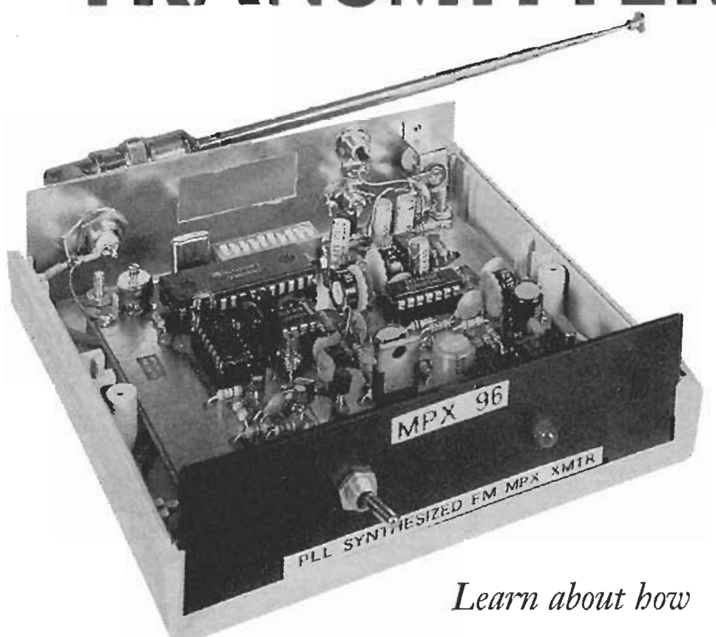
WILLIAM SHEETS K2MQJ AND
RUDOLF F. GRAF KA2CWL

BUILD THIS FM-STEREO TRANSMITTER



Learn about how FM stereo is broadcast with this easy-to-build project—an FM transmitter that can extend your home stereo system anywhere on your property.

Low-power FM transmitters have become a popular hobby item in recent years. They are usually free-running RF oscillators that are frequency-modulated with an audio signal and are used in many applications from wireless microphones to listening devices to small home-entertainment extenders that let you listen to your home stereo anywhere in your house or yard through a portable radio. Stereo operation is also possible, with a number of chips developed for just such a device. However, recent advances in radio technology have brought out some problems in those devices that were not important before.

Digitally-tuned receivers are commonplace nowadays. Those receivers are always exactly on frequency, making tuning to a desired station very simple. The traditional analog "slide-rule" dial has largely disappeared from the higher-end FM receivers, replaced by LCD or LED readouts. Automatic frequency control and fine-tuning adjustments are no longer needed, as such units cannot be tuned off channel. Any received signals must be exactly on frequency. If it is not, either no signal will be received or the signal will be distorted. Of course, that is no problem for commercial FM stations. Their frequencies must be crystal-controlled and held to extremely close tolerances. However, for the user of a simple low-power transmitter, that could be a problem because frequency drift is a fact of life for those circuits.

It is hard to hold simple LC oscillators to a stability much better than 0.1% over a reasonable temperature and supply-voltage range. At 100 MHz, the middle of the FM-broadcast band, that tolerance becomes a drift of 100 kHz. An analog-tuned FM receiver has no problem receiving the signal as it drifts because the AFC circuit automatically retunes the receiver as needed. A digitally-tuned receiver with frequency-synthesized tuning using a phase-locked loop (PLL) circuit cannot do that without special circuitry. Commercial FM receivers have no need to do that because of the stability of commercial FM radio stations. Also, the FM band is crowded with many signals in most populated areas, and a free or unoccupied channel is rare at times. Therefore, as the low-power FM transmitter drifts, it runs into interference from adjacent channels.

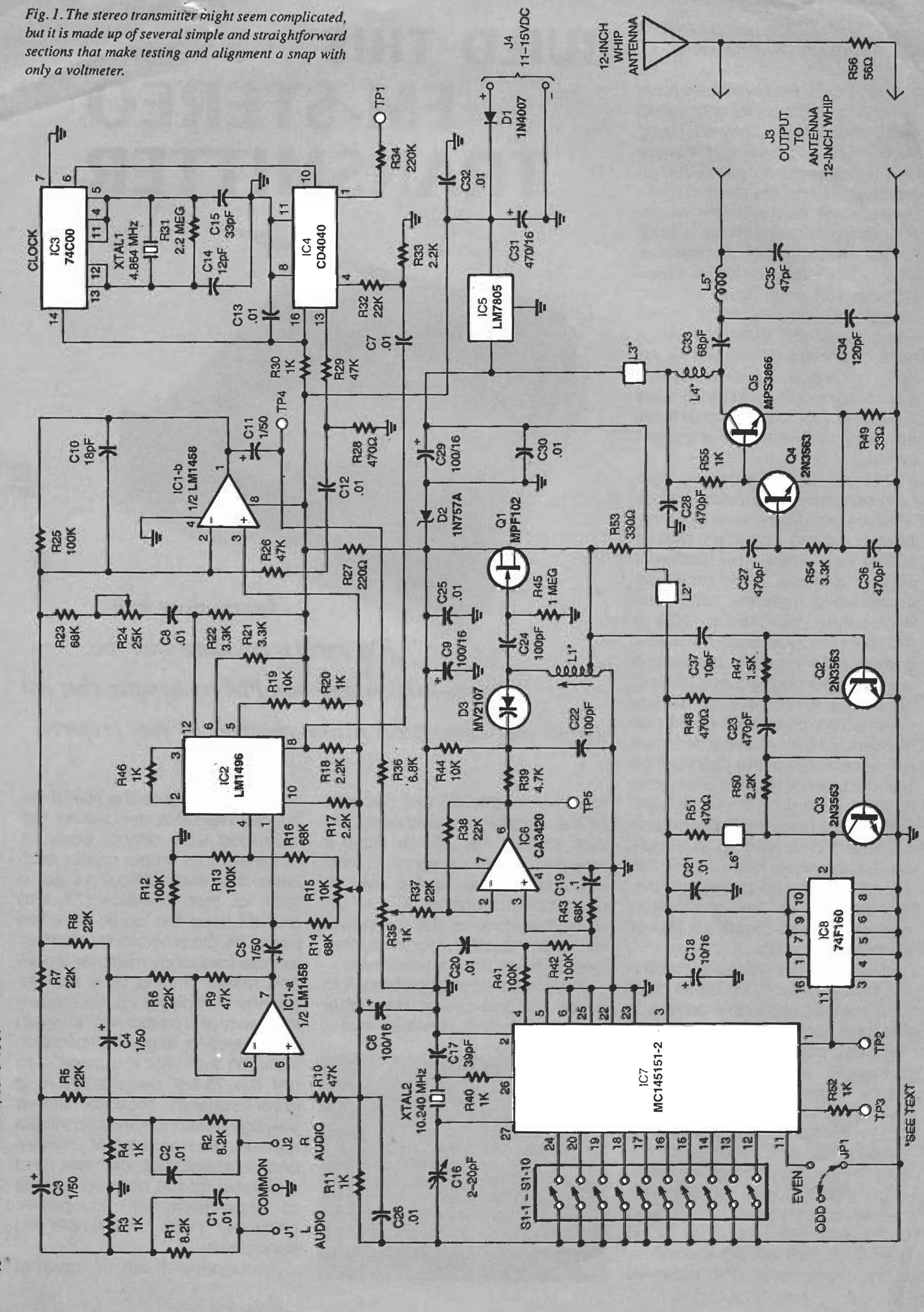
The solution to that problem is to make the low-power transmitter crystal controlled. However, that is not simple because the 75-KHz frequency deviation needed for FM-broadcast work cannot easily be obtained from simple crystal oscillators. It is even difficult to get a tenth of that deviation (7.5 kHz) and still keep the audio distortion below 1%. Commercial FM transmitters use frequency-multiplier stages and mixers, starting at a low frequency, multiplying up, heterodyning down, and multiplying up again to achieve a large multiplication factor. In that way, it is possible to get the 75-kHz deviation from a lower-frequency oscillator with a very tight tolerance. That traditional method requires a lot of circuitry, and is impractical, complex, and expensive for the hobbyist wishing to experiment with low-power, physically small, and simple FM transmitters.

