## Introduction

If you are an engineer mainly working with digital devices these notes should reacquaint you with a little analogue theory. The treatment is non-mathematical, concentrating on practical aspects of circuit design.
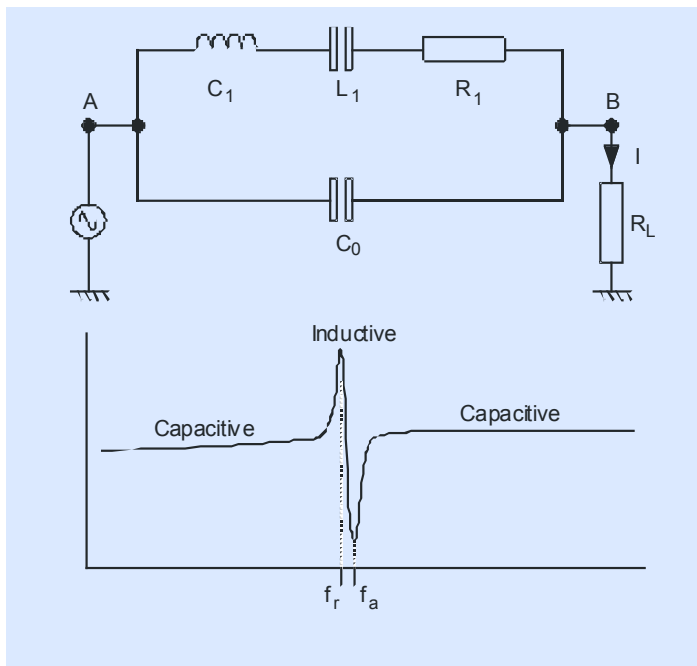
Various oscillator designs are illustrated that with a little experimentation may be easily modified to suit your requirements. If you prefer a more 'in-depth' treatment of the subject, the appendix contains formulae and a list of further reading.

## Series or Parallel?

It can often be confusing as to whether a particular circuit arrangement requires a parallel or series resonant crystal. To help clarify this point, it is useful to consider both the crystal equivalent circuit and the method by which crystal manufacturers calibrate crystal products. (*Some approximate formulae are given in the appendix.*)

There is no intrinsic difference between a 'series' and 'parallel' crystal; it is just a matter of the impedance they present to an external circuit at the calibration frequency. Crystals exhibit two main resonances which are very close to each other, and at which they appear resistive. Series resonance is the lower frequency, low-resistance resonance; parallel or anti-resonance is the high-resistance resonance. In practice, you always consider a crystal whose frequency of oscillation lies between the two resonances to be parallel resonant.

## Crystal Equivalent Circuit



## The Crystal Equivalent Circuit

In the crystal equivalent circuit above, L1, C1 and R1 are the crystal motional parameters and C0 is the capacitance between the crystal electrodes, together with capacitances due to its mounting and lead-out arrangement. The current flowing into a load at B as a result of a constant-voltage source of variable frequency applied at A is plotted below.

At low frequencies, the impedance of the motional arm of the crystal is extremely high and current rises with increasing frequency due solely to the decreasing reactance of C0. A frequency fr is reached where L1 is resonant with C1, and at which the current rises dramatically, being limited only by RL and crystal motional resistance R1 in series. At only slightly higher frequencies the motional arm exhibits an increasing net inductive reactance, which resonates with C0 at fa, causing the current to fall to a very low value. The difference between fr and fa is dependant upon fr and the ration of C1 to C0. At still higher frequencies, disregarding other crystal vibration modes, the current reverts to that due to C0 alone.
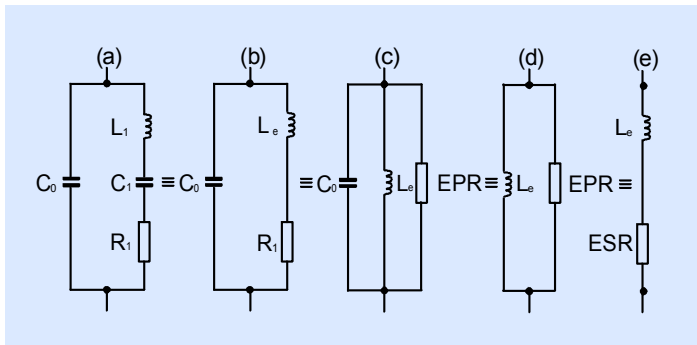
At the two resonant frequencies the crystal 'looks' like a resistor, the applied voltage and resulting load current being in-phase. Practically, this is not quite so owing to the relative positions of R1 and C0 in the equivalent circuit. The zero-phase frequencies are not quite the same as the frequencies of maximum and minimum transmission, but at frequencies below 100MHz where the reactance of C0 is high compared with R1, they may be regarded as such.

