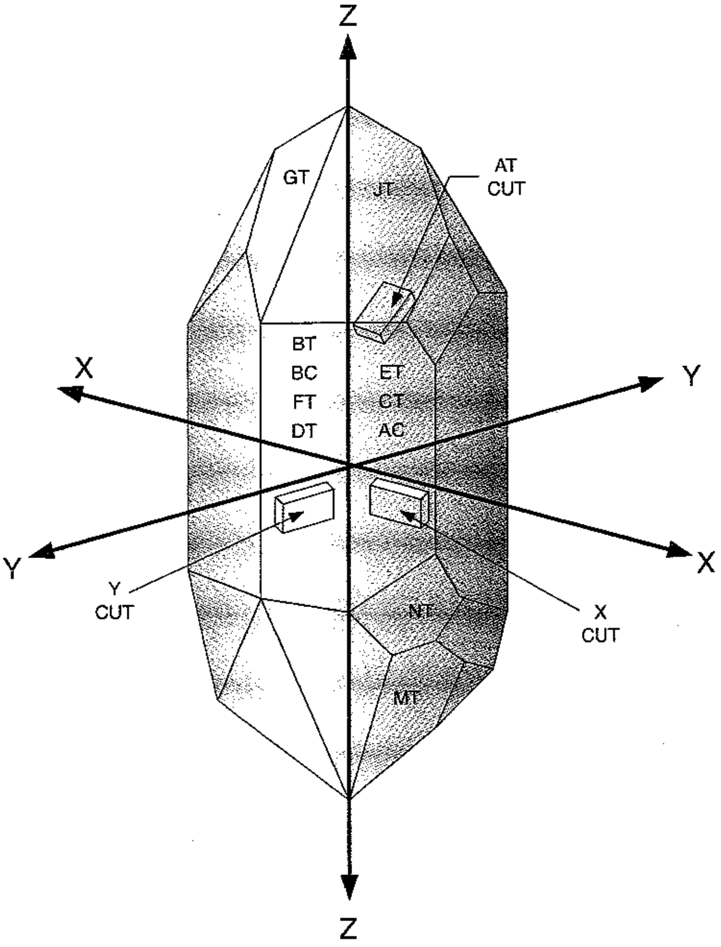
Crystals made clear II



With the theory out of the way, Joe Carr now presents a variety of practical oscillator circuits for use with crystals ranging from 50kHz to 110MHz.

Miller oscillators are analogous to the tuned-input/tuned-output variable-frequency oscillator. This is because they have a crystal at the input of the active device, and an *LC* tuned circuit at the output.

Figure 1 shows a basic Miller circuit built with a junction field effect transistor, or JFET. Any common RF device can be used for Tr_1, like for example the *MPF102*.

Direct-current bias is provided by R_2, which places the source terminal at a potential above ground due to the channel current flowing in Tr_1. The source must be kept at ground potential for AC, so a bypass capacitor, C_4, is provided. The reactance of this capacitor must be less than one-tenth the value of R_2 at the lowest intended frequency of operation.

A parallel-resonant *LC* tank circuit, L_1/C_1, tunes the output circuit of the oscillator. The tuned circuit must be adjusted to the resonant frequency of the oscillator, although best performance usually occurs at a frequency slightly removed from the crystal frequency.

If you monitor the output signal level while adjusting either C_1 or L_1 you will note a distinct difference between the high side and low side of the crystal frequency.

Best operation usually occurs at the low side. Whichever is selected though, care must be taken that the oscillator will start up reliably. Output can be taken either from capacitor C_2 as shown, or through a link coupling winding on L_1.

The Miller oscillator of Fig. 1 has the advantage of being easy to implement, but it suffers from some problems as well. One is that the feedback is highly variable from one transistor to the next because it is created by the gate-drain capacitance of Tr_1. There are also output level variations noted, as well as frequency pulling, under output load impedance variations. These are not good attributes for an oscillator.

Also, there is a large difference in starting ability between JFETs of the same type number, and between different crystals of the same type number from the same manufacturer. I

Surely an equivalent transistor will do?

Be careful when using 'universal' replacement lines of transistors. Crystal oscillators may operate in an unwanted overtone mode – i.e. at a higher frequency. Or because of stray *LC* components they may parasitically oscillate on a VHF or UHF frequency.

Because of this, you will want to keep the gain-bandwidth product of the active device low. But many replacement lines use a single high-frequency transistor with similar gain, collector current and power dissipation ratings as a 'one-size fits all' replacement for transistors with lower gain-bandwidth products.

I've seen that situation in service replacements on older equipment. The original component may not be available, so a universal service shop replacement line device is selected. It is then discovered that there are parasitic oscillations and other problems because the new replacement has a gain-bandwidth product of, say, 200MHz, whereas the old device was a 50MHz part.

This problem can show up especially severely in RF amplifiers and low-frequency oscillators where *LC* components naturally exist, or in any circuit where the stray and distributed *LC* elements provide the required phase shift on some frequency above the unity gain-bandwidth point.

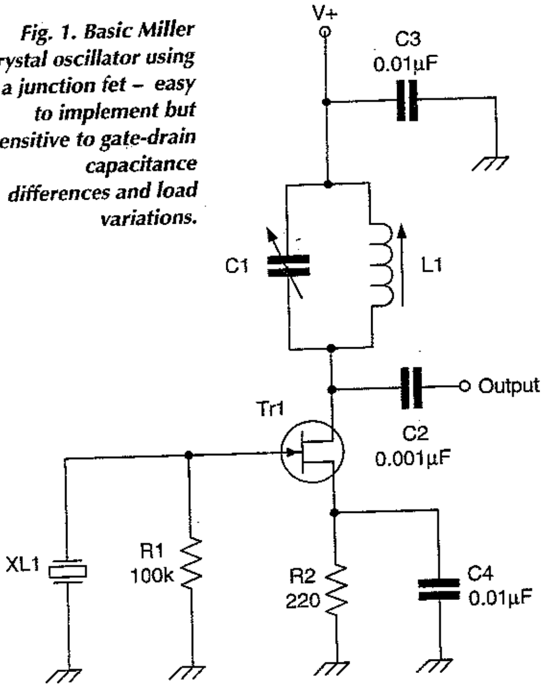


Fig. 1. Basic Miller crystal oscillator using a junction fet – easy to implement but sensitive to gate-drain capacitance differences and load variations.

have also noted problems with this circuit when either the JFET or crystal ages.

