Consequently, the bandwidth of the system will have to be limited. Although the circuit described in this article is capable of operating with a bandwidth of 6 kHz, it has been limited to 3 kHz. This still provides excellent speech intelligibility, for which the induction loop paging system is primarily intended. Normally, persons with impaired hearing are unable to detect higher frequencies, so the limited bandwidth will not be that much of a problem for them. Music reproduced over the system can be compared with 'transistor radio' quality.
The induction loop paging system utilises frequency modulation with a carrier frequency of around 24 kHz. This is still within the audio spectrum, although it is inaudible to the human ear. The major advantage of frequency modulation in the fact that interference to and from other equipment is very much reduced. The use of FM does not eliminate interference completely, but it is certainly superior to other methods of modulation.
There are two main reasons why the frequencies used have to remain in the audio range. In the first place, it is much easier to process audio signals than it is to process high frequency (RF) signals. Secondly, the induction loop paging system starts to show increasing 'aerial effect' with higher frequencies, which is intolerable with regard to the possible interference caused. What is more, the law prescribes that the information must not 'leave' the house!

The receiver

The block diagram of the receiver is illustrated in figure 2. The induced output from the pick-up coil is amplified, demodulated by a phase-locked loop (PLL) and fed to an audio amplifier. If required, an additional headphone amplifier could also be connected. There are a number of ways in which such a block diagram can be realised. In the design presented here, particular attention has been paid to low cost, easy construction and also a limit has been imposed on the size of the printed circuit board.
The complete circuit diagram of the receiver section is shown in figure 3. The pick-up coil has an inductance value of 6 mH. The diameter of this coil is 3 cm. The coil and capacitor C1 form a resonant circuit with a frequency of around 24 kHz. This signal is then amplified by transistors T1 and T2 and 'clipped' by transistors T3 and T4 to compensate for high amplitude input signals. The overall gain from the pick-up coil to the PLL is considerable. The induced voltage in the coil is only a few microvolts, whereas the PLL requires a signal in the order of 500 mV_{p-p} for correct operation.
Noise is unavoidable in wide-band amplifiers, and the four stage circuit shown in figure 3 is no exception. However, this is not necessarily a problem, as the PLL is not so sensitive to harmonics and sub-harmonics as it is to the fundamental frequency. By including capacitor C8, the high frequency content of the input signal is reduced slightly, which is quite sufficient.
A CMOS phase-locked loop (type 4046) is used for the FM demodulator for the

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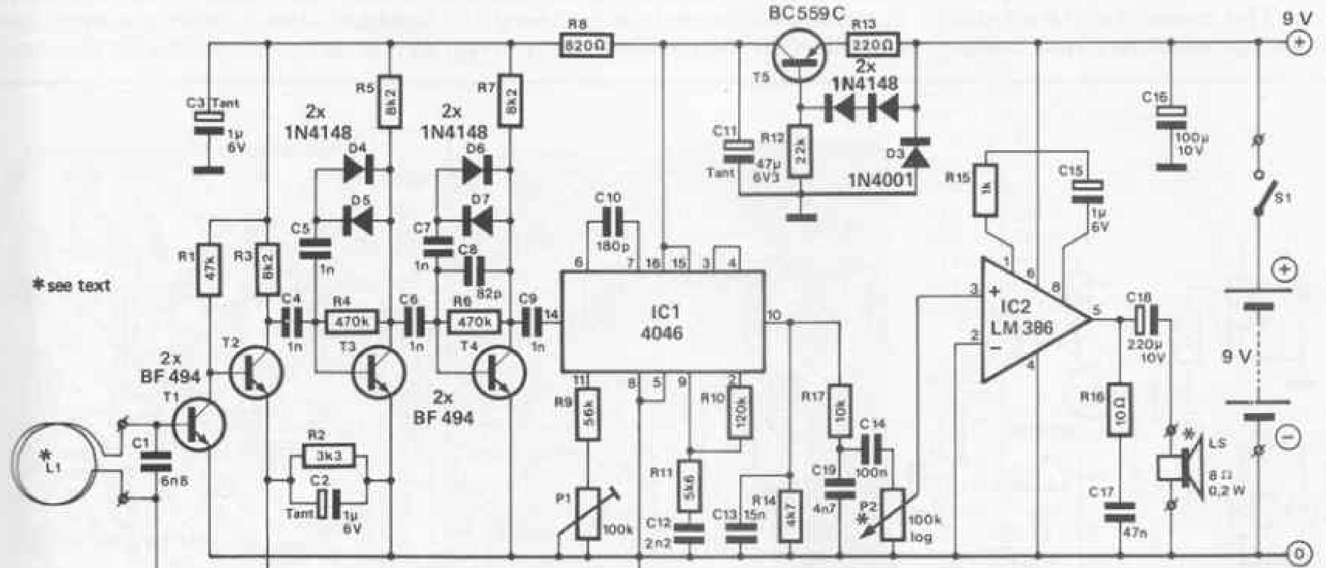