The exact frequency of any oscillator is dependent upon the relative phases of voltages and currents within it, and is not simply the frequency printed on the crystal can. For oscillation to occur at the desired frequency there must be positive feedback or zero loop phase shift at that frequency. The marked crystal frequency is that frequency at which the crystal was made to oscillate
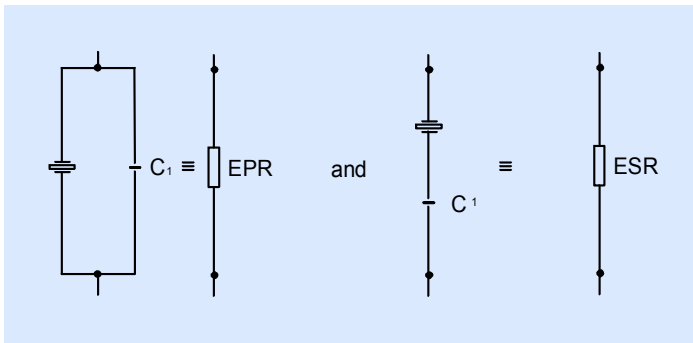
## Network Transformations

Most crystal oscillators are designed to operate the crystal at fr where it appears resistive, or at a frequency between fr and fa; let us call this frequency fL, where the crystal appears inductive. In this case, successive network transformations (see circuit over page) allow you to reduce the crystal circuit to only two components: a net inductance and an equivalent parallel or series resistance.

## Network Transformations



We can retain the same value of inductance in transformations (b) to (c) and (d) to (e) because of the high ratio of inductive reactance to resistance, owing to Q being very high. We can say that, 'to all intents and purposes' a load capacitor CL placed in parallel with a crystal will resonate with it at the same frequency (fL) as if it were in series with it. Consequently, as we are left with a high value resistance (EPR), or a low value resistance (ESR), the load current at that frequency will be in phase with the applied voltage. (*See below*.)
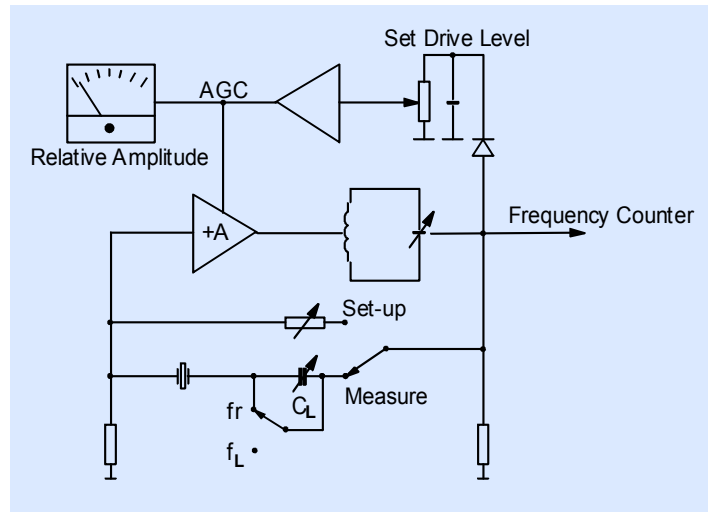


## Crystal Calibration

To enable us as a crystal manufacturer to correctly calibrate a crystal we need to know at what point between fr and fa your circuit will make the crystal oscillate. If your frequency is fr, correlation is no problem; we simply adjust the crystal so that the zero-phase-shift frequency which is closest to the frequency of maximum transmission is within the specified tolerance. For oscillators in which the crystal has to appear inductive we need to know what effective load capacitance will be presented to the crystal by the oscillator circuit. In this case the procedure is the same except that a series combination of the crystal and a capacitor of this value is substituted for the crystal alone. All practical oscillator circuits of this type add capacitance to the crystal, if only 'strays,' and it is advisable for several reasons to make it up to one of the industry standard values of 18pF, 20pF or 30pF.

In a tuned oscillator having a low-impedance, positive-feedback path which can be completed by either a non-inductive variable resistor or by the crystal, if the oscillator is adjusted so that its frequency and amplitude of oscillation is the same for both paths, then the crystal will be oscillating as its zero-phase frequency Fr, and the variable resistor will be equal in value to R1 in the crystal equivalent circuit. Similarly, if a calibrated 'load' capacitor is placed in series with the crystal, oscillation will occur at FL and the variable resistor will equal the crystal ESR. In practice, because of errors due to unavoidable stray capacitance at the junction of the crystal and variable capacitor, the ESR figure is usually calculated rather than measured.

## The Crystal Impedance Meter



After the measurement of C0 in a conventional bridge, values can be assigned to L1, C1 and the EPR. This is the basis of the Crystal Impedance Meter above.

Above approximately 60MHz the crystal C0 can cause non-crystal-controlled oscillation. In fact, if the reactance becomes less than half the value of R1, a zero-phase condition cannot exist. At very high frequencies therefore, C0 is often balanced or tuned out, fL readings becoming meaningless. Alternatively, the frequency of maximum transmission (fM) can be measured by other means.

## Phase-Zero Measuring System

The Phase-Zero Measuring System (PZMS) has been adopted by the IEC. In this system the crystal is made to form the series arm of a low-resistance pi-network attenuator, the input of which is driven by a frequency synthesizer and the output being resistively terminated. Each end of the pi-network is connected to a probe of a vector voltmeter, the AFC output of which controls the synthesizer's frequency such that the system automatically locks to the crystal fr or fL if the crystal has a load capacitor in series with it. Equivalent resistances are calculated for the network loss. The PZMS is capable of high accuracy and repeatability and offers other significant advantage in crystal manufacturing.