In the case of the JFET, I've seen oscillators that worked well, and then failed. When the JFET was replaced, it started working again. What surprised me was that the JFET appeared OK when tested.

Figure 2 shows an improved Miller oscillator. This circuit uses a dual-gate MOSFET, such as the *40673*, as the active element. It is a fundamental-mode oscillator that uses the parallel-resonant frequency of the crystal. The crystal circuit is connected to gate 1, while gate 2 is biased to a DC level. This circuit can provide a stability of 15 to 20 ppm if AT-cut or BT-cut crystals are used.

A problem that you might find with this circuit is parasitic oscillation at VHF frequencies. The MOSFETs used typically have substantial gain at VHF, so could oscillate at any frequency where Barkhausen's criteria are met.

There are two approaches to solving this problem. One approach is to insert a ferrite bead on the lead of gate 1 of the MOSFET. The ferrite bead acts like a VHF/UHF RF choke.

The second approach, shown in Fig. 2, is to insert a snubber resistor – R_S in Fig. 2 – between the crystal and gate 1 of the MOSFET. Usually, some value between 10 and 47Ω will provide the necessary protection. Use the highest value that permits sure starting of the oscillator.

One interesting aspect of the Miller oscillator of Fig. 2 is that it can be used as a frequency multiplier – not to be confused with an overtone oscillator – if the tuned network in the drain circuit of Tr_1 is tuned to an integer multiple of the crystal frequency.

Pierce oscillators

The crystal being connected between the output and input of the active device characterises the Pierce oscillator. **Figure 3** shows the basic Pierce crystal oscillator circuit using a bipolar n-p-n transistor such as a *2N2222* or *2N5179*.

The crystal connects directly from the collector to the base of Tr_1. Output is taken through capacitor C_2 connected to the collector. This circuit is used extensively in low-cost receiver circuits, but is not recommended.

An improved Pierce oscillator is shown in **Fig. 4**. This circuit includes a capacitor, C_1, for pulling the crystal a small amount in order to tune the frequency precisely. With the capacitance values shown, this circuit operates at frequencies between 10 and 20MHz. If the output is lightly loaded, and C_4 kept small, then the oscillator will provide reasonable output stability at a level of near 0dBm.

Figure 5 is a variation on the theme that works in the 50 to 500kHz region. This circuit is almost the same as Fig. 4, except for increased capacitance values to account for the lower frequency.

In both circuits ordinary n-p-n devices such as the 2N2222 can be used successfully.

Butler oscillators

Superficially, the Butler oscillator looks like the Colpitts in some manifestations, **Fig. 6**. The difference is that the crystal connects between the tap on the feedback network and the emitter of the transistor.

This particular circuit is a series-mode oscillator. The value of R_1

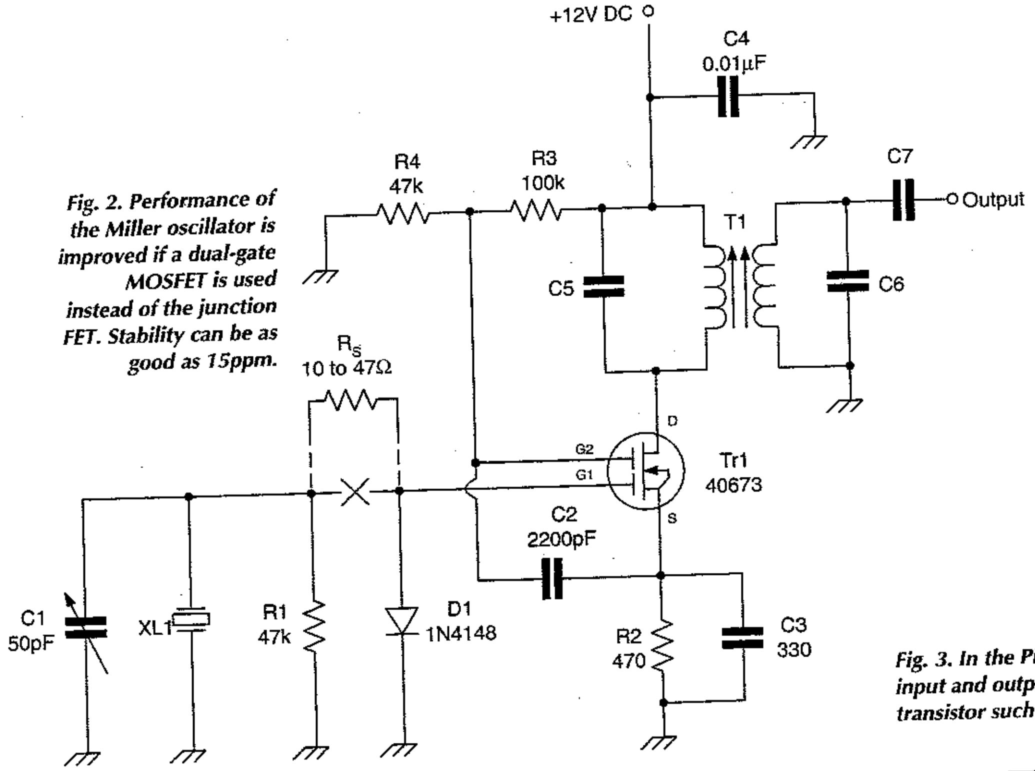


Fig. 2. Performance of the Miller oscillator is improved if a dual-gate MOSFET is used instead of the junction FET. Stability can be as good as 15ppm.

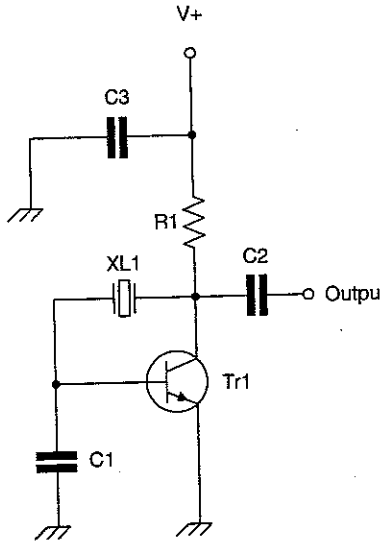


Fig. 3. In the Pierce oscillator, the crystal connects between input and output of the active device – in this case an n-p-n transistor such as the 2N2222

should be whatever value between 100 and 1000Ω that results in reliable oscillation and starting, while minimising crystal dissipation.

