

Crystal Oscillators and Circuits

Bill Sheets K2MQJ

Rudolf F Graf KA2CWL

It is often required to produce a signal whose frequency or pulse rate is very stable and exactly known. This is important in any application where anything to do with time or exact measurement is crucial. It is relatively simple to make an oscillator that produces some sort of a signal, but another matter to produce one of relatively precise frequency and stability. AM radio stations must have a carrier frequency accurate within 10Hz of its assigned frequency, which may be from 530 to 1710 kHz. SSB radio systems used in the HF range (2-30 MHz) must be within 50 Hz of channel frequency for acceptable voice quality, and within 10 Hz for best results. Some digital modes used in weak signal communication may require frequency stability of less than 1 Hz within a period of several minutes. The carrier frequency must be known to fractions of a hertz in some cases. An ordinary quartz watch must have an oscillator accurate to better than a few parts per million. One part per million will result in an error of slightly less than one half second a day, which would be about 3 minutes a year. This might not sound like much, but an error of 10 parts per million would result in an error of about a half an hour per year. A clock such as this would need resetting about once a month, and more often if you are the punctual type. A programmed VCR with a clock this far off could miss the recording of part of a TV show. Narrow band SSB communications at VHF and UHF frequencies still need 50 Hz frequency accuracy. At 440 MHz, this is slightly more than 0.1 part per million.

Ordinary L-C oscillators using conventional inductors and capacitors can achieve typically 0.01 to 0.1 percent frequency stability, about 100 to 1000 Hz at 1 MHz. This is OK for AM and FM broadcast receiver applications and in other low-end analog receivers not requiring high tuning accuracy. By careful design and component selection, and with rugged mechanical construction, .01 to 0.001%, or even better (.0005%) stability can be achieved. The better figures will undoubtedly employ temperature compensation components and regulated power supplies, together with environmental control (good ventilation and ambient temperature regulation) and "battleship" mechanical construction. This has been done in some communications receivers used by the military and commercial HF communication receivers built in the 1950-1965 era, before the widespread use of digital frequency synthesis. But these receivers were extremely expensive, large, and heavy. Many modern consumer grade AM, FM, and shortwave receivers employing crystal controlled digital frequency synthesis will do as well or better from a frequency stability standpoint.

An oscillator is basically an amplifier and a frequency selective feedback network (Fig 1). When, at a particular frequency, the loop gain is unity or more, and the total phaseshift at this frequency is zero, or some multiple of 360 degrees, the condition for oscillation is satisfied, and the circuit will produce a periodic waveform of this frequency. This is usually a sine wave, or square wave, but triangles, impulses, or other waveforms can be produced. In fact, several different waveforms often are simultaneously produced by the same circuit, at different points. It is also possible to have several frequencies produced as well, although this is generally undesirable.

In an oscillator, the feedback network determines the frequency and stability of the generated signal. Frequency is of course the number of cycles per unit time produced and is generally specified in Hz, kHz (1000 Hz), MHz (1 million Hz), or even GHz (1 billion Hz). Stability is another matter. What we are trying to express is how much the oscillator frequency will change in a certain amount of time. The key here is the length of time. Long term stability is generally expressed in frequency drift (ΔF or ΔF) per unit time or specified time interval. Long term drift is caused by component aging due to electrical, thermal, physical, and chemical changes in components over a relatively long (100 hours or more) time period. This is generally, but not always, permanent. This is generally compensated for by readjustment of circuit parameters, either manually or automatically. Short-term stability is usually caused by component changes due to circuit heating, warmup, temperature fluctuations, and instability of components, both