## Conditions for Oscillation

Any oscillator, be it RC, LC or crystal- controlled, requires two conditions to be met for it to operate at the desired frequency; its loop gain must be greater than unity and its loop phase shift must be zero (2n radians where n = 0 or a whole integer) at that frequency.
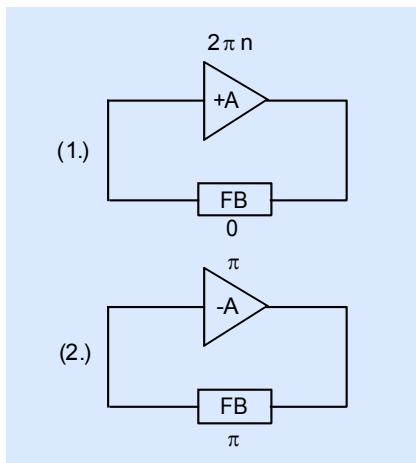
In practice, oscillators can be divided into two groups:

**1.) Non-inverting Maintaining Amplifier.**
The feedback network must provide zero-phase shift at the operating frequency.

**2.) Inverting Maintaining Amplifier.**
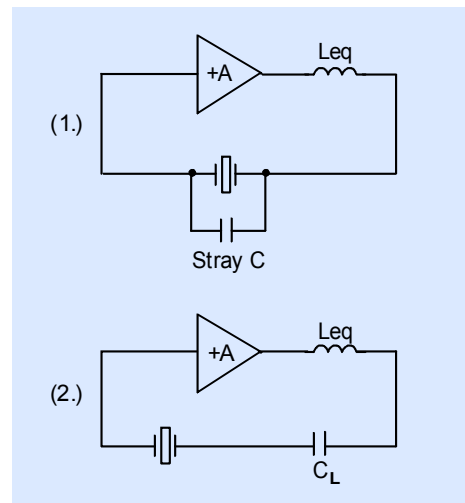The feedback network must provide $\pi$ radians.

## Amplifier Feedback Networks



Since a crystal exhibits zero phase shift at its series resonant frequency fr, it alone can act as the feedback component. (1. above.) As long as the amplifier has sufficient gain to overcome the loss due to its input and output resistance and the crystal R1 acting as a potential divider, the circuit will oscillate at fr.

The circuit can also be made to oscillate at the load or parallel-resonant frequency if a capacitor equal to the load capacitance with which the crystal was calibrated is placed in series with the crystal. The extra capacitor, if a trimmer, provides a convenient means of adjustment of the oscillator frequency and can be used to tune out the crystal calibration tolerance. More amplifier gain will be needed however, as the crystal ESR is slightly higher than R1 being dependent upon CL and C0.
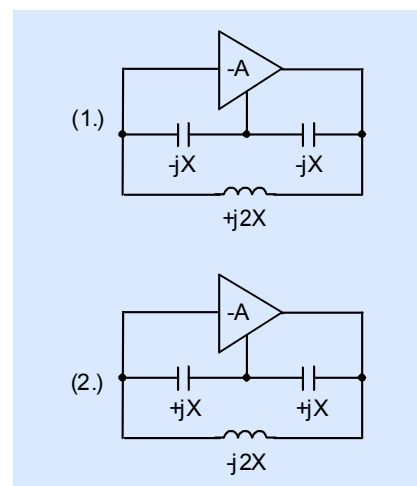
Practically, a 'perfect amplifier' having no unwanted phase shift does not exist. Some non-inverting amplifiers, notably microprocessor clocks and those that employ cascaded logic circuits, may show an appreciable lagging phase shift at the operating frequency. Even worse, is that in some circuits due to many non-linear active stages within these amplifiers, the lag is not constant over the operating cycle. The result is poor short-term stability or jitter.

## Oscillator Phase Shift



A constant lagging phase shift within the amplifier appears to the crystal as an inductance Leq as in (1.) above in series with a perfect amplifier. To enable oscillation the circuit has to present a capacitive reactance in order to cancel this inductance; meaning, it has to oscillate at a frequency below fr. The danger being that non-crystal-controlled oscillation can occur due to inductance resonating with the crystal C0 and any 'strays' in parallel with it. Leq may be cancelled by a series capacitor CL in order to pull the crystal back up to fr, as in figure (2.) above. In this case it must be appreciated that since the crystal is again resistive, CL is not the crystal load capacitance.

## Phase Inversion



The above circuits show the feedback network needed to produce further phase inversion. For a phase shift of radians, the requirement of the networks is that the sum of the two series connected reactances, which need not be equal, cancels the reactance of the third. This occurs when the two arms are resonant. Figure (1) represents the configuration known as the Pierce oscillator and its relations, the Colpitts and Clapp. Figure (2.) represents the Hartley and Miller.
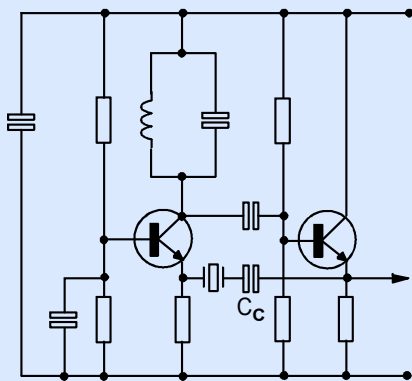
Since a parallel-resonant crystal has been calibrated to offer an inductive reactance at its marked frequency it can be substituted for one of the positive reactances shown above. So long as the total capacitance, including that due to the amplifier and strays, presented to the crystal is equal to the load capacitance with which it was oscillated, the circuit will operate on frequency. One of the capacitors can be a trimmer to allow fine adjustment. The amplifier is likely to be a more perfect one than is the case for the non-inverting configuration since only one active stage need be employed.