Fortunately, there is another

Warning!

The publisher makes no representations as to the legality of constructing and/or using the FM Stereo Transmitter referred to in this article. The construction and/or use of the transmitter described in this article may violate federal and/or state law. Readers are advised to obtain independent advice as to the propriety of its construction and the use thereof based upon their individual circumstances and jurisdiction.

Fig. 1. The stereo transmitter might seem complicated, but it is made up of several simple and straightforward sections that make testing and alignment a snap with only a voltmeter.



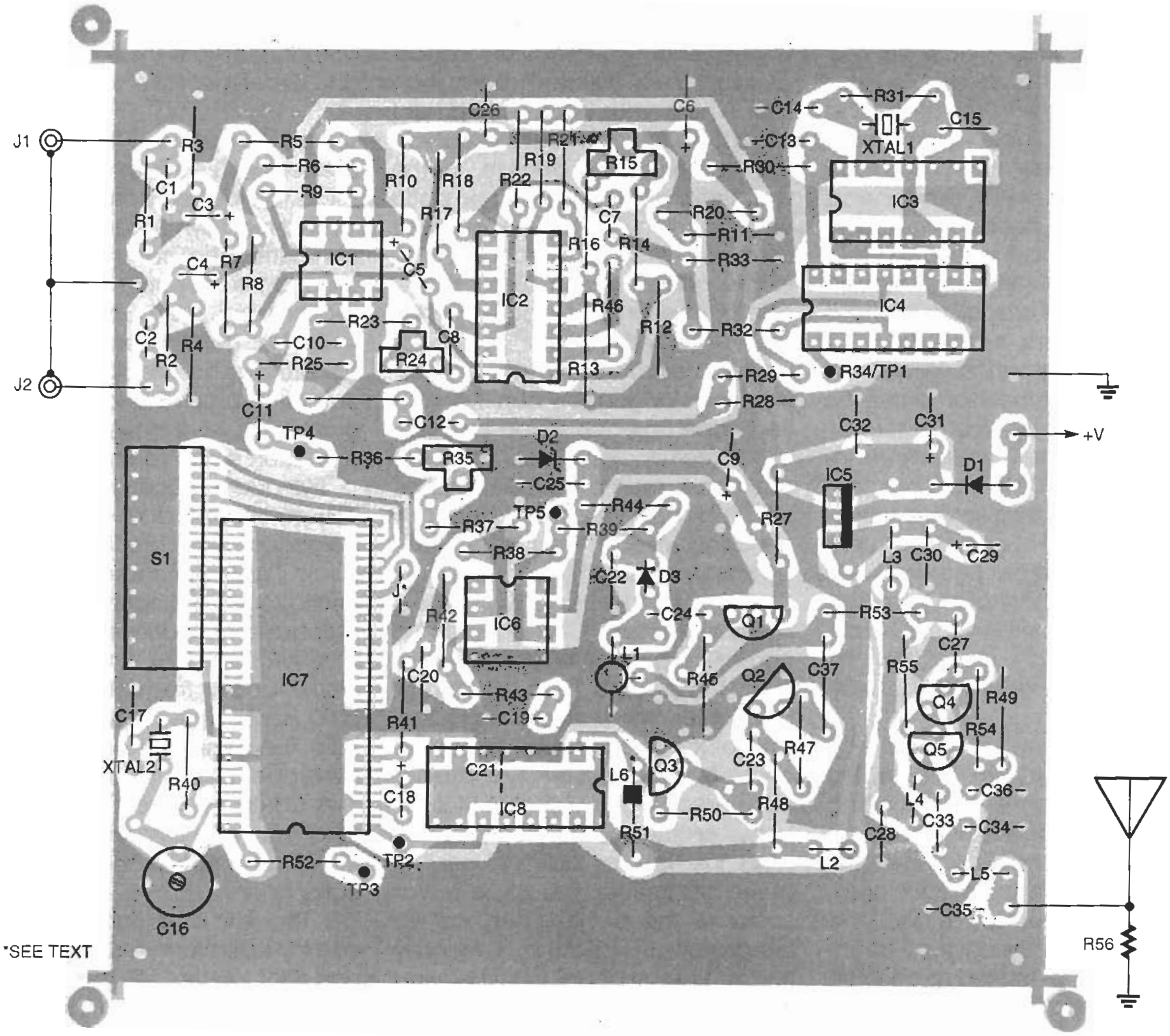


Fig. 2. The transmitter is easily built on a single PC board. A single surface-mount capacitor is soldered to the bottom side of the board. Be sure to solder the component leads on both sides of the board where pads are provided on the component side.

(sum and difference) cannot be combined at this point as there would be no way of keeping the two signals separated. The way to solve that problem is to first modulate the difference signal onto a subcarrier signal that is well above the upper end of the audio band, which extends from about 20 Hz to about 15 kHz. That is done by producing a double-sideband signal at 38 kHz, and then modulating it with the L–R audio signal, which also has audio components from 20 Hz to 15 kHz. A double-sideband signal having sum and difference components of the 38-kHz subcarrier and the L–R audio is produced. Since the L–R signal has frequencies up to 15 kHz, the subcarrier will have components from 38 kHz ±15 kHz, or from 23 to 53 kHz. Because the 38-kHz signal has no information, it is suppressed, leaving only the sum and difference sidebands, which have the L–R information. The subcarrier is produced by IC2, an LM1496N balanced modulator. That device will produce a double-sideband signal at pin 6 or 12 that is the product of the modulation signal at pin 1 or 4 and the unmodulated (continuous wave or CW) subcarrier signal at pin 8 or 10. A bias network for IC2 is formed by R12 through R19, R21, and R22. Potentiometer R15 is provided for exact balancing of the currents through the internal circuitry of IC2. When properly adjusted, the 38-kHz subcarrier signal fed to inputs (pins 8 or 10) can be completely removed from the modulator outputs (pins 6 and 12), leaving only the sum and difference products of the L-R input at pins 1 and 4 and the subcarrier at pins 8 or 10. That is exactly what is wanted.

Only one input pin is used for the audio and 38-kHz subcarrier as the differential input and output capability is not needed here. The output at pin 12 is fed to multiplex amplifier IC2-b through C8, level control R24, and R23. The balanced modulator has a gain of about two and the differential amplifier has a gain of two, giving an overall gain of four times in the L–R channel. In order to keep the gain of the L+R and L–R signals equal, the combined resistance of R23 and R24 should be four times the value R7 or R8. Because of tolerances in the resistors and individual differences in IC2, R24 is adjustable in order to approach made possible by the use of modern digital ICs. This article will describe a simple low-power FM-stereo transmitter using phase-locked loop techniques along with a few digital ICs and analog op-amps to produce a clean, stable, broadcast-quality FM-stereo signal. It is a complete FM-stereo audio link operating in the standard FM broadcast band. It can be operated over a range of 76–108 MHz. That range will work in both the North American domestic FM and the 76–88 MHz frequency range used in the Far East. A channel spacing of 100 kHz assures coverage of all FM frequencies worldwide. Both the FM-carrier frequency and the multiplex-pilot frequencies are crystal controlled, eliminating the drift common with LC oscillators. That permits use of this unit with the digital receivers that you find today.