electrical and mechanical. Generally time periods here are minutes to an hour or so. This is often temporary and tends to follow a pattern, but can be random due to cyclic temperature changes, etc. Even shorter term frequency drift involving periods of a few seconds down to millisecond intervals is caused by circuit noise and mechanical factors (shock and vibration). As the time interval gets shorter, we run into random frequency fluctuations caused by noise in the amplifier and circuit components, as well as naturally occurring thermal noise generated in resistances. This noise is generally called “phase noise” as it appears as random noise modulation in AM, FM, and phase modulation (They are mathematically all related) on the generated signal. This noise is generally measured in a given bandwidth at some specified frequency away from the main carrier. This is done with a spectrum analyzer and notch filters to notch out the main carrier. Note that the main carrier is often 60-120 dB higher in amplitude than the noise level we are trying to measure. This measurement is then converted to a figure expressed in decibels per Hz of bandwidth with respect to the main carrier and expressed as dBc. One often sees oscillator phase noise measurements given in specs for oscillator circuits and prepackaged oscillators. It is hard to say what a good figure is as it depends on application. Low phase noise is important in radio receivers and communications systems. It is less important in applications such as computer clocks, and noncritical timing oscillators used in digital systems and circuits. An oscillator that has high phase noise is said to be “dirty”. As an example, suppose a 10-milliwatt output oscillator running at 1 MHz is specified as having $-70\text{dBc} / \text{Hz} @ 10\text{ kHz}$ phase noise. Sounds good at first? Let’s look at the noise at 1010 kHz (1.01 MHz) in a 10 kHz bandwidth. Since noise power is additive, in a 10kHz bandwidth we will have 10,000 times the noise power, or 40 dB more. The noise power would be minus 30dBc in a 10kHz bandwidth. Of course, the noise spectrum is not flat with frequency, but we will assume for illustration that it is. In this case our 1 MHz oscillator is producing 30 dB below 1 milliwatt (or 10 microwatts) of noise power and assorted garbage in the adjacent 1010 kHz channel. This is quite lousy performance, and unacceptable. If used as a receiver local oscillator, this noise power would act as a “spurious” local oscillator, causing unwanted noise from reception of signals 10 kHz away. This effectively overrides and effectively destroys any really good IF selectivity that the receiver may possess. Used to drive a 10KW AM broadcast transmitter, this oscillator would generate 1 watt of RF noise at 1010 kHz, causing interference with any weaker signals on that channel. This of course is unacceptable. Poorly designed frequency synthesizers would also behave like this. If the noise spec of the oscillator were -110 to -120 dBc at 10kHz this would be much more acceptable. This concept may prove a little difficult to understand at first, but it is very important in practice.

The key component in determining oscillator stability is the feedback network, assuming the amplifier portion has relatively good noise performance. In the amplifier, a low noise transistor or other active device should be employed. The more stable oscillators tend to have better noise specs. Phase noise and drift are manifestations of frequency instability on different time scales. The stability of an oscillator, all other things equal, can be related to the rate of change of feedback network phaseshift versus frequency. This, in plain English, implies something with very high selectivity and therefore high Q, the higher the better. These devices include quartz crystals, ceramic resonators, resonant cavities (UHF and microwave only), and other exotic devices.

The quartz crystal is the most widely used frequency-determining element. It is relatively cheap, widely available, and comes in frequencies from audio to low UHF. Frequencies in the HF range (2-30 MHz) are most common. Distributors generally stock commonly used frequencies as “microprocessor” crystals. Since these are manufactured in large quantities, they are often available for less than a dollar. Custom frequencies specially manufactured are generally several times as costly. By varying the way the crystal is cut and its size, the resonant frequency and temperature characteristics can be controlled. There are many different cuts that are specified by the way the crystal is oriented and cut from the mother crystal (AT, BT, SC, etc). AT crystal cuts are generally used above 1 MHz. Crystals can be operated in a mode called overtone mode. Third overtone, and fifth overtone crystals are commonly used in the lower VHF range 30 to 150 MHz. Seventh and ninth overtone crystals are also used, and can operate up to a few hundred MHz. Most fundamental crystals can be operated on their third and often fifth overtone, and higher order overtone crystals can be operated on their lower order overtones and fundamental as well. Also, spurious modes may exist in many crystals, particularly higher overtone types, which can be totally unrelated mathematically to any “legal” overtones or frequencies. The circuit designer must be aware of these effects and may have to design in certain circuit features to ensure oscillator operation on the

expected oscillator and crystal frequency. This may involve extra tuned circuits and components to suppress unwanted modes.