### The Impedance-Inverting Oscillator

One variant of the circuit (1.) above is the impedance-inverting oscillator. Using a Pierce or Colpitts circuit, instead of allowing the crystal to cancel the oscillator reactance, fit an inductor in series with the crystal. This arrangement is often employed in oscillators using overtone crystals to give selectivity, reducing the likelihood of unwanted modes, and also allows the use of series calibrated crystals. (This is mandatory at very high frequencies.) Take care however, that oscillation does not occur through the crystal C0; this is possible if the crystal is being pulled high of fr.

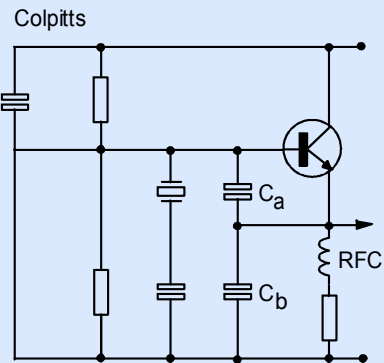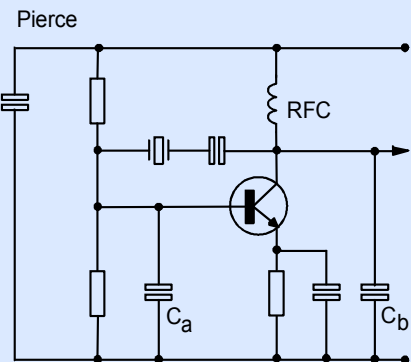### Typical Oscillator Circuits



**Butler Oscillator**

### Butler Oscillator

The maintaining amplifier of the Butler oscillator consists of a tuned-out non-inverting grounded base stage and an emitter follower, also non-inverting. Temporarily replacing the crystal with a low value resistor will cause oscillation controlled by the LC tank in the collector of the grounded base stage. If the capacitor CC is only a DC blocking capacitor and the free-running frequency is coincident with the crystal fr, oscillation will be crystal controlled close to fr. As in the Crystal Impedance Meter, CC can be made equal to the crystal load capacitance for operation with parallel-calibrated crystals.

### Uses of Butler Oscillator

Being a tuned oscillator, the Butler is useful for overtone crystal operation up to at least 100MHz. However, because oscillation may occur through the crystal C0, it is advisable to tune this out with a small parallel inductor. The emitter follower can be dispensed with if you put a low impedance tap in the tank circuit for the driven end of the crystal; the circuit then becoming a grounded-base oscillator. To operate with fundamental mode crystals the LC tank can be replaced by a resistor.



### Pierce and Colpitts Oscillators

The circuit arrangement of Pierce and Colpitts oscillators is similar; capacitors Ca and Cb together with the crystal from the feedback network and are connected between the same transistor electrodes in each case. The design equations for both oscillators are the same, differing only in the matter of which transistor electrode is grounded.

The Pierce oscillator has the advantage that the transistor bias-resistor chain shunts Ca only. In the Colpitts it shunts Ca and Cb in series, whose combined reactance is larger than that of Ca alone. This has a greater effect upon the circuit Q as you are more effectively shunting the crystal EPR; a higher transistor current will be needed for the same oscillation amplitude and the short-term stability will be more seriously effected. FETs can be used to overcome this problem, but they are not as temperature stable and require higher operating current than bipolar devices.

One of the two capacitors Ca or Cb can be replaced by a trimmer, but as their series combination is likely to be higher than a normal value of crystal load capacitance, it is more usual to put the trimmer in series with the crystal. Pierce and Colpitts oscillators have the advantage that since Ca and Cb are in parallel with the transistor dynamic capacitances, the larger they are the greater will be their swamping effect and the better the stability of the oscillator.

## Gain and Drive Level

### Gain

To ensure freedom from parasitics or oscillation on the wrong crystal mode, it is advisable to ensure that the loop gain is just enough to ensure satisfactory operation under worst-case conditions. A gain margin limit of only two to three times that required for oscillation with a crystal at the limit of its activity should be sufficient.