Frequency selection is done by setting a ten-position DIP switch with a binary code corresponding to the desired transmitter frequency. That frequency can be any unused FM channel in your area. Once the frequency is set, the transmitter will stay on that channel, as it is phase locked to an internal crystal oscillator. Audio input can be any line-level source of 0.5- to 1-volt rms, and can be either a stereo signal or two individual monophonic signals. An on-board audio-tone generator, set to 1200 Hz, makes setting the transmitter and receiver easy. All seven IC devices in the transmitter are readily available. Circuit setup is very simple, with only a volt-ohmmeter needed. A single 12- to 15-volt DC negative-ground supply is needed to power the transmitter. With a current drain of 120 milliamps, a simple battery pack can be used as a power source. The RF output is about 10 milliwatts into a 50-ohm load (0.7V rms). At that level, the transmitter complies with US requirements for unlicensed transmitters when used with a 12-inch antenna and a 56-ohm shunt resistor. For use outside the USA, the output power can be increased to 150 milliwatts with a simple circuit change.

There are many ways to use the transmitter. You can listen to your CD player or tape deck on a pocket radio in a different room than that where your audio equipment is located. You can even be outside the house, in the garage, in the workshop, or on the deck or patio while listening. A private or in-house broadcast systems for schools, real-estate offices, health clubs, stores, offices, museums, etc. could be set up. For entertainment of groups where a second language is spoken, two languages can be carried—one on each stereo channel. Using small pocket-stereo receivers, audience members can choose which language they hear by choosing whether they listen to the left channel or right channel.

A Short History. An early stereo transmitter project was published in the March 1988 issue of **Radio-Electronics**. That project also used several ICs to generate the carrier frequency. Soon after that project appeared, the BA1404/BA1405 IC came on the scene, greatly simplifying the task of building an FM-stereo transmitter. The BA1405 was similar to the BA1404, but had no integrated RF section. Originally meant to play portable CD players through FM-stereo auto radios, those ICs were useful for making a simple stereo transmitter. The BA1404 had poor RF stability and taught little about FM-stereo circuit operation to the experimenter. It also had the disadvantage of requiring a low supply voltage (below 3 volts) and required a fragile 38-kHz crystal.

The transmitter presented here is a simplified version of the earlier circuit, adding some improvements and eliminating several setup adjustments. Two IC devices now handle multiplex-signal generation, and a crystal-controlled design replaces the three large coils originally used. The fragile 38-kHz crystal used by the BA1404 for the pilot and subcarrier frequencies has been replaced by a rugged 5-MHz type, and two common CMOS ICs generate the 38-kHz and 19-kHz signals. As an extra bonus, a 1.2-kHz audio signal is developed in one of the ICs for test purposes. The total cost is low and, unlike the BA1404/BA1405 approach, all of the multiplex-signal components are available for study and experimentation.

Circuit Operation. The transmitter uses eight IC devices and five transistors to create a complete phase-locked-loop synthesized FM stereo transmitter. The transmitter can be divided into several sections. Those sections are the audio generator, multiplex (MPX) generator, clock generator, phase-locked loop, and output amplifier. The schematic diagram in Fig. 1 will make the following discussion easier to understand.

The audio section is made up of IC1, an LM1458 dual op-amp, and balanced modulator IC2. Line-level audio inputs connected to both J1 and J2 are fed to two R–C pre-emphasis networks made up of R1/C1/R3 and R2/C2/R4. Those networks boost frequencies above 2000 Hz for a better signal-to-noise ratio. The same technique is used in FM broadcasting. Coupling capacitors C3 and C4 pass those signals to a matrixing circuit consisting of R7, R8, and IC1-a and associated components R5, R6, R9, R10, and C5. The left and right inputs are combined to form a sum of the left and right inputs (L+R) by R7 and R8. That signal is passed to the input of IC1-b, where it is combined with two other signals. One of those signals is the audio subcarrier containing the difference of the two audio inputs (L–R). Note that if the two audio inputs are identical, the difference signal is zero.

Op-amp IC1-a is configured as a differential amplifier with a gain of about two. The left audio input is fed to the non-inverting input through R5 and R10. A network consisting of R11, R20, C6, and C26 provides a fixed bias of half the supply voltage to bias both the IC1-a and IC1-b inputs. That avoids the need for a split power supply. The right audio input is fed to the inverting input of IC1-a through R6. The ratio of R9 to R6 sets the gain. Resistors R5, R6, R9, and R10 are chosen so that equal gain is obtained for both audio inputs. Since the right input is inverted in IC1-b, the output of IC1-b is proportional to the difference of the audio inputs.

The two combined audio signals

allow the gain of those signals to be set equal to each other. The gain of IC2 is set by R46 to about two.

In order for the receiver to recover the L–R information, a reference is required so that the recovered L–R information will have the correct phase and frequency content. It would be difficult to try to filter that from the subcarrier signal, which might have L–R audio components as low as 20 Hz. There is, however, an easier way to do that.

A 20-Hz audio signal would produce both 37,980 Hz and 38,020 Hz subcarrier components, which are very close to 38 kHz and are easily separated from the 38-kHz carrier without the need of an expensive filter. A pilot signal at half that frequency, or 19 kHz, is used as a reference instead. That frequency fits into the composite signal quite well, being halfway between the L+R audio maximum frequency of 15 kHz and the lower limit of the L–R at 23 kHz. The pilot signal is supplied by the clock-generator circuit, which will be discussed shortly. The pilot signal is fed to IC1-b through coupling capacitor C12 and R26. It has a level about one quarter of the peak of either the L+R or L–R signals. In addition, it is used by most stereo receivers to activate both their stereo-decoding circuit and their stereo-indicator LED. If a monophonic receiver is tuned to the stereo signal, only the L+R portion would be used. Any frequencies above the audio spectrum are rejected, which include the L–R and the pilot signals. The L+R signal is, of course, the combination of the left and right stereo channels. That ensures compatibility between stereo broadcasts and mono receivers, just as black-and-white TV sets can receive color broadcasts and still display a black-and-white version of the color picture.

Three signals are present at the input of IC1-b: the L+R signal, the L–R subcarrier signal, and the pilot signal. Those signals are added together in IC1-b and the composite signal appears at the output. The overall gain is set by R25 to about four, and C10 restricts the bandwidth of the stage to less than 100 kHz at 3 dB down. The composite signal is coupled by C11 to TP4, R36, and deviation control R35. The deviation control is used to set the level of the composite signal to the FM modulator, and R36 limits the maximum level in order to avoid overdeviation.

The clock-generator circuit consists of IC3, IC4, and their associated components. Its purpose is to generate a stable 38-kHz subcarrier, a 19-kHz pilot signal, and a 1.2-kHz audio signal for testing and alignment purposes. For stability, it is crystal controlled. A NAND gate, IC3-a, is connected as an inverter, and is biased by R31 so it will initially act as an amplifier. A feedback network consisting of XTAL1 and capacitors C14 and C15 let the circuit oscillate at 4.864 MHz. Output from IC3-a is fed to IC3-b to buffer the clock signal. The buffered output drives IC4, a 12-stage counter and divider, which divides the clock signal by up to 4096. An output is available at each division stage. Thus, a 38-kHz signal (4864÷128), a 19 kHz signal (4864÷256), and a 1187.5 Hz signal (4864÷4096) are produced and are all in phase with respect to each other. The outputs are reduced to lower levels by R29, R28, R32, R33, and R34 as the nominal 7- to 8-volt signals are far more than needed. The power supply for IC3 and IC4 is reduced to about 8 volts by R30 and C13. Those components also decouple the supply line from any noise generated by those ICs. Using a rugged and inexpensive 5-MHz-range fundamental crystal and a divider circuit gets rid of the fragile and expensive 38-kHz crystal used in other approaches, such as the BA1404, and supplies a 1.2-kHz audio tone for setup purposes at no extra cost.