Figure 3. The circuit diagram of the complete receiver. Current consumption is only 10 mA.

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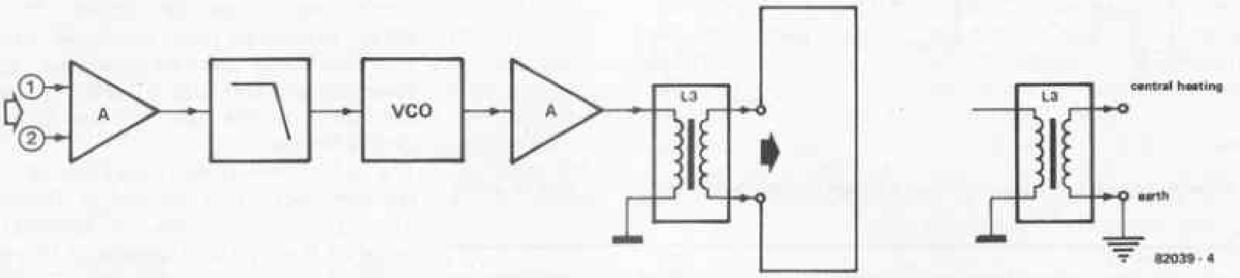

Figure 4. The block diagram of the transmitter section of the induction loop paging system.

following reasons; its low voltage supply requirements; its low current consumption and (more importantly?) its low cost. One disadvantage is that the VCO frequency is not particularly stable. This slight drawback is compensated for by the wide tuning range prodived by preset potentiometer P1. Moreover, this disadvantage is virtually eliminated due to the fact that this device has a very wide capture and hold range.

The zener diode contained in the IC (pin 15) is used to stabilise the supply voltage to the PLL and the preamplifier. The zener voltage is between 5 and 6 V. The actual value is not critical, but any change (as a result of decreasing battery voltage) is. The frequency of the VCO is dependent on the supply voltage as well as the conversion constant (which is the relationship between the frequency and the control voltage) of the PLL. This means that the resultant output voltage could vary with changes in supply voltage even though the input signal is constant. For this reason, the usual series dropper resistor associated with zener diodes is replaced by a series transistor (T5). Thus the receiver can still be used with a supply voltage of about 6 V without motor-boating (low frequency oscillation).

The audio amplifier produces a power output in the region of 0.5 W. To make the receiver as compact as possible, an IC has been used here. However, the major drawback here is the fact that this device has a current consumption in the order of 7 mA. The total current consumption of the receiver is about 10 mA. Therefore, the choice between 'ordinary' batteries and NiCad cells depends on how often and for how long the receiver is to be used.

The receiver has a very high sensitivity, which offers the advantage of being able to operate far beyond the periphery of the induction loop when there is little or no interference present. However, this parameter is not obtained automatically. Radiation from the moving coil of the loudspeaker (or the dynamic headphone) and radiation from the inductance loop could have a detrimental effect on each other if the installation is not carried out correctly.

The transmitter

The block diagram and the circuit diagram for the transmitter section of the induction loop paging system are shown in figures 4 and 5, respectively. The transmitter consists of a low frequency preamplifier, a VCO and a 'switching' output stage. The input preamplifier is a simple mixer to which two possible signal sources can be connected. Input 1 is the most sensitive and has the lowest input impedance. Sensitive, low impedance microphones can be connected directly to this input.