Fig 2 is an approximate equivalent circuit of a crystal. This circuit is a pretty good approximation near the crystal resonant frequency. It has two fundamental resonances, one series, the other parallel (anti-resonant). The crystal behaves as an inductor at certain frequencies as well. In many crystals, the effective series inductance may be measured in henries, while the capacitance is a small fraction of a picofarad, and the resistance is in the 20Ω to 100Ω range. Since the Q value of a series resonant circuit is $2\pi fL/R$, if the frequency is 1 Mhz, the series effective capacitance $C1 = .025$ pf, the inductance $L1 = 1$ henry, and resistance $R_s = 50$ ohms, the circuit Q is 125,600. The shunt capacitance $C2$ is usually a few pf. This resonator would have a bandwidth of about 8 Hz at 1 MHz center frequency. Contrast this with a typical Q of 100 at 1 MHz with a 10 kHz bandwidth obtainable using conventional small size coils and capacitors. The crystal gives a 1250 times improvement in this example. Crystals may be purchased for series or parallel operation. Parallel crystals are usually specified with a circuit capacitance (Usually 18, 20 or 32 pF) load. This capacitance is that with which the crystal will operate on its marked frequency. Series crystals do not have this specification. Commonly parallel crystals are fundamental types and series crystals overtone types, but there are many exceptions to this rule, so no reliable data can be assumed for any crystal. Either a series or parallel crystal usually will work in a given circuit, but the oscillation frequency may be not as marked. This discrepancy could be several kHz, with inability to adjust the frequency to specs. The crystal should be placed in a suitable test circuit and measurements made to obtain reliable data

Crystal oscillator circuits are similar to L-C oscillator circuits, often substituting the crystal for L-C components. In some circuits the crystal is used as a series resonator, in others as a parallel inductor or resonator. The main difference is that in an L-C oscillator we can employ a tapped or multi-winding inductance. Since we cannot install taps on a crystal, capacitance divider techniques and configurations are used instead. It is no trick at all to get stability an order of magnitude better than the best L-C oscillators from a crystal oscillator. A few parts in a million (ppm) would be typical. (One ppm = .0001%) With careful design, proper choice of crystal cut, and the use of temperature compensation, 1 part in ten million is achievable over a reasonably wide (50 degrees C) range without too much trouble. These circuits are called temperature compensated crystal oscillators (TCXOs). With solid state components the entire crystal and associated circuitry can be placed in an oven heated by a watt or less of power, and the internal temperature maintained at a specified figure (60 to 85 deg C typically). Stabilities of another order of magnitude (1 part in 100 million) can result. These are called oven controlled crystal oscillators (OCXOs) and can be obtained as prepackaged assemblies. There are circuits in which the amplitude of oscillation is also regulated with automatic gain control, keeping the amplitude of oscillation within the linear region of the circuitry. It is also possible to do this with L-C and crystal oscillators, rather than depending on circuit nonlinearity for amplitude limiting. The Wein Bridge oscillator is an example of an R-C oscillator that uses a tungsten lamp filament or a thermistor to do this. This improves noise performance, waveform purity, and frequency stability, as it minimizes drive to the crystal. This helps to keep thermal frequency drift to a minimum. However, these circuits will not be covered here, as they are not generally encountered by the hobbyist or experimenter.