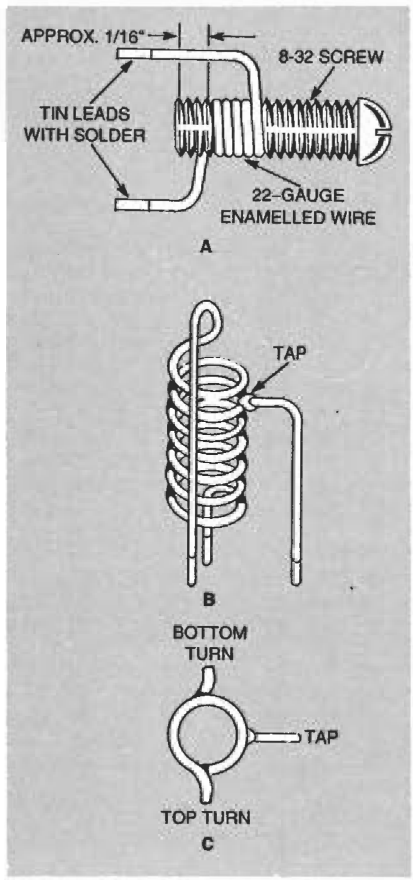


Fig. 3. Making L1 is simplified by using an 8-32 screw as a winding form (A). Be sure the screw is steel instead of brass, or you might solder the coil to the screw when attaching the tap (B). After the coil is installed in the PC board and the screw removed, it should look like (C) when viewed from overhead.

The phase-locked-loop (PLL) synthesizer section uses an MC145151-2 chip. That chip contains a reference oscillator, a reference divider, a charge-pump phase detector, and a variable divider that can be set for division ratios from 3 to 16,384. The reference divider is programmed by grounding control pins to generate various division ratios. For our needs, the reference divider is set to divide by 1024 so that a standard 10.240-MHz crystal will provide a reference frequency of 10 kHz. That sets the resolution of the synthesizer. The maximum input frequency that the chip can directly handle is around 12 MHz.

The FM broadcast band has channels at 200-kHz spacing. In the USA and Canada, they start at 88.1 MHz and increment in 200 kHz steps (*i.e.* 88.3, 88.5, 88.7) to 107.9 MHz. In many parts of the world, channels with even spacing (i.e. 90.0, 90.2, 90.4) are common. In some parts of the Far East, frequencies as low as 76 MHz are used. The transmitter circuit will cover all frequencies, but in the interest of best synthesizer performance, cost limitations, and circuit simplicity, the tuning range has been restricted to about 8 MHz without need for the VCO to be reset—that tradeoff is well worth the convenience of having just one simple adjustment. The synthesizer supports all channels between 76 and 108 MHz in 100 kHz increments.

Table 1

Frequency in MHz		S1 Settings									
Even Channels	Odd Channels	1	2	3	4	5	6	7	8	9	10
88.0	88.1	on	on	on	off	off	off	on	off	off	on
88.2	88.3	off	on	on	off	off	off	on	off	off	on
88.4	88.5	on	off	on	off	off	off	on	off	off	on
88.6	88.7	off	off	on	off	off	off	on	off	off	on
88.8	88.9	on	on	off	off	off	off	on	off	off	on
89.0	89.1	off	on	off	off	off	off	on	off	off	on
89.2	89.3	on	off	off	off	off	off	on	off	off	on
89.4	89.5	off	off	off	off	off	off	on	off	off	on
89.6	89.7	on	on	on	on	on	on	off	off	off	on
89.8	89.9	off	on	on	on	on	on	off	off	off	on
90.0	90.1	on	off	on	on	on	on	off	off	off	on
90.2	90.3	off	off	on	on	on	on	off	off	off	on
90.4	90.5	on	on	off	on	on	on	off	off	off	on
90.6	90.7	off	on	off	on	on	on	off	off	off	on
90.8	90.9	on	off	off	on	on	on	off	off	off	on
91.0	91.1	off	off	off	on	on	on	off	off	off	on
91.2	91.3	on	on	on	off	on	on	off	off	off	on
91.4	91.5	off	on	on	off	on	on	off	off	off	on
91.6	91.7	on	off	on	off	on	on	off	off	off	on
91.8	91.9	off	off	on	off	on	on	off	off	off	on
92.0	92.1	on	on	off	off	on	on	off	off	off	on
92.2	92.3	off	on	off	off	on	on	off	off	off	on
92.4	92.5	on	off	off	off	on	on	off	off	off	on
92.6	92.7	off	off	off	off	on	on	off	off	off	on
92.8	92.9	on	on	on	on	off	on	off	off	off	on
93.0	93.1	off	on	on	on	off	on	off	off	off	on
93.2	93.3	on	off	on	on	off	on	off	off	off	on
93.4	93.5	off	off	on	on	off	on	off	off	off	on
93.6	93.7	on	on	off	on	off	on	off	off	off	on
93.8	93.9	off	on	off	on	off	on	off	off	off	on
96.0	96.1	on	on	on	on	on	off	off	off	off	on
98.0	98.1	on	off	on	off	on	off	off	off	off	on
100.0	100.1	on	on	off	on	off	off	off	off	off	on
102.0	102.1	on	off	off	off	off	off	off	off	off	on
104.0	104.1	on	on	on	off	on	on	on	on	on	off
106.0	106.1	on	off	on	on	off	on	on	on	on	off
107.8	107.9	off	off	on	off	off	on	on	on	on	off
Frequencies outside US/Canada											
76.0	76.1	on	on	off	off	off	off	off	on	off	on
80.0	80.1	on	on	on	on	off	on	on	off	off	on
84.0	84.1	on	on	off	on	on	off	on	off	off	on

In order to eliminate a microprocessor and display, the desired frequency is set by S1, an on-board ten-section DIP switch. The desired transmitter frequency is selected from Table 1, and the switches are set accordingly. Once the transmitter is set to a clear channel, it will usually be left alone. In most populated areas, there are relatively few clear channels and in some major cities in the US, they are very rare, so there is little need to often reset the transmitting frequency. Additionally, most low-power FM transmitters operate between 88 and 92 MHz, so a microprocessor and display is overkill and relatively useless. Although the synthesizer can cover a wider range than 76 to 108 MHz, it has not been tested to those extremes. There is no reason that it shouldn't work down into the HF range (below 30 MHz) with suitable design changes in the loop-filter network, VCO, and output-buffer amplifier. Higher frequencies are best handled by using suitable frequency multipliers. Those modifications will not be discussed and are left to the experimenter.

Since IC7 will only handle about 12 MHz, IC8, a 74F160ACP prescaler, is used to divide the VCO frequency (76-108 MHz) by ten. The synthesizer will thus see 7.6 to 10.8 MHz in 10 kHz steps—one tenth of the transmitter frequency. The PLL phase detector is buffered by IC6, and provides a very high impedance for the sample-and-hold circuit, minimizing 10-kHz reference-frequency sidebands, and allowing smaller capacitors to be used in the compensation network. It also provides an easy method for injecting an audio signal into the VCO for directly modulating the carrier frequency. A voltage-controlled oscillator built around Q1 feeds buffer amplifier Q2/Q3 to interface with the prescaler IC8 and drive output buffer amplifier Q4/Q5.