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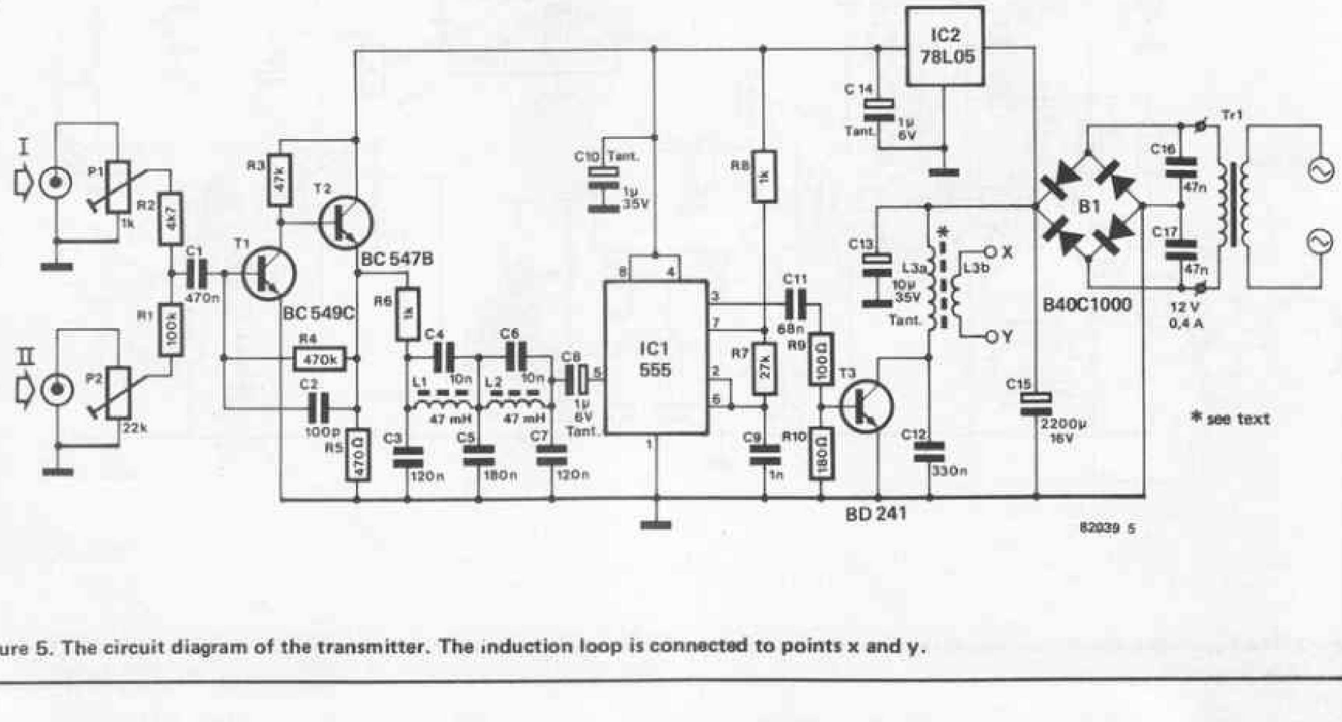

figure 5. The circuit diagram of the transmitter. The induction loop is connected to points x and y.

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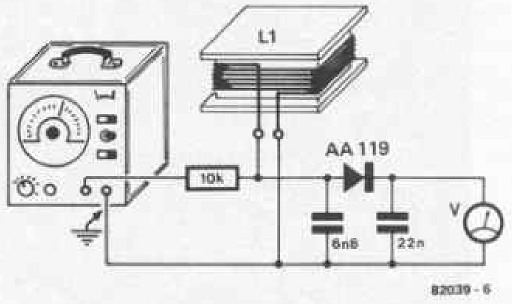

Figure 6. The correct number of turns for the pick-up coil can be determined quite simply using this set-up. The signal generator should have an accuracy greater than 5%.

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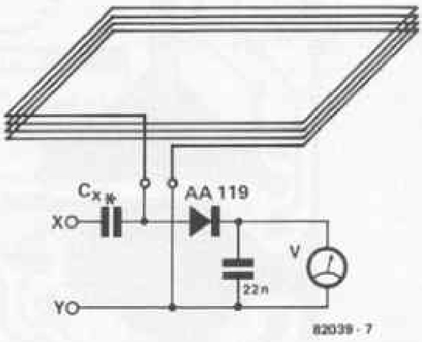

Figure 7. In order to achieve optimum efficiency, the induction loop should be series resonant. Using the method shown here, the maximum meter reading will indicate the correct value for C_x.