A table of capacitance values for feedback network C_1/C_2 is provided. For the 3 to 10MHz range, use 47pF for C_1 and 390pF for C_2; for 10 to 20MHz select 22pF for C_1 and 220pF for C_2.

The collector circuit is tuned by the combination of C_1 and L_1. This circuit may well oscillate with the crystal shorted, and care must be taken to ensure that the 'free' oscillation and the crystal oscillation frequencies are the same. The crystal should take over oscillation when it is in the circuit.

The Butler oscillator of Fig. 6 is

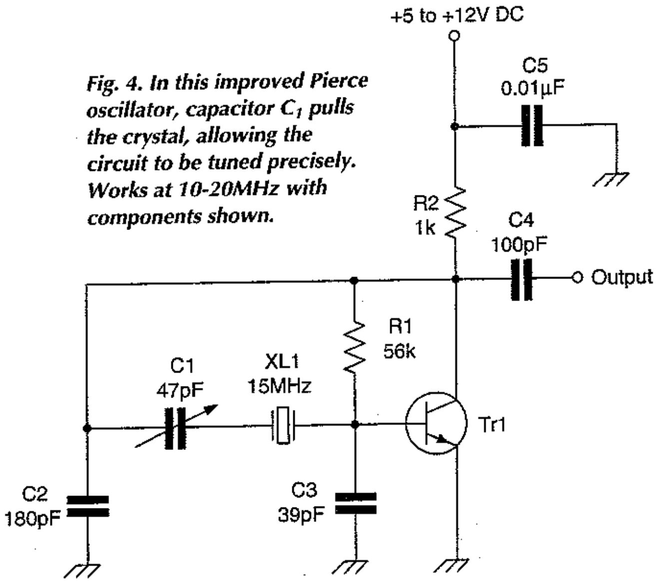
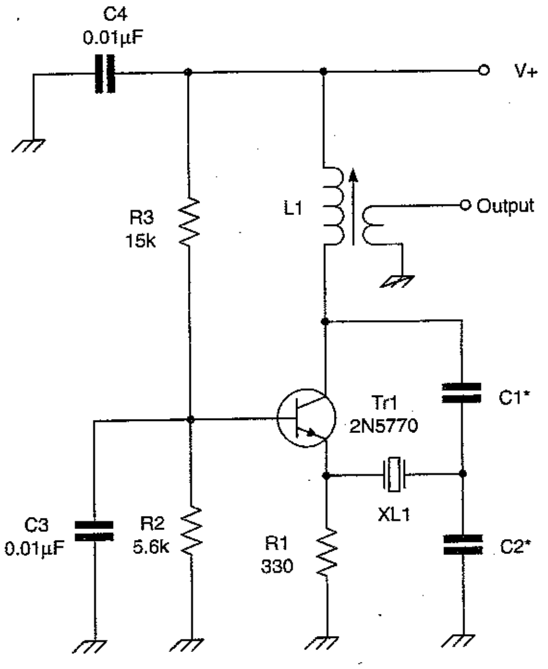


Fig. 4. In this improved Pierce oscillator, capacitor C_1 pulls the crystal, allowing the circuit to be tuned precisely. Works at 10-20MHz with components shown.



Freq (MHz)	C1 (pF)	C1 (pF)
3 - 10	47	390
10 - 20	22	220

Fig. 6. The Butler oscillator is capable of stability down to 10ppm if an output buffer with good isolation is used.

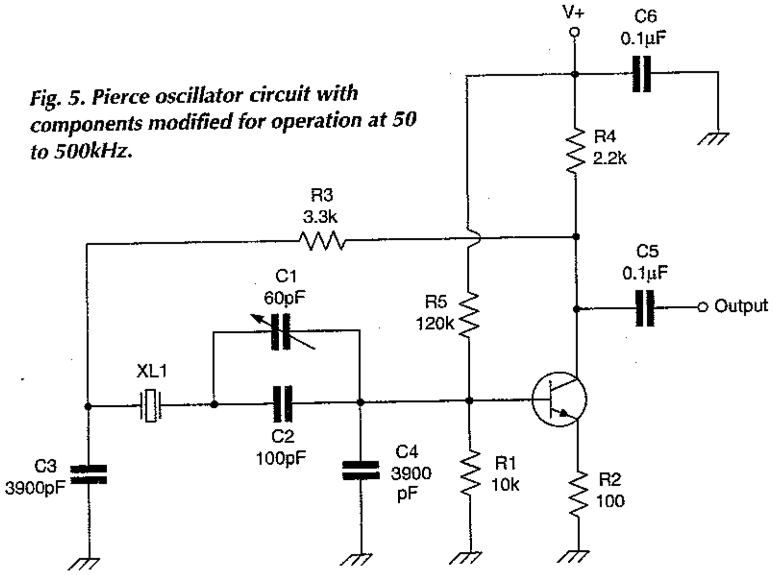


Fig. 5. Pierce oscillator circuit with components modified for operation at 50 to 500kHz.