The PLL oscillator consists of Q1, L1, and D3. Oscillator frequency is set by L1, D3, and stray capacitance from Q1 and the circuit in general. Bias for Q1 is provided by R45 and D3. Any stray RF on the anode of D3 is shunted to ground by C22. The capacitance of D3 is set by a DC voltage from R44 and R39. Depending on the voltage and the tuning of L1, the frequency will be anywhere from 76 to 108 MHz.

The output of the oscillator (the source of Q1) is passed to amplifier stages Q2 and Q3 through C37. The Q2/Q3 amplifier is connected as a wideband-feedback stage with R47 and R48 for feedback and bias. The first stage output from Q2 is coupled by C23 to the base of Q3. The second stage is biased by R51 and R50. The signal appearing at the collector of Q3 is now strong enough to drive IC8, a 74F160 TTL decade counter.

A signal of one-tenth the input frequency appears at pin 11 of IC8, which is fed to the variable-programmable divider section of IC7. The actual division is set by S1 to divide between 760 and 1080, which is equal to the desired output frequency times ten. For example, if the desired frequency is 89.7 MHz, then the divide ratio will be set to 897 with S1. The internal variable divider will produce a signal to be fed to the phase detector at the transmitter frequency divided by 8970, since we have divided 10

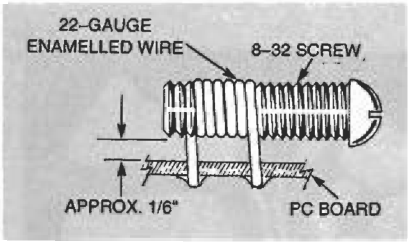


Fig. 4. Make L4 and L5 the same way as L1. Use 5 turns for L4 and 4 turns for L5.

times with IC8 and 897 times with the programmable divider. Meanwhile, the phase detector is fed a 10-kHz reference signal from an internal reference oscillator and divider that uses external components R40, C17, XTAL2, and C16. Those parts determine the oscillator frequency. The frequency is set exactly to 10.240 MHz by adjusting C16. An internal divider divides that frequency by 1024 to produce the 10-kHz reference. The accuracy of the output frequency depends on having an exact 10 kHz, which in turn needs an exact 10.240 MHz crystal-oscillator frequency.

The phase detector generates a voltage that depends on the relative phase difference between the reference and variable divider output waveforms. For example, suppose the divider output starts to lag the reference. That means that the VCO frequency is dropping. In that case, the phase detector produces positive going pulses and feeds them to the sample-and-hold network made up of R41, C20, R42, R43, and C19. The pulses charge C19 to a higher DC voltage. A high-impedance CMOS voltage amplifier consisting of IC6, R37, R38, R39, and R40 produces a positive-going output, which is fed to D3 through R39 and R44, causing the oscillator frequency to increase. The opposite happens if the VCO drifts higher, causing the divider output to lead the reference. The voltage on D3 is then lowered, and causes the VCO to lower its frequency. In that way, the VCO frequency is locked to the reference frequency. It will be exactly equal, in kilohertz, to one hundred times the programmed divide ratio. In the example, the divider is set to 897, so that the output frequency will be 100 × 897 or 89,700 kHz (89.7 MHz)

Frequency modulation is accomplished by injecting the audio signal from the audio amplifier into IC6. Instead of being returned to ground, R37 is fed from potentiometer R35. The audio voltage is superimposed on the voltage to varactor D3. Since the bandwidth of the synthesizer loop is less than 20 Hz, the relatively high audio frequencies are not "corrected out," and as long as no DC component is injected (we're assuming symmetrical FM, which is the usual case), the variations in frequency under modulation are averaged out. The resulting modulation is clean and low in distortion since the VCO has a dynamic range of several volts and a 1-volt change produces about a 1-MHz frequency change. Therefore, only about 100 to 150 millivolts peak-to-peak of audio is needed for full modulation. The VCO is highly linear over such a small range.

A transmitter output signal of about 10 milliwatts is produced by amplifying a portion of the VCO signal. The signal from the VCO is fed through R53 and C27 to feedback pair Q4/Q5 and associated components R49, R54, R55, and C36. In that stage, the signal is amplified to the final output level and then fed to a matching network and harmonic filter (L4, C33, C34, L5, and C35). Output is at 50 ohms, and it is recommended to terminate the transmitter into a load (R56) and use a simple 12-inch whip as an antenna to confine the signal to only that area needed. The supply line is decoupled by C28 and L3.

The supply voltage to IC6, IC7, and the output amplifier is regulated by IC5. The regulated supply line for IC7 and IC8 is further decoupled by L2, C18, and C21. Additional transient protection is provided by C29 and C30. The audio and clock sections IC1 through IC4 operate directly from 12 volts, while the VCO and IC6 are supplied with +9V from Zener regulator D2, R27, and decoupling capacitors C9 and C25. Input filtering of the 12-volt supply input is done by D1, C31, and C32. The supply voltage might vary from 11 to 15 volts in actual use. Exceeding the 15-volt level might cause damage, and less than 11 volts might result in the PLL not functioning. Also, excess noise on the DC supply line may cause the noise to be heard on the transmitted signal as interference and hum.

Building the Transmitter. Because of the RF signals involved, the transmitter should only be built on a PC board. If you wish to do so, artwork is provided in order to fabricate a PC board. A complete kit of all components can also be obtained from the source given in the Parts List.