The other input can be used with higher level signals such as the line output of an audio amplifier. A low-pass filter has been added after the preamplifier to reduce any high frequency interference.
For example, let us assume that input 2 is connected to the sound output of a television receiver. This means that the line oscillator frequency (about 16 kHz) will also be present — especially with cheaper sets. This gives a difference of about 8 kHz when a carrier frequency of 24 kHz is used. Moreover, the third harmonic of the TV line oscillator and the second harmonic of the VCO are very close to each other. In other words, interference would be very prominent. A similar example can be given with the 19 kHz and 38 kHz products of an FM stereo receiver. Therefore, it is imperative to reduce the bandwidth of the signal presented to the transmitter VCO.

A simple active filter is not sufficient, as the attenuation of the filter has to increase rapidly beyond a certain frequency value. A passive LC filter is ideal, especially as very few components are required. The filter used in the transmitter, consisting of L1, L2 and C3 . . . C7, provides 6 dB attenuation at a frequency of 3 kHz and as much as 60 dB attenuation at a frequency of 5.5 kHz. The attenuation will never be less than 70 dB for higher frequencies (up to 50 kHz).
The transmitter VCO is constructed around a 555 timer. This provides excellent frequency stability and sufficient 'power' to drive the output stage. Unfortunately, this device has its limitations in that the frequency modulation obtained is not absolutely perfect and a slight amplitude modulation of the output signal occurs. This, however, is not noticeable in the receiver due to the limiters and the AM suppression

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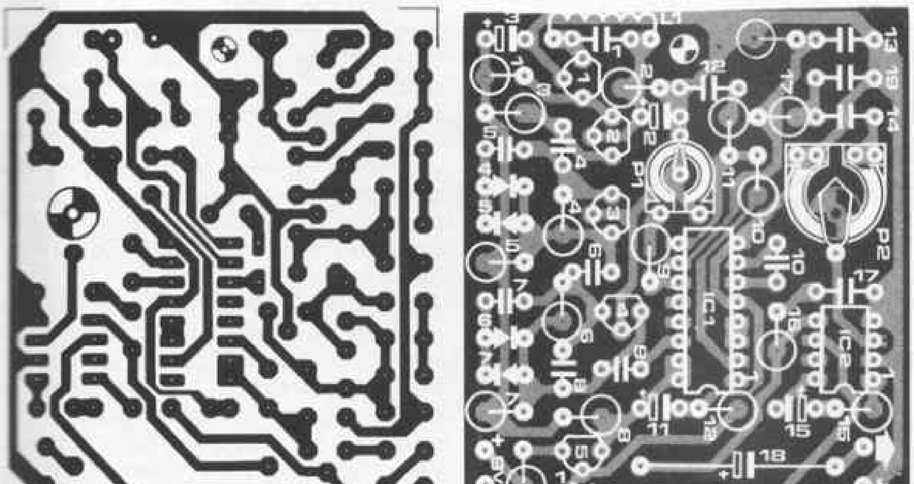

Figure 8. The printed circuit board and component overlay for the receiver section.

Parts list for the receiver

Resistors:
R1 = 4k7
R2 = 3k3
R3,R5,R7 = 8k2
R4,R6 = 470 k
R8 = 820 Ω
R9 = 56 k
R10 = 120 k
R11 = 5k7
R12 = 22 k
R13 = 220 Ω
R14 = 4k7
R15 = 1 k
R16 = 10 Ω
R17 = 10 k
P1,P2 = 100 k preset

Capacitors:
C1 = 6n8
C2,C3 = 1 μ/6 V tantalum
C4 . . . C7,C9 = 1 n ceramic
C8 = 82 p
C10 = 180 p
C11 = 47 μ/6 V tantalum
C12 = 2n2
C13 = 15 n
C14 = 100 n
C15 = 1 μ/6 V
C16 = 100 μ/10 V
C17 = 47 n
C18 = 220 μ/10 V
C19 = 4n7

Semiconductors:
T1 . . . T4 = BF 494
T5 = BC 559C
D1,D2,D4 . . . D7 = 1N4148
D3 = 1N4001
IC1 = 4046
IC2 = LM 386

Miscellaneous:
L1 = 500 turns of 0.1 mm ϕ, enamelled copper wire coil diameter about 3 cm (see text)
S1 = on/off switch