### Drive Level

Low-frequency crystals, particularly the miniature types, are very easily damaged by excessive drive, and VHF crystals can show significant frequency shift if they are not operated within at least an order of magnitude of the drive level at which they were calibrated. It is advisable not to exceed the manufacturers recommended maximum drive level if a high degree of stability is required. Precision frequency standards usually operate high-frequency crystals at well under one microwatt, held at this level by an AGC circuit rather than by the limiting action of the active device itself.
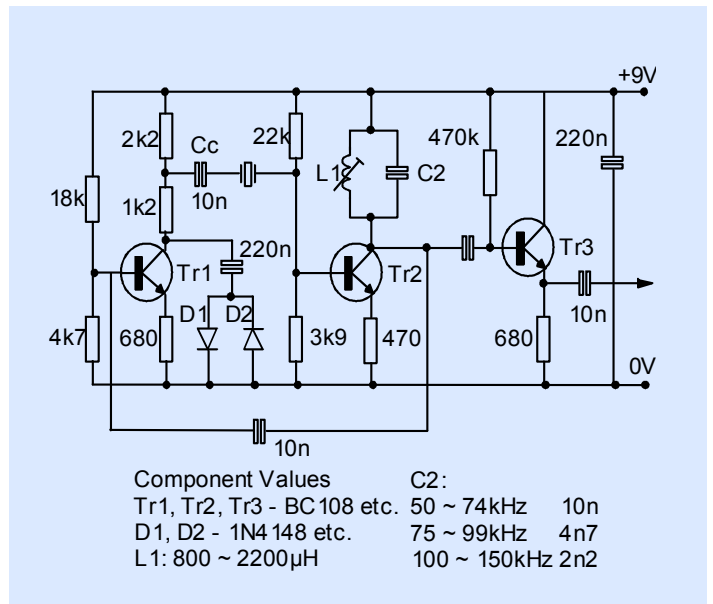
If possible, the circuit should be optimised for stability, gain and drive level before consideration is given to the needs of the following stage. The signal can be extracted from the various parts of the circuit so long as impedance levels are considered; excessive loading of the oscillator circuit will affect both stability and gain margin.

## Practical Circuits

### Below 150kHz

Two grounded-emitter transistors forming a non-inverting amplifier provide the gain necessary to guarantee oscillation with the low activity of crystals at these frequencies. The L1 and C2 tank circuit, which should be adjusted for maximum output, provides some selectivity and prevent oscillation on a wrong crystal mode. Diodes D1 and D2 limit the crystal drive to a safe level for standard crystals. For fine frequency adjustment, Cc may be a trimmer, the mid value of which should be approximately equal to the load capacitance of parallel-calibrated crystals.

### Below 150kHz



Component Values
Tr1, Tr2, Tr3 - BC 108 etc.
D 1, D 2 - 1N4 148 etc.
L 1: 800 ~ 2200µH

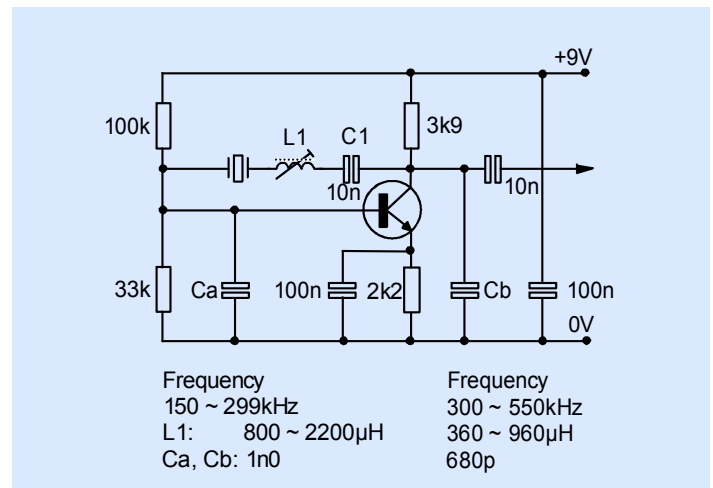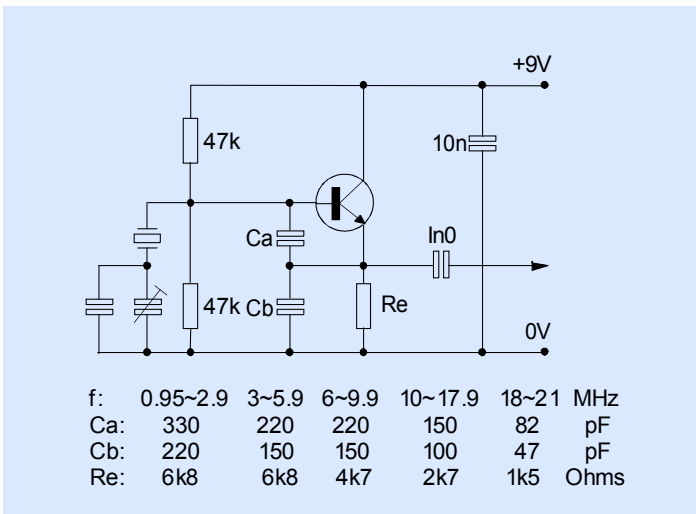| C2: | |
| --- | --- |
| 50 ~ 74kHz | 10n |
| 75 ~ 99kHz | 4n7 |
| 100 ~ 150kHz | 2n2 |

Two grounded-emitter transistors forming a non-inverting amplifier provide the gain necessary to guarantee oscillation with the low activity of crystals at these frequencies. The L1 and C2 tank circuit, which should be adjusted for maximum output, provides some selectivity and prevent oscillation on a wrong crystal mode. Diodes D1 and D2 limit the crystal drive to a safe level for standard crystals. For fine frequency adjustment, Cc may be a trimmer, the mid value of which should be approximately equal to the load capacitance of parallel-calibrated crystals.