With the exception of C21, all components are mounted on the

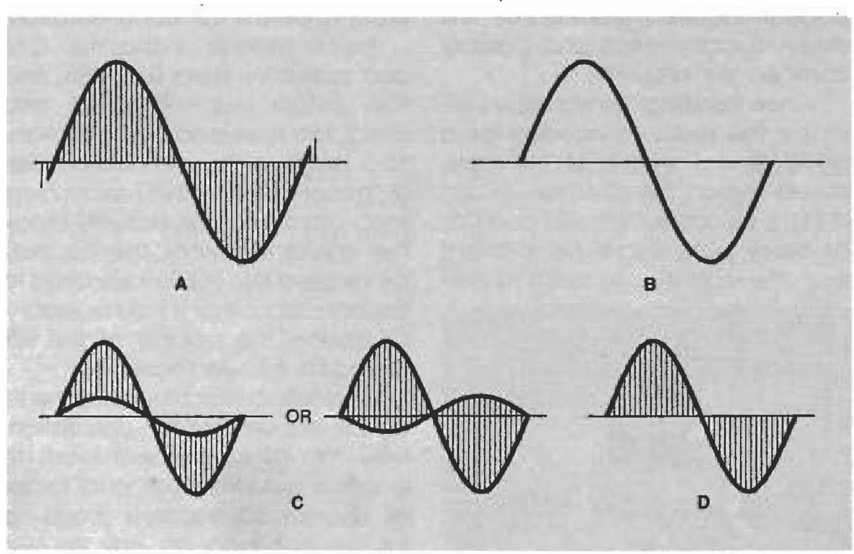


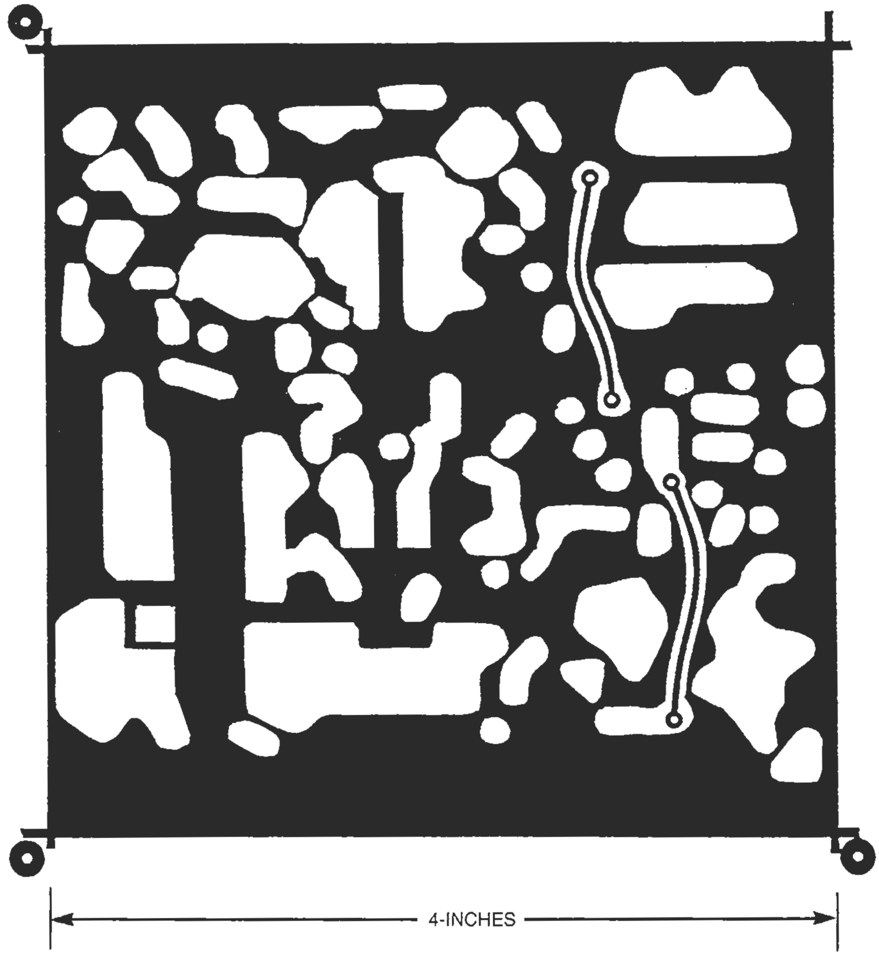
Fig. 6. If you have access to more sophisticated test equipment, you can perform more exact adjustments to the transmitter for optimum stereo separation and distortion. The waveform in (A) will be seen at TP4 with an audio tone applied to only one input channel. If the same tone is applied to both inputs, the output will look like (B). If R24 is misadjusted, the waveform will not be flat (C). Adjust R24 for the waveform in (D).

component side of the board. That capacitor, as well as the coils, will be mounted last. If you use the artwork to make your own board, the parts-placement diagram in Fig. 2 should be followed. Whenever possible, do not solder any leads until as many components as possible have been inserted in the board. The components should be mounted as tight as possible to the board in order to minimize any stray capacitance or noise pickup.

Start by inserting the resistors. As with any good construction technique, double check the values of all components before soldering them. A ferrite bead is placed over one lead of R51. The parts-placement diagram shows which lead of R51 gets the ferrite bead. Stand R34 vertical when installing it into its single hole. After soldering R34 in place, bend the unconnected lead into a "J"-shaped hook. That hook becomes TP1. Solder the bottom connections first, then solder any ground connections on the top side. You should only use rosin-core solder when making connections—a low-residue type is preferred. Acid-core solder should not be used on electronics under any circumstances.

The diodes should be installed next, followed by the capacitors. The polarity of the diodes and electrolytic capacitors should be carefully observed. Any polarized component installed backwards will cause a malfunction and possibly damage the circuitry.

When installing the transistors, reshape the leads as needed for a good fit. The shape of the case should match the direction shown in Fig. 2. Be careful with Q2 and Q3, as those parts might be different than the lead shapes seem to indicate. If Q2 and Q3 have preformed leads, straighten them with pliers in order to permit correct orientation.



Here's the foil pattern for the component side of the transmitter. Using a double-sided board allows the inclusion of a ground plane that helps shield the RF circuitry.

Install trimmer capacitor C16 and potentiometers R15, R24, and R35. Before installing XTAL1 and XTAL2, trim their leads, using scissors, to a length of $^{3}/_{16}$-inch. Do not use diagonal cutters—the mechanical snap produced can actually break the crystal elements. The ICs may be installed into sockets soldered to the board, but that is not necessary. Of course, the polarity of the ICs should be followed carefully.

Carefully check all work done so far for accuracy and orientation. Now trim all component leads to length if not done yet, and solder all bottom connections made so far. Do not plug up any unused holes yet.

Figure 3 illustrates how to make L1. Wind 6-$^{1}/_{2}$ turns of 22-gauge magnet wire onto the threads of an 8-32 screw. Shape the ends of the wire so that it looks like Fig. 3A. Scrape the enamel from the wire at a spot 1-$^{3}/_{4}$ turns from the top end (Fig. 3B). A 1-inch length of resistor lead is soldered to the coil at that spot. Using the screw as a handle, install L1 into the PC board and solder the connections. Be careful not to unsolder the tap connection when soldering the coil to the board. After the solder has cooled, remove the screw and replace it with a ferrite slug. The coil should look like Fig. 3C when viewed from above.

The same procedure is used to make L4 and L5. Coil L4 should be 5 turns and L5 will be 4 turns. Follow Fig. 4 when installing them in the PC board. After installing the coils, remove the screws. Those coils do not get any ferrite slugs.

Fabricate the ferrite-bead chokes L2 and L3 as shown in Fig. 5.

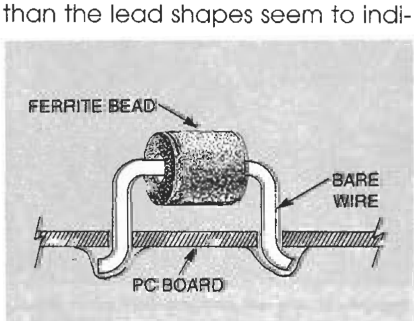
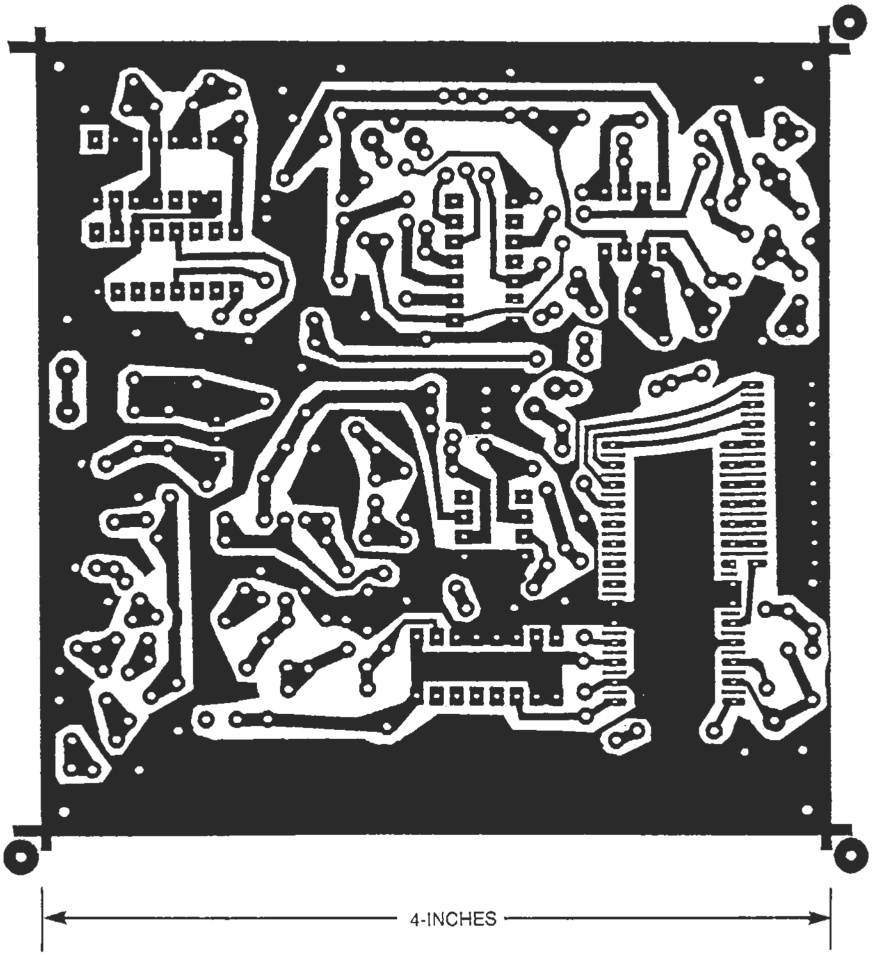


Fig. 5. The chokes for L2 and L3 are simply a length of scrap resistor lead with a ferrite bead.