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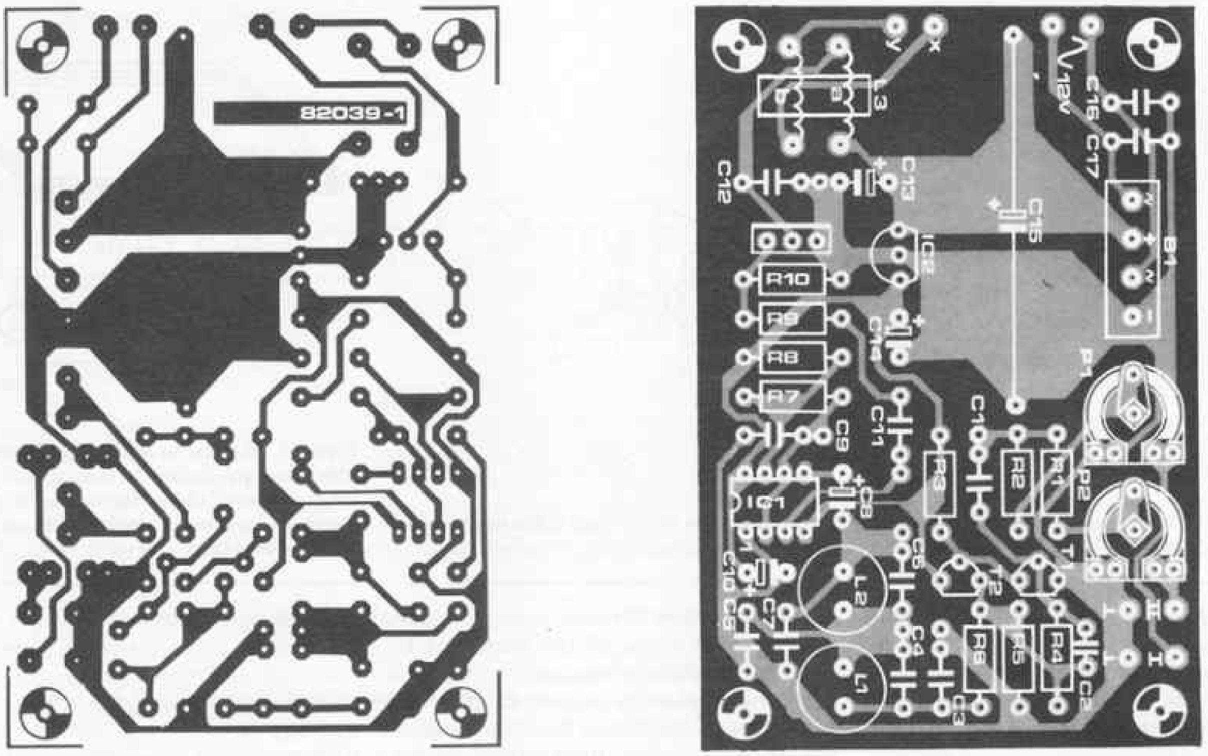

Figure 9. The printed circuit board and component overlay for the transmitter section.

provided by the PLL. The linearity of the 555 VCO leaves much to be desired, but it has no disturbing effect on the quality of reproduction.

Transistor T3 amplifies the VCO output signal in order to supply the induction loop of the paging system with sufficient power. The signal has to be filtered before it is fed to the loop and some form of coupling between the loop and the output stage must be found. It is recommended to isolate the loop from the output stage. This can be accomplished by using a (modified) 40 μH 'anti-interference' coil (for example, a toroid as used in light dimmers). This then functions as a 'tank' circuit. Although the efficiency is not particularly impressive at the operating frequency of 24 kHz, it serves the purpose quite well. Attenuation of harmonics is quite considerable, which is useful for this application.

The modification to the toroid is very simple and is performed by adding a number of secondary windings around the coil. For a typical living room, ten secondary windings are sufficient. In this way the circuit is electrically isolated from the loop itself. There is plenty of room to wind the secondary around the toroid with well insulated wire, the diameter of which should be at least 0.5 mm.

Construction

Installation of the transmitter will be dependent on the application. If it is used for TV sound, it may be possible to mount the transmitter inside the TV cabinet. It may even be possible to derive the power supply for the transmitter from the TV, especially if a circuit diagram is available. A word of warning:remember that the guarantee may not be effective if additional circuitry is added. Also, the majority of TV sets do not use a mains transformer and very often the chassis is live!

The current consumption of the transmitter is about 400 mA, which means that it should not be too difficult to construct a suitable power supply if the need should arise. It is preferable to connect the audio input to a signal source which can not be influenced by external means — before the volume control! It is important to make sure that the coils of the low-pass filter (L1 and L2) are not situated in the vicinity of supply transformers. If the circuit is mounted inside a TV receiver, it should not be placed near the line oscillator, the line transformer or the deflection coils.