Fig 3 is a circuit of a grounded base oscillator using the crystal as a series resonator. This circuit is usually used for overtone operation. It is simple in concept. The transistor Q1 is biased in the active region as an amplifier. A resonant circuit L1C1 is placed in series with the collector. Note that C_e is a relatively "small" capacitor (not the usual 470pF to 0.1 uf we might use in an RF amplifier stage). C_e is used to bypass the emitter resistor. The internal collector to emitter capacitance C_c provides feedback to the emitter, the ratio set by the values of C_c and C_e . At a frequency where the crystal is series resonant, the base is effectively grounded at this frequency. This allows oscillation, the transistor acting as a common base amplifier at this frequency. This oscillator is efficient and has a good power output (10-20 milliwatts) but the stability and phase noise are not the greatest, since the base circuit resistance in series with the crystal lowers the operating Q somewhat. It is also somewhat susceptible to stray oscillation modes, since there is little selectivity in the crystal circuit other than the crystal itself. By tuning L1 and C1 over a wide range, it is possible to produce oscillation on unwanted overtones and spurious modes. Also, stray capacitance across the crystal and associated leads may allow for uncontrolled spurious oscillation, and off frequency operation away from the true series resonant frequency. The crystal has to be specially ordered

with an offset in frequency to get the exact desired frequency. This has to be determined by experiment. A series inductor or capacitor in the base circuit can be used to adjust or “pull” the frequency somewhat. Replacing the crystal with a dead short allows the circuit to function as a straight common base oscillator. This circuit is OK for general-purpose use but is not recommended where critical frequency control or phase noise is an issue.

Fig 4 is a circuit using logic gate ICs. A crystal is used as a parallel inductor together with capacitors C1 and C2 to form a resonant circuit, with an inductor (xtal) and tapped capacitor network. There is a 180-degree phase inversion at resonance. The CMOS logic gate (74C00N, 74C04, CD4049, etc) used as an amplifier supplies the other 180 degrees phaseshift. This circuit, actually a “Pierce” oscillator, is very simple and cheap, and is widely used in digital applications. Like the previous circuit, it has less than ideal phase noise and in addition, can overdrive the crystal with its high drive voltage, causing spurious operation. Use of fast logic chips and too much feedback can cause unwanted third overtone operation, producing clock frequencies around 3 times that expected. A resistor R2 in series with the output of the logic gate can be used to control drive and is typically a few hundred ohms to several k Ω . C1 can be made variable to adjust frequency. A parallel mode fundamental crystal is best used with this circuit. The oscillator output can be fed to another gate on the same IC chip to square it up and buffer it before using it to drive other circuits. This circuit is not the best one for use in critical applications needing really good stability and low phase noise. It is fine for digital system and computer clocks, microprocessors, and as a reference for frequency synthesizers where lowest phase noise is not necessary. We are not implying that the noise performance will be really rotten, only that it will not be as good as can be obtained using other circuits. But even a poor crystal oscillator is usually quite “clean” as compared to a good L-C oscillator.

Fig 5 shows a more conventional “Pierce” type oscillator using a JFET . It uses fundamental mode crystals. It is simple, and with a low noise JFET or transistor is reasonably decent and reliable as to performance. The capacitance C1 from collector (or drain) to ground controls the feedback. A parallel mode crystal is used, and a shunt capacitance C2 across the crystal can be used to adjust frequency. This circuit is good in applications where a number of crystals must be switched in and out over a frequency range, as there is no tuning required.

Fig 6 is a JFET equivalent of the old-fashioned vacuum tube “tuned plate-tuned grid” oscillator. It is useful for overtone operation and uses parallel mode crystals. Basically, the drain circuit contains a tuned circuit L1 and C1 tuned slightly above the expected output frequency, therefore looking inductive. By feedback via the collector to drain capacitance, the input resistance of the JFET appears as a negative resistance. This allows oscillations to start. As in the previous circuit, shunt capacitance across the crystal (C2) can be used to adjust the output frequency to specs. This circuit configuration was widely used in the vacuum tube days as an overtone oscillator. However, it can work well with fundamental mode crystals as well.