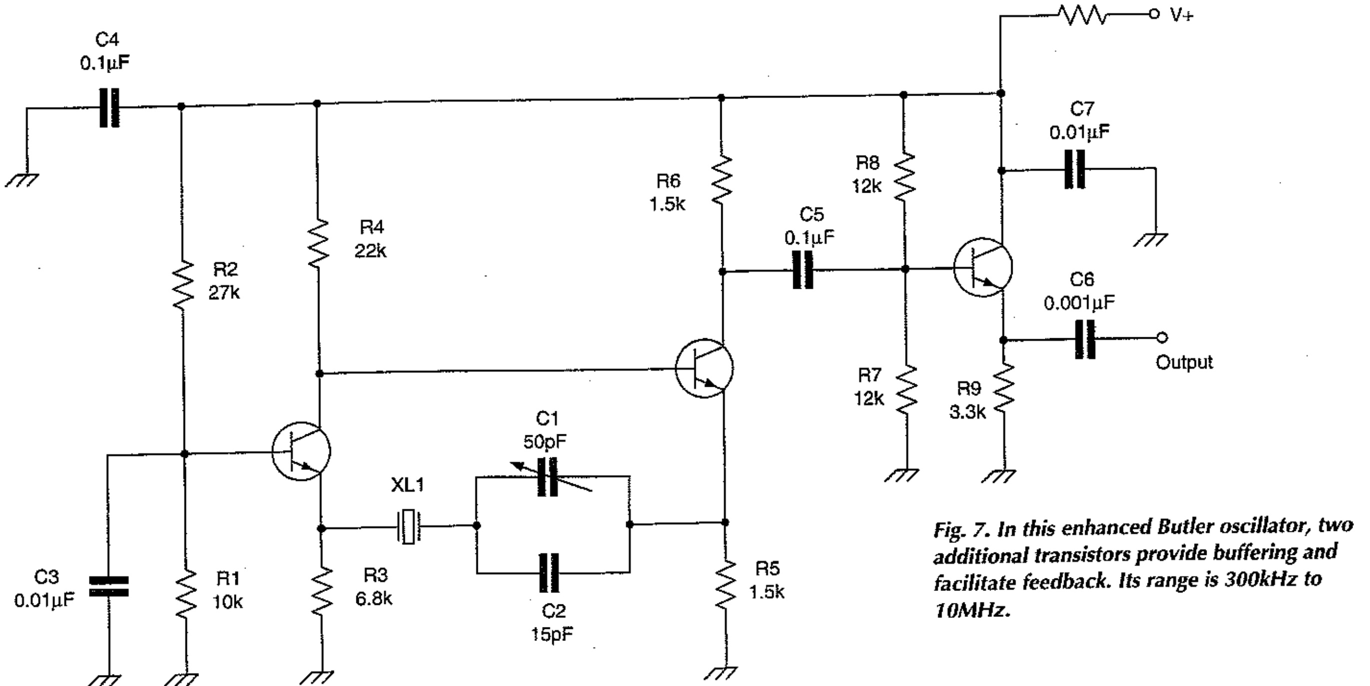


Fig. 7. In this enhanced Butler oscillator, two additional transistors provide buffering and facilitate feedback. Its range is 300kHz to 10MHz.

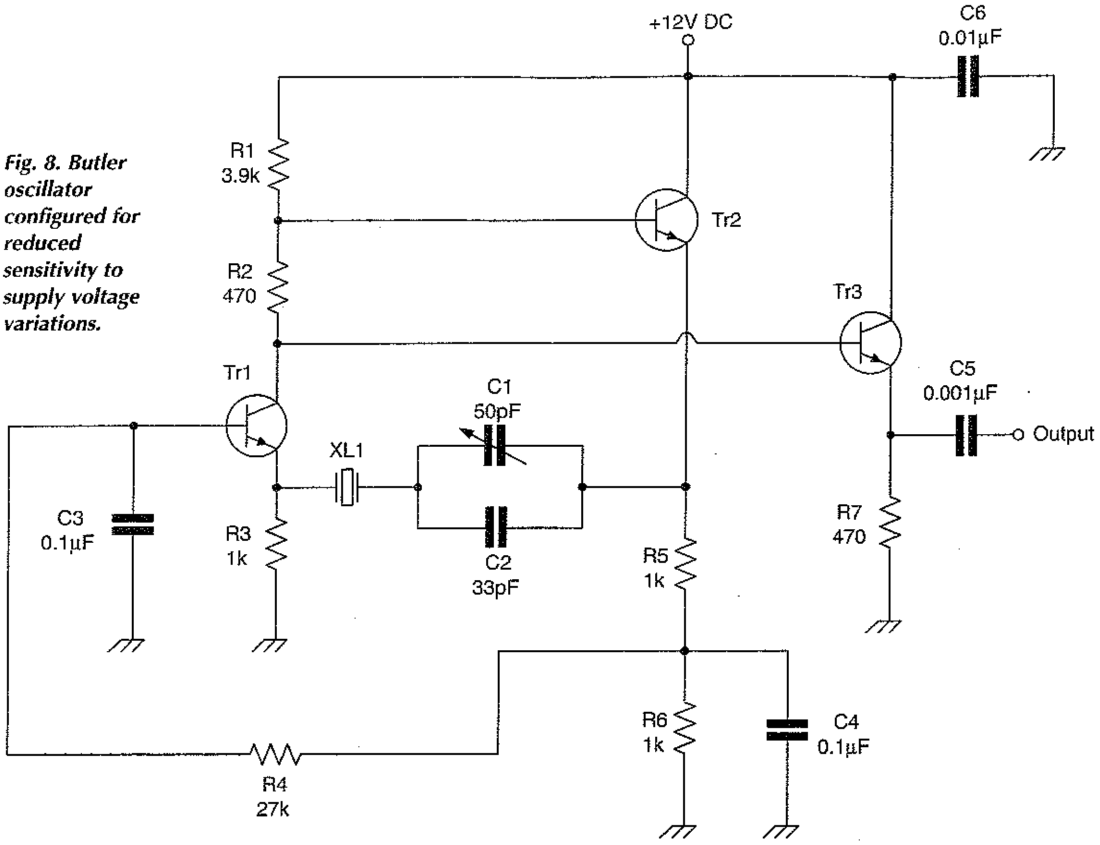


Fig. 8. Butler oscillator configured for reduced sensitivity to supply voltage variations.

capable of 10 to 20ppm stability if a buffer amplifier with good isolation is provided at the output. Otherwise, some frequency pulling with load variations might be noted.

The output signal is taken from a coupling winding over L_1. This winding is typically only a few turns of wire on one end of L_1. Alternatively, a tap on L_1 might be provided, and the tap connected to a low value capacitor. That approach might change some resonances unless care is taken.

Another alternative output scheme is to connect a small value capacitor to the collector of Tr_1. Keep the value low so as to reduce loading, and also to reduce the effects of the output capacitor on the resonance of L_1/C_1.