As far as the receiver is concerned, it is advisable to wind the pick-up coil around the inside of the housing to be used. Consequently, it may not be possible to use the type of coil illustrated in the diagram. The inductance value of 6 mH is essential, along with the size of the coil which should occupy at least 7 cm^2. The shape of the coil is not important as long as the above conditions are fulfilled.

It is always difficult to predict how many turns are actually required. The easiest solution is to wind a hundred

Parts list for the transmitter

Resistors:

R1 = 100 k
R2 = 4k7
R3 = 47 k
R4 = 470 k
R5 = 470 Ω
R6,R8 = 1 k
R27 = 27 k
R9 = 100 Ω
R10 = 180 Ω
P1 = 1 k preset
P2 = 22 k preset

Capacitors:

C1 = 470 n
C2 = 100 p
C3,C7 = 120 n
C4,C6 = 10 n
C5 = 180 n
C8,C14 = 1 μ/6 V Tantalum
C9 = 1 n
C10 = 1 μ/35 V Tantalum
C11 = 68 n
C12 = 330 n
C13 = 10 μ/35 V Tantalum
C15 = 2200 μ/16 V
C16,C17 = 47 n

Semiconductors:

T1 = BC 549C
T2 = BC 547B
T3 = BD 241
IC1 = 555
IC2 = 78L05
B1 = B40C1000 (1 amp) bridge rectifier

Miscellaneous:

L1,L2 = 47 mH microchoke
L3a = 40 μH anti-interference coil
L3b = insulated copper wire
Cu $\phi \geq$ 0.5 mm on L3a (see text)
Tr1 = 12 V/0.4 A transformer

turns around the coil, connect a 6n8 capacitor across it and determine the resonant frequency with the aid of a signal generator. Thus, having found the resonant frequency to be 79 kHz, for example, the number of turns required would be: (100 x 79) / 24 = *329*. This method is quite accurate enough. The test 'set-up' is shown in figure 6. It is important to ensure that the signal generator used is accurately calibrated. If there is any doubt, the final check can be carried out with the transmitter instead of the tone generator. The value of the parallel capacitor should be between 4n7 and 8n2, otherwise the bandwidth of the circuit would be outside the preset limits.

The connection leads to the pick-up coil should be as short as possible. This is not necessarily a problem as the connection points for the coil are situated near the edge of the printed circuit board (see figure 8). As mentioned previously, there should be no form of coupling between the input and output, as otherwise the sensitivity of the receiver would be drastically reduced. Consequently, the connections to the loudspeaker or headphone have to be installed as far away as possible from the input.

Although the transmitter output can be connected directly to the induction loop, a considerable increase in signal strength can be gained by tuning the loop. Figure 7 illustrates how this can be accomplished. Initially, the value of capacitor C_X should be 22 n when the measuring circuit is connected to the induction loop. The meter reading should be noted. The value of C_X is then increased until the meter reading starts to drop. The capacitor value which gives the highest reading should then be connected between point X and the loop. In practice, the value of the capacitor, which forms a series resonant circuit with the loop, will be somewhere between 47 and 680 n.

Although the loop is now 'tuned', it does not mean that the system necessarily operates at maximum effectiveness. For example, a 'free' induction loop formed by central heating or water pipes would have a much lower inductance value than a 'living room' loop with four turns, but the range of the 'free' loop would be much greater. The reader is quite free to experiment with different kinds of induction loop, as long as the output stage of the transmitter is not overloaded. With a correct 'interface' the voltage at points x and y will be around 2 . . . 6 V_{p-p}. Therefore, a reading of 1 . . . 3 V will be obtained with the half-wave rectifier circuit given in figure 7.

Perfectionists can also experiment with the number of turns for L3b, after having found the correct value for the series capacitor C_X. The optimum number will be that which gives a maximum reading on the test set-up of figure 7. Although a gain of as much as 20 dB can be obtained by tuning the induction loop, it is not really necessary if the system is to be used indoors. However, tuning will reduce interference from other sources quite considerably.