Fig 7 is a Colpitts crystal oscillator using a transistor and a parallel mode crystal. The crystal acts as an inductance in this circuit. A large value capacitive divider is used between gate, source, and ground, and a small series capacitor is placed in the crystal circuit. The ratio of C2+C3 to C1 should be as high as possible, 5 to 10 to 1 is usually used. Typical values are shown in the circuit. This circuit places little loading on the crystal and the relatively high values of C2 and C3 “swamp out” variations and drift caused by variations in device characteristics. Frequency is adjusted with C1. A relatively clean sine wave appears at the emitter of the transistor.

Fig 8 is a common base overtone oscillator which uses a series mode crystal. It is somewhat better than the circuit of Fig 1 as the crystal sees a low drive impedance and feeds a low load impedance, keeping the effective Q somewhat higher. It is also more predictable as to output frequency, as the crystal can be operated exactly at series resonance without circuit problems, and its loading can be controlled. A small inductor L2 is placed across the crystal to tune out its shunt capacitance. This circuit can be made with high selectivity by using a high Q circuit for L1, C1 and C2, and this enables predictable high order (7th and 9th overtone) operation, with little difficulty and good performance.

While there are other crystal oscillator circuits, we cannot cover them all due to space limitations. However, most of the circuits that the experimenter or service technician is likely to encounter have been covered and the reader can consult the literature for others, as well as for design information.

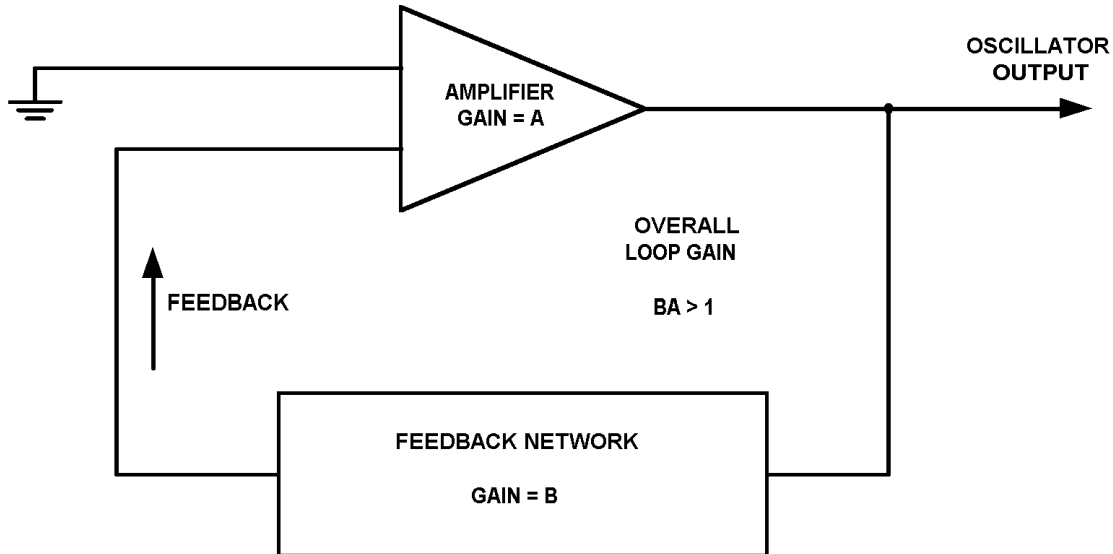
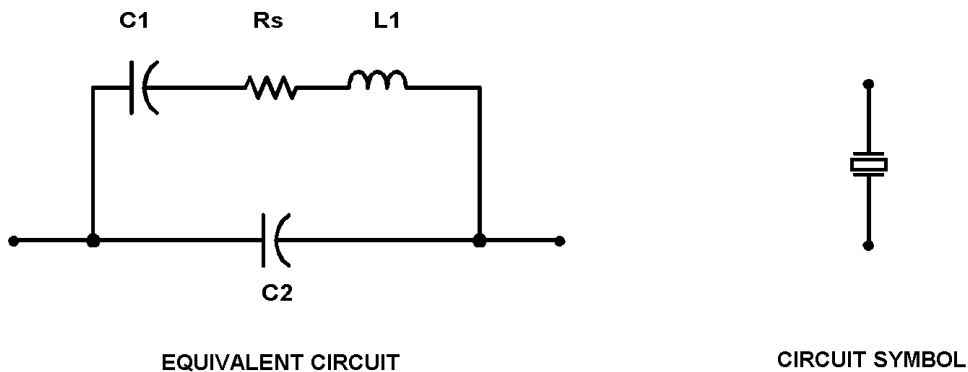