A somewhat more complex Butler oscillator is shown in **Fig. 7**. This circuit is sometimes called an aperiodic oscillator circuit. It uses two additional transistors to provide buffering and also serve as part of the feedback circuit. The circuit will operate from about 300kHz to 10MHz, but the transistor may need to be selected carefully.

Many low-frequency crystals exhibit a lower equivalent series resistance, or

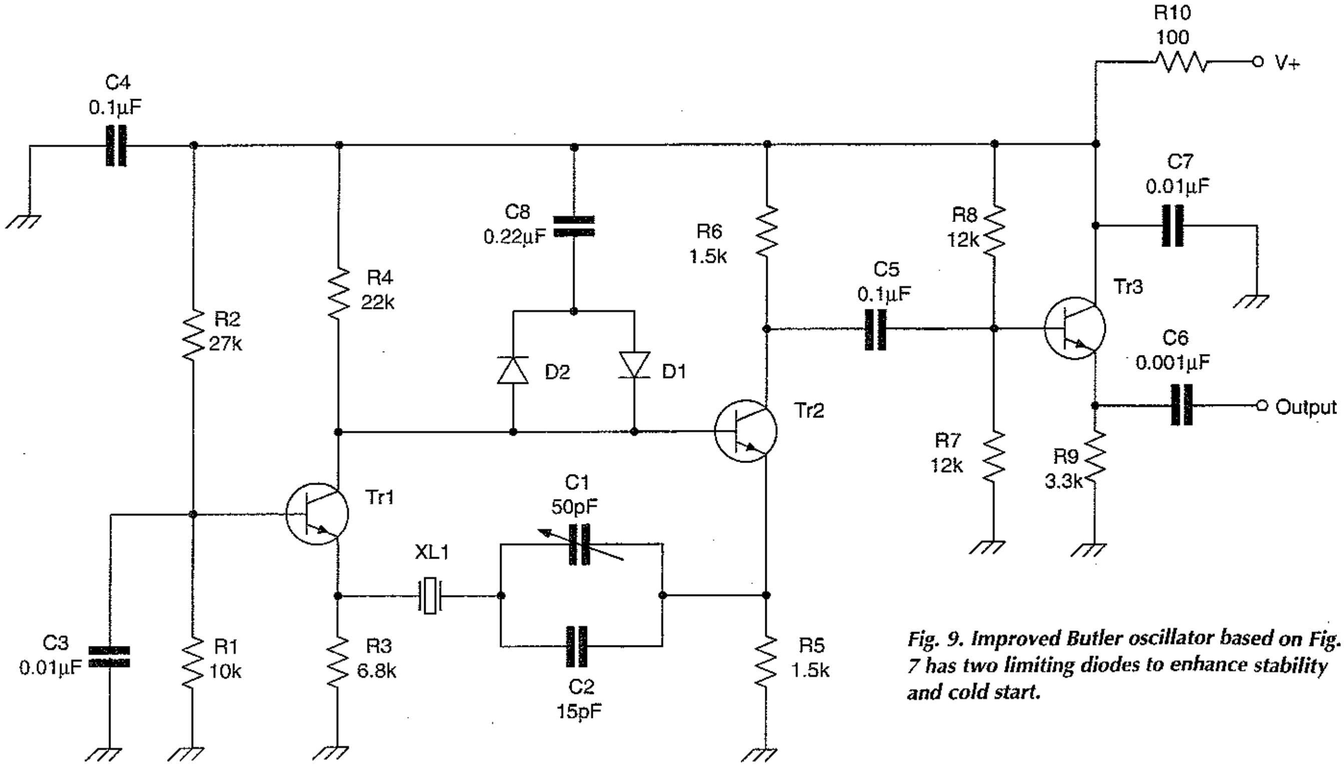


Fig. 9. Improved Butler oscillator based on Fig. 7 has two limiting diodes to enhance stability and cold start.

ESR, in one of the higher-frequency modes of oscillation than in the fundamental mode. As a result, you might find this circuit oscillating at some frequency in the medium wave or HF region, rather than at LF. The key to preventing this problem is to use a transistor with a lower gain-bandwidth product, such as a *2N3565*. An explanation is given in the panel entitled, 'Surely an equivalent transistor will do?'

The circuit of **Fig. 7** produces a sine wave output, but not without relatively strong harmonic output. The second and third harmonics are particularly evident. However, if harmonics are desired – when the oscillator is used in a frequency multiplier for example – then strong harmonics up to 30MHz can be generated from a 100kHz crystal if R_5 is reduced to about 1kΩ.

The output of this oscillator is taken through an emitter-follower buffer. This circuit can be used as a general buffer for a number of oscillator circuits. It is generally a good practice to use a buffer amplifier with any oscillator in order to reduce loading and smooth out load impedance variations.

Another variation on the Butler theme is shown in **Fig. 8**. This circuit is similar to Fig. 7, but is a bit less sensitive to frequency pulling due to DC power supply voltage variations. It is good engineering practice to use a separate voltage regulator for all oscillator circuits though, in order to prevent such variation. The availability of low cost three-terminal integrated circuit voltage regulators makes this easy.

An improved Butler oscillator is shown in **Fig. 9**. This circuit is based on Fig. 7. Both circuits can be used at frequencies from LF up to the mid-HF region – about 12 to 15MHz – if appropriate values of R_3 and R_5 are used.

The improvement of Fig. 9 over Fig. 7 stems from the limiting diodes $D_{1,2}$ between the two oscillator transistors, $Tr_{1,2}$. These diodes can be general-purpose 1N4148 small-signal types.

The circuit of Fig. 9 is preferred over Fig. 7 because it is more stable because crystal dissipation is limited, and it offers more reliable cold starting.

The Butler oscillators above are series-mode circuits, but because of the series capacitors, they are able to use parallel-mode crystals. For a strictly series-mode circuit, eliminate the capacitors in series with the crystal and replace them with a short circuit.

Colpitts oscillators

A feedback network consisting of a tapped capacitive voltage divider characterises the Colpitts oscillator. In **Fig. 10** the feedback is provided by C_1 and C_2, although the situation is somewhat modified by the gate capacitances of Tr_1. This circuit can be used with parallel mode crystals from about 3 to 20MHz with proper values of C_1 and C_2 as in the table in Fig. 10.