### 150kHz to 550kHz



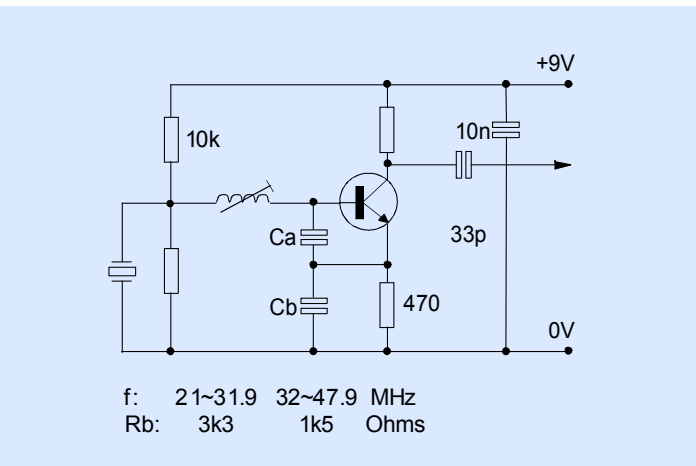| Frequency | Frequency |
| --- | --- |
| 150 ~ 299kHz | 300 ~ 550kHz |
| L1: 800 ~ 2200µH | 360 ~ 960µH |
| Ca, Cb: 1n0 | 680p |

This is an impedance-inverting Pierce oscillator that suppresses the principal twice-frequency spurious mode of DT and CT cut crystals. For use with crystals calibrated at parallel resonance, C1 can be replaced by a capacitor equal to the crystal load capacitance. L1 is adjusted for on-frequency operation.

## 950kHz to 21MHz



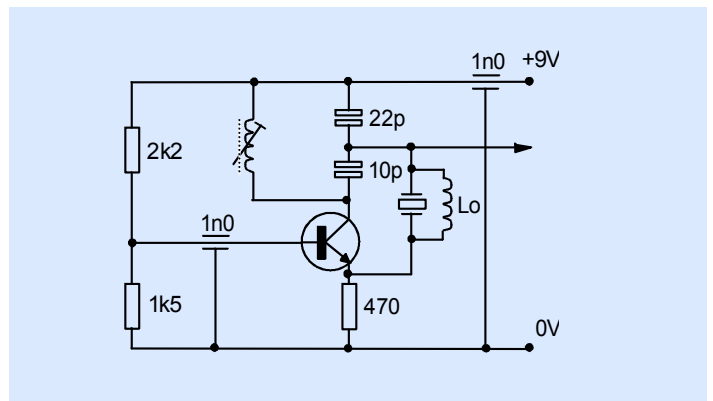| f: | 0.95~2.9 | 3~5.9 | 6~9.9 | 10~17.9 | 18~21 | MHz |
|---|---|---|---|---|---|---|
| Ca: | 330 | 220 | 220 | 150 | 82 | pF |
| Cb: | 220 | 150 | 150 | 100 | 47 | pF |
| Re: | 6k8 | 6k8 | 4k7 | 2k7 | 1k5 | Ohms |

This is a Colpitts oscillator with series trimming. The series combination of Ca, Cb and the mid-value of the trimmer, plus its parallel padding capacitor if required, should be made equal to the crystal load capacitance. At higher frequencies, you should allow 5pF or so for the shunting effect of the transistor and stray capacitance. You can extract a crystal harmonic frequency if an LC tank, tuned to the harmonic, is inserted into the transistor collector. The output in this case should be taken from the collector.

## 21MHz to 105MHz



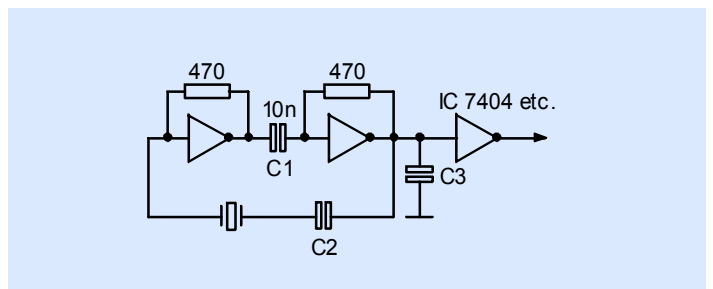| f: | 21~31.9 | 32~47.9 | MHz |
|---|---|---|---|
| Rb: | 3k3 | 1k5 | Ohms |

Suitable for use with 3rd and 5th overtone crystals respectively, the above circuits describe impedance inverting, Colpitts oscillators. With the crystal temporarily shunted by a bypass capacitor, L1 should initially be adjusted such that at its minimum value, free-running oscillation occurs at the crystal frequency. If the crystal is offset positively by a small amount (10-40ppm depending upon the crystal tolerance and the available inductance swing) L1 will allow precise frequency setting. Harmonic extraction can be achieved as described for the lower-frequency Colpitts circuit.