FIG 1
BASIC OSCILLATOR



EQUIVALENT CIRCUIT

CIRCUIT SYMBOL

FIG 2
QUARTZ CRYSTAL AS A CIRCUIT ELEMENT

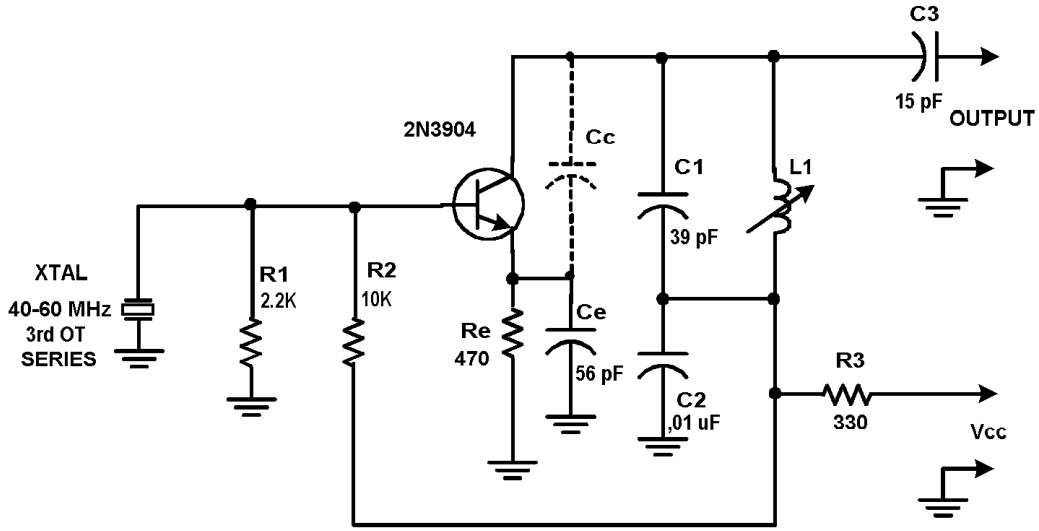


FIG 3
SIMPLE 3rd OVERTONE GROUNDED BASE OSCILLATOR