Frequency trimming of the oscillator can be done by shunting a small value trimmer capacitor across the crystal. Alternatively, the trimmer can be placed in series with the crystal.

If the oscillator tends to oscillate parasitically in the VHF region, then try using the snubber resistor method, R_4 in Fig. 10. This could occur because the JFET used at Tr_1 will have sufficient gain at VHF to permit Barkhausen to have his due at some frequency where strays and distributed *LC* elements produce the correct phase shift.

A value between 10 and 47Ω will usually eliminate the problem. Alternatively, a small ferrite bead can be slipped over the gate terminal of Tr_1 to act as a small value VHF/UHF RF choke.

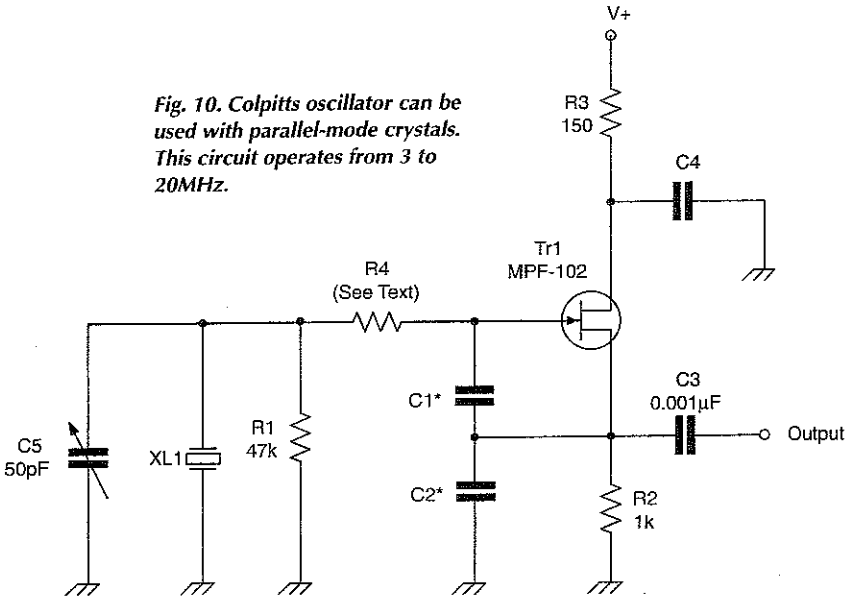


Fig. 10. Colpitts oscillator can be used with parallel-mode crystals. This circuit operates from 3 to 20MHz.

Freq (MHz)	C1 (pF)	C2 (pF)
3 - 10	27	68
10 - 20	10	27

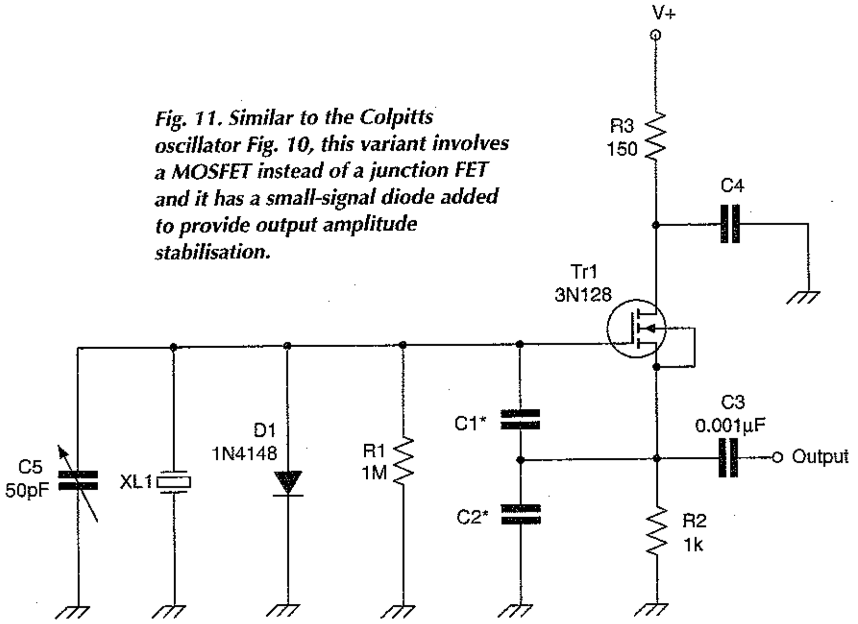


Fig. 11. Similar to the Colpitts oscillator Fig. 10, this variant involves a MOSFET instead of a junction FET and it has a small-signal diode added to provide output amplitude stabilisation.

Freq (MHz)	C1 (pF)	C2 (pF)
3 - 10	22	180
10 - 20	10	82

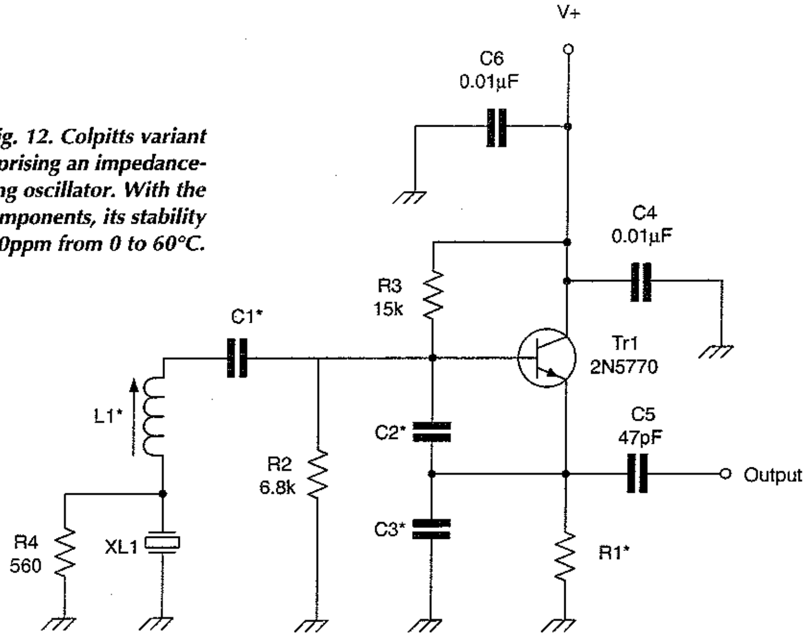


Fig. 12. Colpitts variant comprising an impedance-inverting oscillator. With the right components, its stability can be 10ppm from 0 to 60°C.