Here's the foil pattern for the solder side of the transmitter. Be sure to align both patterns carefully when etching the board.

The chokes are simply wires passed through ferrite beads. The ferrite beads should be broadband types designed for VHF to UHF frequencies. Install the chokes into the PC board. Scrap resistor leads with one end bent into a small "J" hook similar to R34 can be used as TP2–TP5. Finally, install C21 on the underside of the PC board.

Carefully inspect all work so far. Look for solder shorts, poor joints, missing parts, incorrect part orientation or placement, etc. Once the board is built, you are ready to test your handiwork.

Testing the Transmitter. Setting up and testing the transmitter is simple and straightforward. An analog volt-ohmmeter with an input impedance of 20,000 ohms-per-volt or better is the only piece of test equipment needed. A digital voltmeter will also work, but an analog VOM is preferred. The power supply should be well-regulated with a low-ripple, 13.2-volt DC output. Nine AA-, C-, or D-cell batteries connected in series make a good supply, and is recommended if you have no other supply. Do not use a wall-type transformer, as those items are usually poorly regulated and could cause bad hum or damage to the circuitry. A stereo FM-broadcast receiver, a line-level audio source such as a CD player or tape deck, stereo patch cables for connecting the audio source to the transmitter round out the equipment list.

Before connecting power to the transmitter, inspect the PC board once again for shorts, missing or wrong parts, IC and transistor orientation, polarity of diodes and electrolytic capacitors, and any assembly mistakes such as missing or poor solder connections. If everything looks good, connect the VOM between the 13.2-volt power supply and D1, with the negative power supply lead connected to ground. The meter should be set to measure DC current at 1 amp. If your supply has a meter that measures current, the VOM need not be connected. In that case, connect the positive supply lead directly to D1. When the power is turned on, the current drawn should be about 120 ma. If appreciably less than that (under 100 mA), or more (over 140 mA) is being drawn, shut down the supply and re-check the components and soldering, as something might be wrong. Nothing should be getting hot, although IC5 will normally run warm after a few minutes. If everything is OK, remove the VOM (if used) and directly connect D1 to the positive supply terminal.

With the meter set to read 15 volts DC, check the following points for proper voltages. The voltages listed are based on a 13.2-volt supply. If your supply provides a slightly different voltage, your readings may vary accordingly:

IC5 input—12.6 volts
IC8 pin 16—5.0 volts
IC7 pin 3—5.0 volts
Q5 collector—5.0 volts
Q4 collector—1.6 volts
Q1 drain—8.5 volts
IC6 pin 7—8.5 volts
IC1 pin 3—6.4 volts
IC1 pin 7—6.4 volts
IC1 pin 1—6.4 volts
IC4 pin 16—8 to 10 volts

Variation of 10 percent or less in the above readings is acceptable. Remember to allow for meter accuracy and component and supply voltage variations. If any major variations are noted, go back and check your work again.

Set S1 for a frequency of 88.1 MHz, or the closest clear channel if 88.1 MHz is used in your area. Listing 1 shows what switch settings will produce the desired frequency. If you want to produce even channels, install the jumper next to IC7 and set the transmitter for 88.0 MHz. Connect the meter across pins 1 and 4 (polarity does not matter) of IC2, and adjust R15 for a zero voltage reading. Use lowest scale you can.

Tune a nearby FM receiver to the selected channel. Monitor that channel as you proceed. Set the plates of C16 to 25% mesh and R15, R24, and R35 to their center. Set the slug in L1 so it is fully inserted. Connect the meter to TP5 (pin 6 IC6). While listening on the FM receiver, start backing out the slug with a nonmetallic screwdriver. The meter will read initially about 8-9 volts. As you back out the slug further, a point should be reached where the meter reading starts to decrease. At that moment, the FM receiver should suddenly quiet down, and you will hear the carrier. As you adjust the slug, the carrier should still be heard in the receiver. Set the slug so that the voltage at TP5 is between 3 and 4 volts. The stereo-indicator light on the FM receiver should be lit. If it is not, adjust R35 towards maximum until it does light, and then a little further. The receiver should be quiet. Remove the 13.2 V supply. The stereo indicator on the receiver should drop out and the receiver background noise should reappear. If everything is OK so far, the next step will be to test the unit with an audio-signal input.

Connect a 12-inch antenna to the RF-output connection and apply a stereo-audio signal to inputs J1 (left) and J2 (right). Reconnect the DC supply and listen to the FM receiver. You should hear the audio in the receiver. Adjust R35 so that the received audio is at the same volume as other local stations in your area. Connect the audio-tone test point TP1 to each input individually using a test lead. The audio tone should sound in the receiver's left or right channels accordingly. Adjust R24 for best separation if necessary. If R24 seems to have little effect, leave it in the middle position.

The basic setup is complete. If you are fussy and have access to test equipment, you may perform the following additional steps:

Connect a frequency counter to the RF output and adjust C16 for exactly 88.1000 MHz, or whatever frequency that you have programmed.

Connect a counter or scope to TP1 and check for a 1187.5-Hz squarewave. That verifies that the pilot and subcarrier frequency are at 19 and 38 kHz.

With a scope connected to TP4, adjust R15 for a minimum of 38-kHz subcarrier feedthrough. Temporarily kill the 19 kHz pilot by grounding the junction of R28, R29, and C12 in order to make that easy to see.

Using sinewave audio generator of 1.5 volts p-p and a frequency of 1000 Hz, check for waveform shown in Fig. 6 at TP4, with the left, right, and finally both inputs connected to the audio generator. Adjust R24 for best agreement to the figures. Some compromise may be necessary as the optimum setting for the left and right channels might be slightly different due to normal circuit and component tolerances. Split any residual minor difference between the left and right channels so each has equal error.

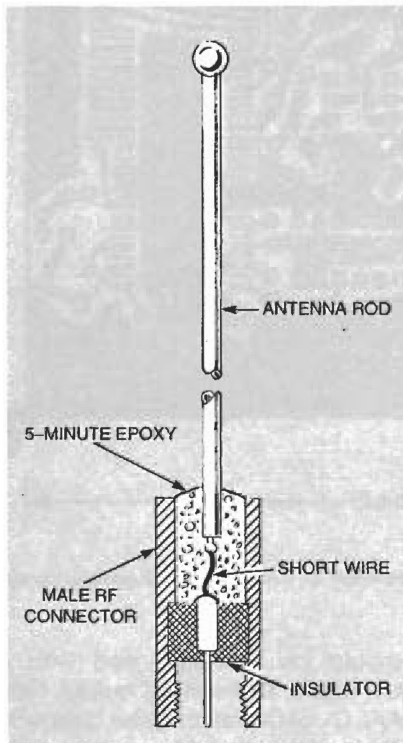


Fig. 7. A collapsible antenna soldered and epoxied to an RF connector makes an easily removed and replaced unit for the transmitter.