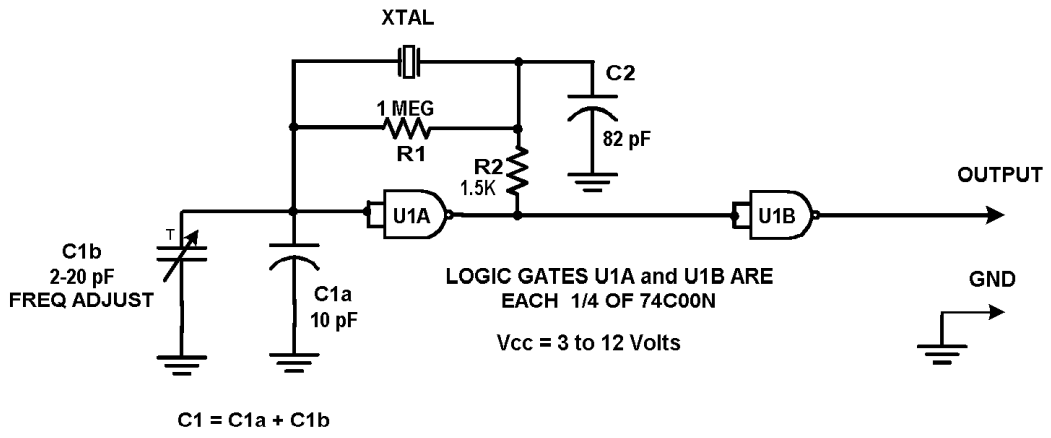


FIG 4
LOGIC GATE XTAL OSCILLATOR

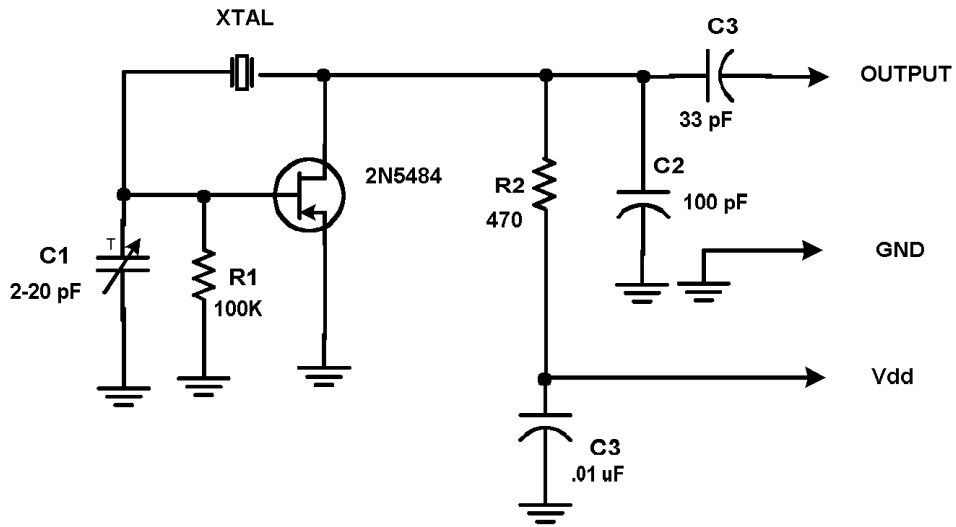


FIG 5
PIERCE XTAL OSCILLATOR

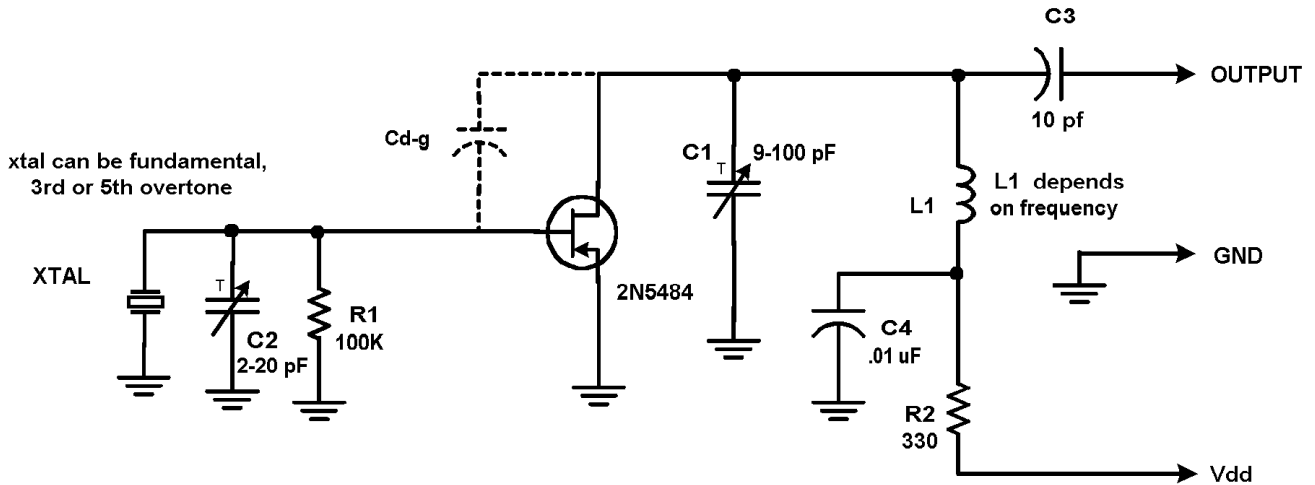