Freq (MHz)	C1 (pF)	C2 (pF)	C3 (pF)	R1	L1 (turns)
2 - 4	1000	270	270	1.5k	60
4 - 6	1000	270	270	1.5k	40
6 - 10	1000	270	270	1.5k	25
10 - 15	100	220	220	680	15
15 - 20	100	100	100	680	10

Figure 11 is the same as Fig. 10, except for two features. First, the active device is an n-channel MOSFET rather than a JFET. Any of the single-gate devices, such as a *3N128*, can be used, but remember that such MOSFETs are very sensitive to ESD damage.

The other difference is a *1N4148* small-signal diode that shunts the gate-source path to provide a small amount of automatic gain control action. When the signal appearing across the crystal and feedback network is sufficiently large, the diode rectifies the signal and produces a DC bias on the gate that counters the source bias provided by R_2. This diode helps smooth out amplitude variations, especially when more than one crystal is switched in and out of the circuit.

Another variation on the Colpitts theme is the impedance inverting oscillator circuit of **Fig. 12**. It provides stability of 10ppm over a wide temperature range of 0°C to 60°C provided that the components are carefully selected. Bear in mind that $C_{1\text{-}3}$ and L_1 are particularly troublesome here.

The circuit will also remain within ±0.001% over a DC power supply variation of 2:1 – provided the crystal

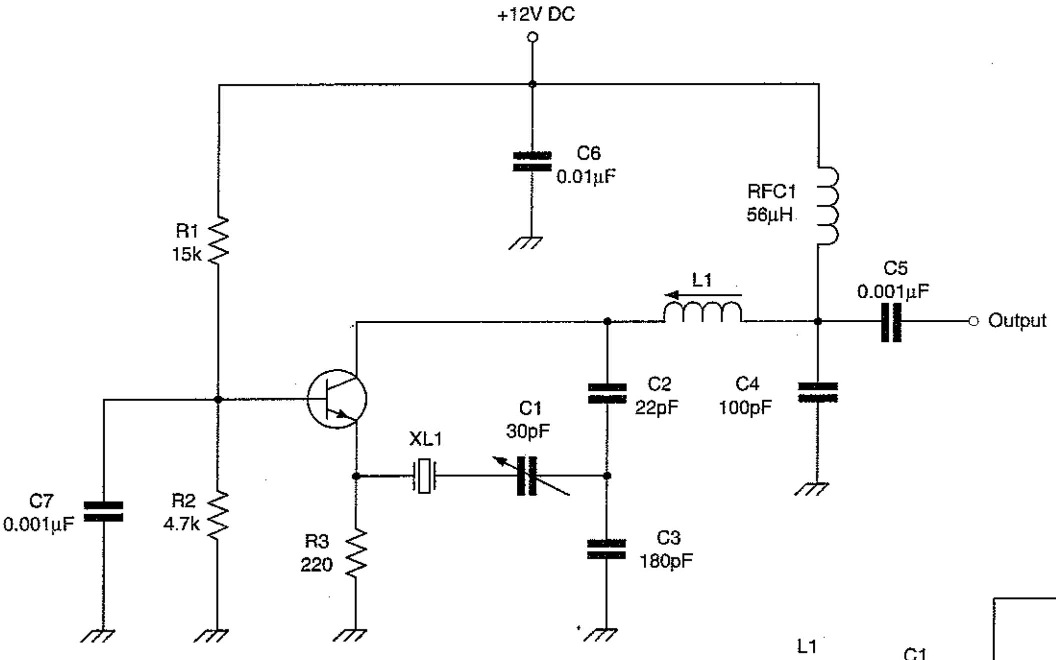


Fig. 13. Third-overtone Butler oscillator for 15 to 65MHz. Tuning inductor L_1 helps ensure that the circuit oscillates at the desired overtone frequency.

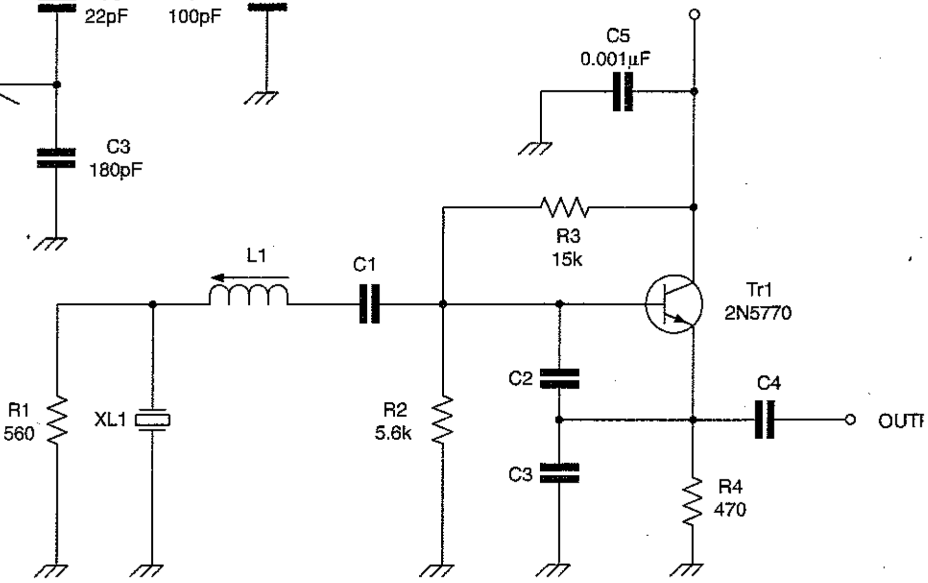


Fig. 14. Alternative impedance-inverting third-overtone circuit based on the Colpitts oscillator. Again, this circuit works from 15 to 65MHz.