## Above 105MHz



Oscillator circuit design above 105MHz is difficult and we would suggest a grounded-base oscillator similar to the above circuit. Lo is fitted to tune out the crystal C0 which otherwise might cause spurious oscillation. Ideally, on-frequency operation should coincide with maximum output, for which L1 should be tuned. L1 can also provide a limited trimming range and is can be adjusted simultaneously with a trimmer in series with the crystal. The close tolerance crystal required, with various circuit phase shifts make it advisable to experiment with a sample crystal whose characteristics have been accurately measured beforehand. Any frequency offset that may be necessary can then be written into the crystal specification. In order to avoid parasitic oscillation, VHF circuit layout practice is essential. It is also important to make sure that the load reflected back into the transistor collector tank can have an extra capacitive tap to achieve this, keeping the total capacitance in the same order, or some 'real' resistance can be added in parallel with it.
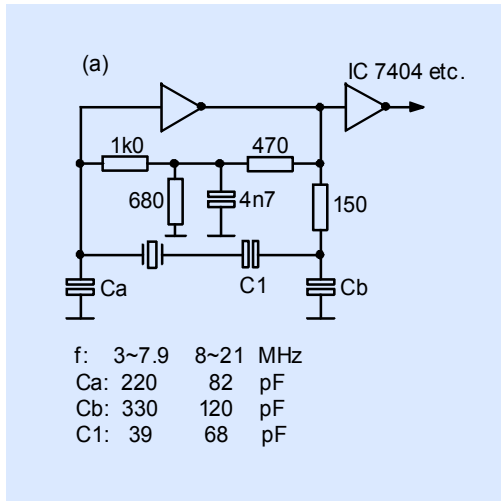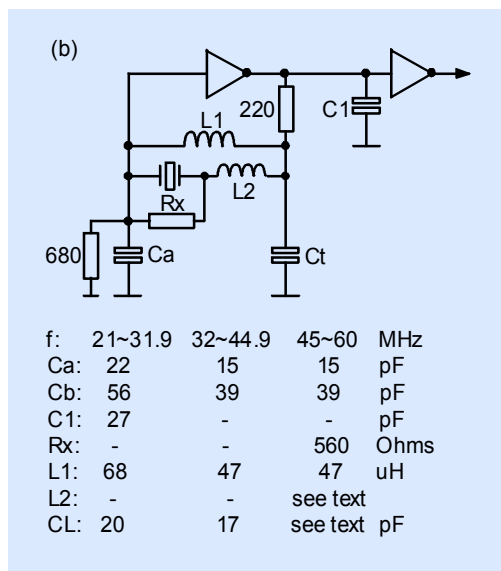
## TTL OSCILLATORS



This is a commonly used circuit employing TTL inverters or gates with AT-cut crystals. Due to the low cost of components this is a popular circuit, and there are invariably spare invertors on a PCB that can be pressed into service as a clock oscillator. However, getting this arrangement to work can sometimes be frustrating, as these devices were never intended to be used as linear amplifiers. Capacitor C2 (which can be a trimmer) is intended to cancel the effective series resistance of the invertors and not to act as a load capacitor for the crystal. At high frequencies, C2 may have to be too small a value in order to properly perform this function. Unfortunately, the lagging phase shift problem is aggravated by the presence of C3, which is necessary to prevent fast wave fronts from exciting the crystal third-overtone mode; this can be a nuisance below 8MHz. If third overtone operation is intended, instead of C1 being merely a coupling capacitor, it can be a low value in order to act as high-pass filter. Possibly better still, would be a series LC tank at this point.

For fundamental-mode crystals, select C3 so that the 3rd overtone is just suppressed, double it to be safe, and then select C2 to give on-frequency oscillation. There may be significant differences in the parameters of one IC to another, so it is best to try different brands and stick to the one that works best. One other word of caution, decouple the supply as close as possible to the IC with 10nF or so, and if possible use a different package for the output

## Logic Gate Circuit (a)



```
f:   3~7.9  8~21  MHz
Ca:  220    82    pF
Cb:  330    120   pF
C1:  39     68    pF
```

## Logic Gate Circuit (b)



```
f:   21~31.9  32~44.9  45~60    MHz
Ca:  22       15       15       pF
Cb:  56       39       39       pF
C1:  27       -        -        pF
Rx:  -        -        560      Ohms
L1:  68       47       47       uH
L2:  -        -        see text
CL:  20       17       see text pF
```
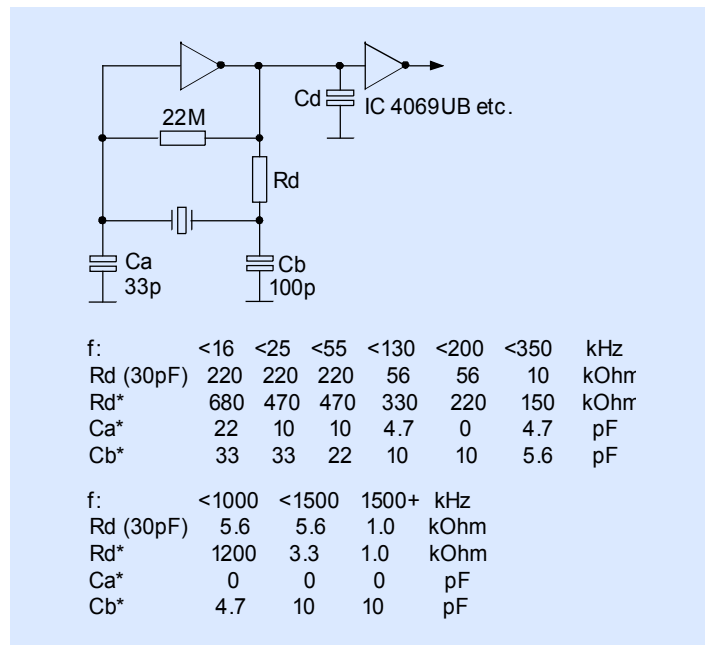
If you can tolerate a greater component count, the Pierce oscillators above will give a superior performance compared with the simple two-inverter oscillator. Their phase stability is better and the crystal drive level is more reasonable.