Set the slug in L1 so that 3 volts is obtained at TP5 at the lowest desired operating frequency (usually 88.1 MHz). Set S1 for a frequency of 94.5 MHz, and verify that the voltage at TP5 is above 7 volts and still varies with slug setting. That tests the synthesizer frequency range. It is OK if the slug is almost out of the winding. Secure the slug with clear lacquer, cement, hot glue, or a drop of wax. Set the transmitter for the desired output frequency you wish to use, and the transmitter is ready to go.

Final Packaging. The transmitter may be mounted in almost any case that will accept the PC board. Either metal or plastic can be used and since no significant heat is produced, ventilation is not critical, although it is a good idea to allow some airflow if possible. Make sure that any metal is at least $^1/_4$-inch away from the bottom of the board. If a plastic case is used it is a good idea to line the bottom of it with copper or aluminum foil to act as a ground plane for the antenna. In addition, a ground bus of some sort will be needed with a plastic case. RCA-type phono jacks may be used for the audio connections, a 2.5-mm jack for the DC power supply, and a BNC connector for the RF output. Be sure to ground the shell of the RF output connector with a short lead to the ground foil on the PC board. Remember to keep the RF leads short. Audio connectors should be grounded to the audio ground, and audio leads shielded or kept short in order to avoid RF pickup and possible distortion. Metal or plastic standoffs can be used to mount the PC board to the case.

Antennas can be almost any suitable arrangement. One possible arrangement is to use a collapsible 12-inch antenna mounted into a right-angle BNC male connector with epoxy, which makes a neat, compact antenna. The construction details in Fig. 7 are self-explanatory.

The power supply could be a regulated 13.2-volt DC type commonly sold for powering CB radios and hobby projects. Any well-regulated supply should do fine if it has low ripple. Batteries can also be used, but will, of course, wear out eventually. However, for short periods where continuous use is not contemplated, they are excellent and do not introduce possible hum that can occur with AC-operated supplies. Wall-transformer types are definitely not recommended.

Using the Transmitter. For best results, a relatively clear channel is

PARTS LIST FOR THE STEREO FM TRANSMITTER

SEMICONDUCTORS

IC1—LM1458 dual op-amp, integrated circuit
IC2—LM1496 balanced modulator, integrated circuit
IC3—74C00 quad NAND gate, integrated circuit
IC4—CD4040 12-bit counter, integrated circuit
IC5—LM7805 5-volt voltage regulator, integrated circuit
IC6—CA3420 op-amp, integrated circuit
IC7—MC145151-2 phase-locked loop, integrated circuit
IC8—74F160 decade counter, integrated circuit
Q1—MPF102, field-effect transistor
Q2–Q4—2N3563, NPN transistor
Q5—MPS3866, NPN transistor
D1—1N4007, silicon diode
D2—1N757A, Zener diode
D3—MV2107, varactor diode

RESISTORS

(All resistors are ¼-watt, 5% units unless otherwise noted.)
R1, R2—8,200-ohm
R3, R4, R11, R20, R30, R40, R46, R52, R55—1,000-ohm
R5–R8, R32, R37, R38—22,000-ohm
R9, R10, R26, R29—47,000-ohm
R12, R13, R25, R41, R42—100,000-ohm
R14, R16, R23, R43—68,000-ohm
R15—10,000-ohm potentiometer
R17, R18, R33, R50—2,200-ohm
R19, R44—10,000-ohm
R21, R22, R54—3,300-ohm
R24—25,000-ohm potentiometer
R27—220-ohm
R28, R48, R51—470-ohm
R31—2.2-megohm
R34—220,000-ohm
R35—1,000-ohm potentiometer
R36—6,800-ohm
R39—4,700-ohm
R45—1-megohm
R47—1,500-ohm
R49—33-ohm
R53—330-ohm
R56—56-ohm

CAPACITORS

C1, C2, C20—0.01-µF, 10%, Mylar
C3–C5, C11—1-µF, 50 WVDC, electrolytic
C6, C9, C29—100-µF, 16 WVDC, electrolytic
C7, C8, C12, C13, C25, C26, C30, C32—0.01µF, ceramic disc
C10—18 pF, ceramic disc, NPO-type
C14—12-pF, ceramic disc, NPO-type
C15—33-pF, ceramic disc, NPO-type
C16—2–20 pF trimmer
C17—39 pF, ceramic disc, NPO-type
C18—10-µF, 16 WVDC, electrolytic
C19—0.1-µF, 10%, Mylar
C21—0.01-µF, ceramic, surface-mount
C22, C24—100-pF, ceramic disc, NPO-type
C23, C27, C28, C36—470-pF, ceramic disc
C31—470-µF, 16 WVDC, electrolytic
C33—68-pF, ceramic disc, NPO-type
C34—120-pF, ceramic disc, NPO-type
C35—47-pF, ceramic disc, NPO-type
C37—10-pF, ceramic disc, NPO-type

ADDITIONAL PARTS AND MATERIALS

L1–L6—See text
XTAL1—4.864-MHz crystal, 0.005%, HC49/U case
XTAL2—10.240-MHz crystal, 0.005%, HC49/U case
S1—SPST switch, 10 position, dual-inline package
Slug for L1 (Cambion "Blue" 5153255-06-00, 30–400 MHz or similar), 22-gauge magnet wire, PC board, ferrite beads (Ferrox[3] 267300101 or similar), hardware, enclosure, solder, etc.

Note: The following is available from: North Country Radio, PO Box 53, Wykagyl Station, New Rochelle, NY 10804; Website: http://www.northcountryradio.com.: Complete kit consisting of an etched and drilled PC board and all parts that mount on it, $75.00; Enclosure, $15.50. Please add $4.50 for shipping and handling.

necessary. The PLL helps tremendously by keeping the signal on frequency. In large metropolitan areas, it may be difficult or impossible to find a clear channel. In this case try using an in-between channel, *i.e.* even 100-kHz channels in the USA, odd 100-kHz channels in areas using even channel allocations. Also, you might try to get between two weak stations. That can be impossible for digitally-tuned receivers, but analog (continuously tuned) receivers will have no problem. Many lower-end pocket stereos are still analog. It is best to operate between 88 and 92 MHz as that part of the band tends to be used by lower-powered stations.

Do not set deviation control R35 too high, as distortion and interference to other stations may result.

Typically R35 is set about 75% of full open when a typical line-level input (0.5- to 1-volt rms) signal is fed into J1 and J2. Exceeding that will result in distortion and loss of separation. In order to avoid hum, make sure the transmitter is properly RF grounded, especially if a whip antenna is to be used.

Where regulations permit (not in the USA), the voltage on the output amplifier can be raised as high as 15 volts, with up to 150-milliwatts output possible, though not guaranteed. In that case, a matched antenna should be used and L4 should be adjusted by compressing or expanding the turns for maximum output. A range of up to a mile or more might be possible, depending on local terrain if a properly matched antenna is used. Keep the antenna at least 25–30 feet from the transmitter when operating above the 10-milliwatt RF output level, as it is possible that stray RF feedback from the antenna might cause instability and loss of lock in the PLL circuit. The transmitter is strictly an entertainment device and is not meant for commercial broadcasting; therefore no guarantees of any kind can be offered nor any technical assistance be provided for export use. Those details must be worked out by the individual user.

There you have it—a stereo FM transmitter that is as fun and easy to use as it is educational. Ω