Freq (MHz)	C1 (pF)	C2 (pF)	C3 (pF)	C4 (pF)	L1 (0.25in form)
15 - 25	100	100	68	33	12t, #30, CW
25 - 55	100	68	47	33	8t, #30, CW
50 - 65	68	33	15	22	6t, #22, CW

dissipation is not exceeded. Harmonic output of this configuration is typically low.

Frequency of oscillation is set by adjusting inductor L_1. The turns counts shown in the table in Fig. 12 assume a 6.5mm slug-tuned coil form designed for use in the frequency range 3 to 20MHz. Some experimentation is needed depending on the particular former used. The idea is to set the resonant frequency of the coil and C_{1-3} combined to something near the crystal frequency.

It is sometimes appealing to add a tuned circuit to the output circuit of oscillators. The harmonics of the oscillator are suppressed when this is done. But in this case, a transistor equivalent of the old-fashioned TGTP oscillator will result because of the action of the output tuned circuit and the L_1/C_{1-3} combination. Don't do it!

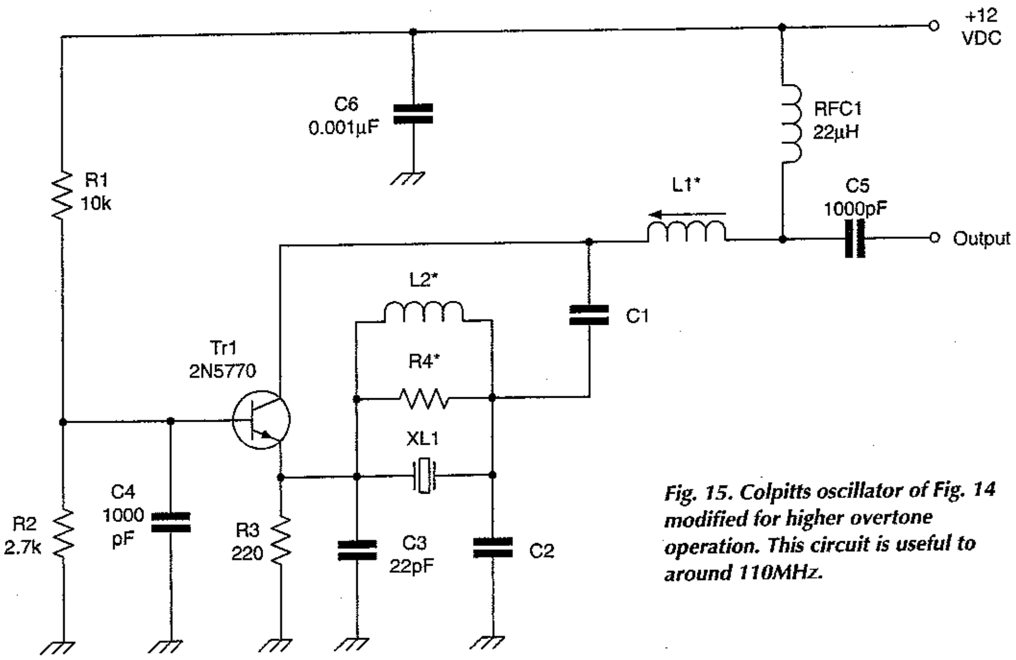


Fig. 15. Colpitts oscillator of Fig. 14 modified for higher overtone operation. This circuit is useful to around 110MHz.

Freq (MHz)	C1 (pF)	C2 (pF)	C3 (pF)	L1	L2
65 - 85	15	150	100	7 t, #24, 3/16in. CW	10t #34 over 10Ω 1/4W
85 - 110	10	100	68	4 t, #24, 3/16in. 1WD	10t #34 over 10Ω 1/4W

CW = close wound
1WD = spaced 1 wire diameter

Overtone oscillators

So far I have only discussed the fundamental oscillating mode. But crystals oscillate at more than one frequency.

The oscillations of a crystal slab are in the form of bulk acoustic waves, or BAWs. These can occur at any frequency that produces an odd half-wavelength of the crystal's physical dimensions, for example $1\lambda/2$, $3\lambda/2$, $5\lambda/2$, $7\lambda/2$, $9\lambda/2$, where the fundamental mode is $1\lambda/2$.

Note that these frequencies are not harmonics of the fundamental mode. They are actually valid oscillation modes for the crystal slab. The frequencies fall close to, but not directly on, some of the harmonics of the fundamental – which often causes confusion.

The overtone frequency will be marked on the crystal, rather than the fundamental. It is rare to find fundamental mode crystals above 20MHz or so, because their thinness makes them more likely to fracture at low values of power dissipation.

The problem to solve in an overtone oscillator is encouraging oscillation on the correct overtone, while squelching oscillations at the fundamental and undesired overtones. Crystal manufacturers can help with correct methods, but there is still a responsibility on the part of the oscillator designer.

Figure 13 shows a third-overtone Butler oscillator that operates at frequencies between 15 and 65MHz. Inductor L_1 is set to resonate close to the crystal frequency, and is used in part to ensure overtone mode oscillation. If moderate DC supply voltages are used – 9 to 12 volts in most cases – the harmonic content is low, at around –40dB. In addition, stability is at least as good as a similar fundamental mode Butler oscillator.

Figure 14 is a third-overtone impedance inverting Colpitts style oscillator that operates over the 15 to 65MHz range. As in similar circuits, inductor L_1 is tuned to the overtone, and is resonated with C_1, combined with the capacitances of C_2 and C_3. Values for C_1 through C_3, and winding instructions for a 6.5mm low-band VHF coil former are shown on the diagram.

Note the resistor across crystal Y_1. This resistor tends to snub out oscillations in modes other than the overtone, including the fundamental. Take care not to make L_1 too large, otherwise it will resonate at a lower frequency with C_{1-3}, forming an oscillator on a frequency not related to either the crystal's fundamental or overtones. The oscillator may well be perfectly happy to think of itself as a series-tuned Clapp oscillator!

Operation of the circuit of Fig. 14 to 110MHz, with fifth or seventh overtone crystals, can be accomplished by modifying this circuit to the form shown in **Fig. 15**.

In summary

The crystal oscillator is probably the best way to obtain a single-frequency source. Crystal oscillators are also used to provide accurate references and time base in such applications as frequency counters and frequency synthesisers.

With proper care and component selection, these circuits can be used to provide a stable, accurate signal. ■