IIn circuit (a) above, C1 is provided just to put standard 30pF crystals onto frequency, it could be a trimmer for higher accuracy, or left out completely if accuracy is unimportant. In the overtone design of the circuit (b) above, L1 can be a small moulded choke and L2, required only for the highest frequency range, can be a few turns on a slugged former, adjusted to make the oscillator free run in the range 5% to 15% of the crystal frequency with the crystal shorted. Since the pullability of standard 3rd overtone crystals is quite small, standard series-calibrated crystals will give and acceptable degree of frequency precision for most applications. However, for the best accuracy, the load capacitances stated should be specified. In the highest frequency range, an offset of ±10ppm from series resonance is required. Once again, make sure that the supply to these oscillators is well bypassed.

## CMOS OSCILLATORS

### CMOS 'Pierce' Oscillator



| f: | <16 | <25 | <55 | <130 | <200 | <350 | kHz |
|---|---|---|---|---|---|---|---|
| Rd (30pF) | 220 | 220 | 220 | 56 | 56 | 10 | kOhm |
| Rd* | 680 | 470 | 470 | 330 | 220 | 150 | kOhm |
| Ca* | 22 | 10 | 10 | 4.7 | 0 | 4.7 | pF |
| Cb* | 33 | 33 | 22 | 10 | 10 | 5.6 | pF |

| f: | <1000 | <1500 | 1500+ | kHz |
|---|---|---|---|---|
| Rd (30pF) | 5.6 | 5.6 | 1.0 | kOhm |
| Rd* | 1200 | 3.3 | 1.0 | kOhm |
| Ca* | 0 | 0 | 0 | pF |
| Cb* | 4.7 | 10 | 10 | pF |

This is a typical Pierce circuit used for both conventional 30pF and miniature crystals. Only unbuffered invertors or gates should be used. The values given for Ca and Cb are for use with 30pF crystals; Cd need on be included if there is a tendency to oscillate at a higher frequency crystal mode. The value of the DC feedback resistor may seem high, but it is necessary at low frequencies in order to reduce its degenerative effect. Above 200kHz it can be reduced to 10M. Ca or Cb may be wholly or partly a trimmer to allow frequency adjustment. (However, the frequency trimming range will be small.)

## Crystal Series Resonant Frequency

$$f_R = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

## Parallel or Anti-Resonant Frequency

$$f_A = \frac{1}{2\pi\sqrt{L_1 \dfrac{C_1 C_0}{C_1 + C_0}}}$$

### Separation

$$f_A - f_R = \frac{f_R C_1}{2 C_0}$$

## Load Resonant Frequency

$$f_L = \frac{1}{2\pi\sqrt{L_1 \dfrac{C_1 C_T}{C_1 + C_T}}}$$

## Trimming Range

$$\Delta f_L = \frac{f_{L1} C_1 (C_{T1} - C_{T2})}{(C_0 + C_{T1})\,(C_0 + C_{T2})}$$

## Equivalent Parallel Resistance (EPR) at $f_L$

$$EPR = \frac{1}{\omega^2 C_T^2 R_1}$$

## Equivalent Series Resistance (ESR) at $f_L$

$$ESR = R_1 \left[ 1 + \frac{C_0}{C_L} \right]^2$$

## Quality Factor (of the crystal alone)

$$Q = \frac{\omega_R L_1}{R_1} = \frac{1}{\omega_R C_1 R_1} = \frac{\omega_L L_e}{ESR}$$

## Crystal Dissipation

### At Series Resonance

$$P_X = \frac{V_X^2}{R_1} = I_X^2 \times R_1$$

### With a Parallel Load Capacitor

$$P_X = \frac{V_X^2}{EPR}$$

### With a Series Load Capacitor

$$P_X = I_X^2 \times ESR$$

### In a Pierce or Colpitts Oscillator

$$P_X = V^2 \omega^2 Cb^2 . ESR$$

Where V is the RMS value of the AC component of the voltage across Cb. When used with miniature crystals the following formula will be useful:

$$P_X = ESR \left[ \frac{0.45 V_{DD}.\omega\, Cb}{1 = Cb^2\, Rd^2 ESR} \right]$$

## Further Reading

Possibly out of print now but if you can track down a copy these publications are informative:

Frerking, M. E.,
'Crystal Oscillator Design and Temperature Compensation'
Van Nostrand Reinhold

Parzen, B.,
'Design of Crystal and other Harmonic Oscillators'
John Wiley & Sons

Bottom, V. E.,
'Introduction to Quartz Crystal Unit Design'
Van Nostrand Reinhold

Heising, R. A.,
'Quartz Crystal for Electrical Circuits'
E1A, 2001 Eye Street, Washington DC, 20006