Operation

Firstly, it is essential to make sure that no mistakes were made during construction. This is especially true of the transmitter as the 555 timer and output transistor will just not cope with short circuits! Once everything has been checked and found to be satisfactory, the transmitter can be turned on and a suitable audio signal (speech or music) connected to the input. The induction loop is then connected to the output, bearing in mind the point made previously about the voltage across points x-y. When the receiver is switched on the signal fed to the transmitter should be audible. The input level can then be adjusted by means of P1 or P2 of the transmitter (depending on the input used) until the distortion (if any) is reduced to a minimum and/or is acceptable.

Preset potentiometer P1 in the receiver is then adjusted to give optimum reproduction of the transmitted signal. In order to perform this adjustment correctly, the receiver should be moved away from the transmitter until reception is barely audible, since the capture range of the PLL is very wide. The setting of P1 can be checked by switching the receiver off for a moment. When it is turned back on, the PLL must lock in immediately.

If the PLL does lock, but the sound level differs from the previous level, the VCO will be tuned to a harmonic or subharmonic of the fundamental frequency. When the PLL is correctly locked the voltage at pin 9 of the 4046 will be in the region of 2 . . . 3 V. This value can only be measured with a high impedance (FET) voltmeter. If such an instrument is not available, the voltage at pin 10 can be measured, which should be about 0 . . . 0.5 V greater than that at pin 9.

As can be expected, the results that can be achieved with a correctly set up circuit depend entirely on the type of induction loop used and the 'interface' to the transmitter. The prototype was tested using a set-up similar to a normal living room. A television set was even placed inside the area of the induction loop (22 m^2) to provide an interference source. Besides this, the system was also tested with a 'free' induction loop comprised of an earth connection and the central heating pipes. The results obtained are as follows: Using a single 'untuned' winding the system was usable to a distance of 2 m outside the loop area. However, the receiver could not be used any closer than 2 m to the TV set without interference from the line oscillator.

With a 'tuned' loop of three windings the receiver could be used as close as 1.5 m to the TV. The reception was still acceptable up to a distance of 4 m outside the area.

When the central heating pipes were used as the induction loop, the system exhibited an acceptable reception range of 20 m. After tuning, the signal-to-noise ratio improved and the range outside the building increased to 50 m.

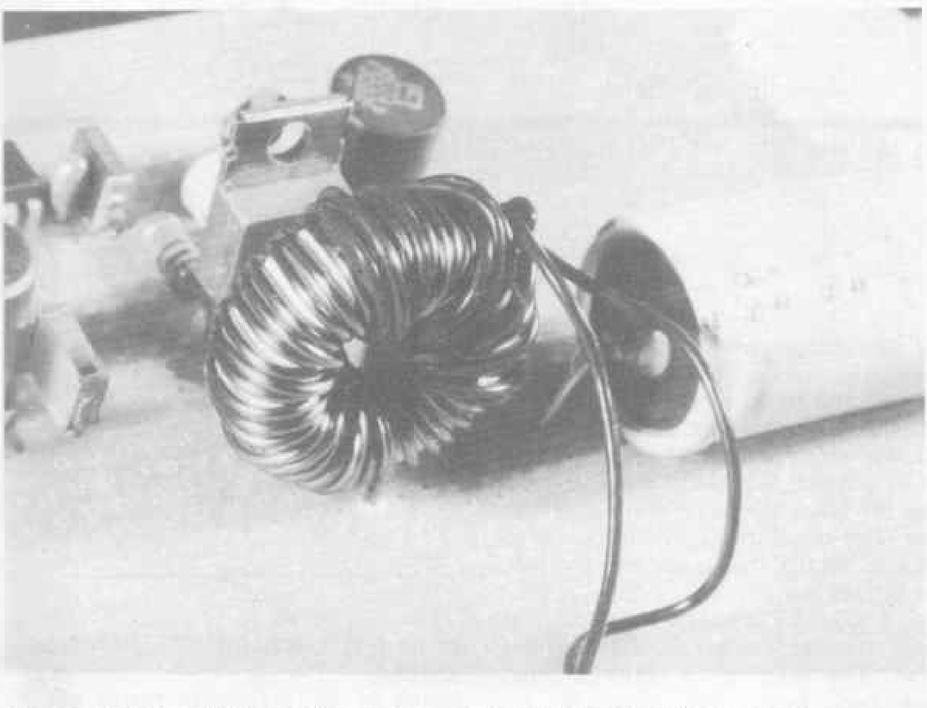

Photo. This close-up illustrates the relative size of the pick-up coil of the paging system.