FIG 6
JFET TUNED DRAIN XTAL OSCILLATOR

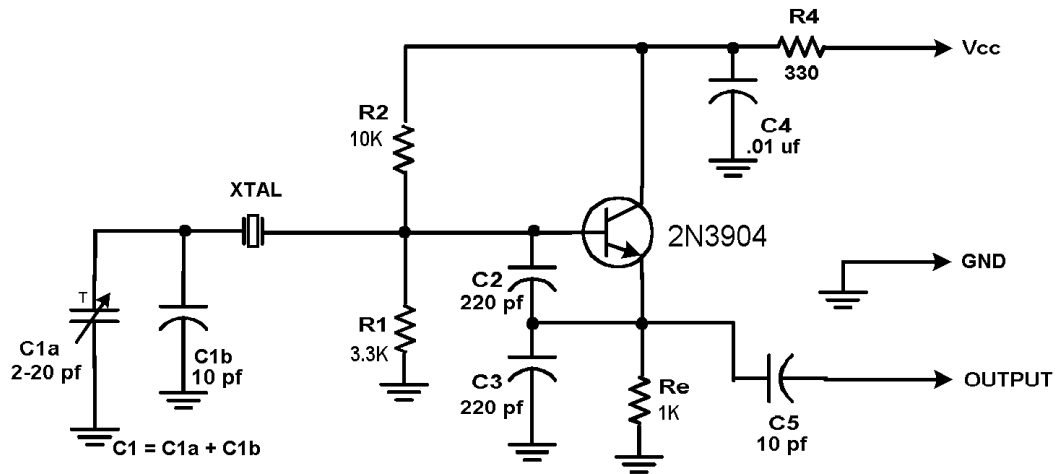


FIG 7
COLPITTS XTAL OSCILLATOR

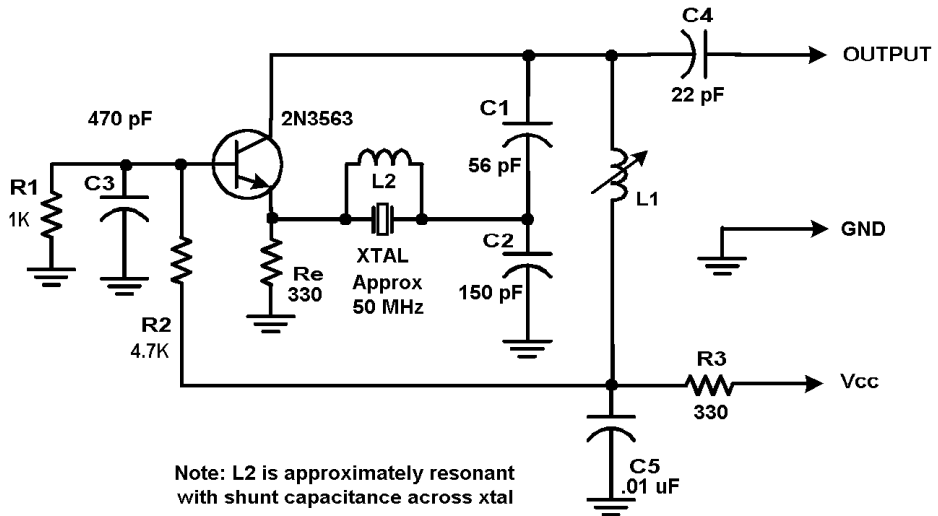


FIG 8
IMPROVED COMMON BASE XTAL OSCILLATOR