10

The Semi-isolated Colpitts Oscillator

10.1 INTRODUCTION

By the semi-isolated Colpitts oscillator is meant the oscillator whose circuit is shown in Fig. 10.1. All the components shown in the circuit are physical; that is, they are all installed components.

The theory of the oscillator is extensively covered in Chapter 5. Some additional theory is presented in Chapters 7 and 9, and also in this chapter.

This chapter develops the additional and/or modified relations of Chapters 5, 7, and 9. It also contains comments about the practical aspects of the design. Finally, it formulates a design algorithm for *be* cutoff limiting. The algorithm is specifically applicable to the self-limiting crystal oscillator, but it is also useful for non-self-limiting types and other types of resonators.

10.2 OSCILLATOR CIRCUIT ANALYSIS

10.2.1 General Oscillator Description

This oscillator is a variation of the normal Colpitts oscillator discussed in Chapter 9. It has several important properties:

1. It is capable of large values of P_L/P_3.
2. The output frequency can be the same as the frequency of oscillation, f, or a harmonic, Mf.

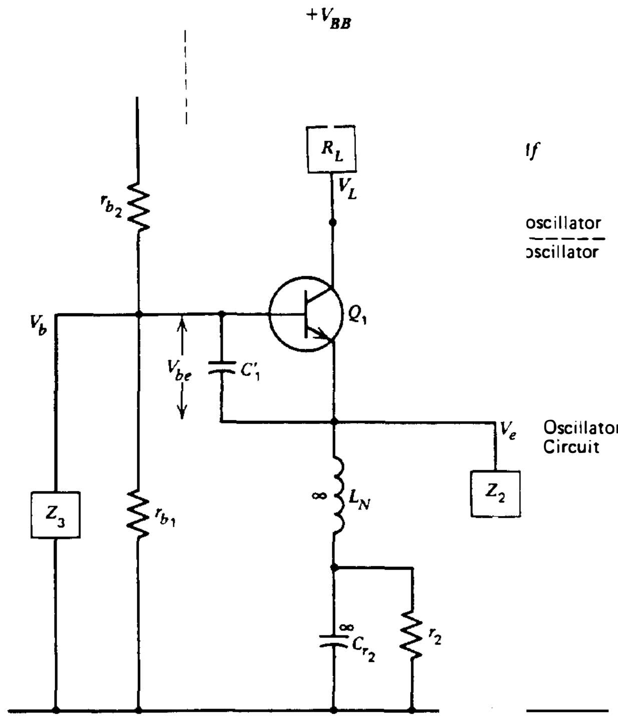


Figure 10.1 Semi-isolated Colpitts oscillator.

3 Moderate isolation is provided at the fundamental output frequency, which is the reason why it is called *semi-isolated*. At the harmonic output frequencies it provides excellent isolation.
4 The output power is relatively independent of the values of R_3, which is very important in crystal oscillators, where considerable variation in R_3 is normal.
5 Production units tend to be very much alike.

It will be seen from the above that the properties are very desirable. It is, however, rather difficult to design, but it is well worth the effort.

Because of property 1, the circuit is particularly useful when substantial power output at low crystal power dissipation is required.

10.2.2 Discussion of Fig. 10.1

If one compares Fig. 10.1 to Fig. 5.8, one is struck with the similarity. The only major difference is the location of the power output point. One would therefore expect the theory to be similar, which it is. Another point worth noting is that at harmonic power output the fundamental voltage at point c is close to zero, so that the two circuits below point c are identical and can be analyzed identically. However, when the output is at the fundamental frequency the two circuits differ in Miller effects, which seriously deteriorate the isolation in the circuit of Fig. 10.1. This aspect is discussed later.

10.2.3 Isolation Characteristics

One of the important assumptions, which is fairly realistic, made in this book is that the currents and voltages at the different harmonic frequencies do not interact. As a result of the assumption, it follows that the isolation at harmonic output frequencies is excellent since the oscillator operates at the fundamental frequency. However, the isolation for fundamental output frequency is much worse, primarily because of Miller effects, which are very serious for high ratios of P_L/P_x because of the high values of V_L/V_b and V_b/V_e.

10.2.4 The Miller Effects

Figure 10.2*a* shows the various ac voltages existing at each electrode to ground and the capacitances between the electrodes. It should be noted that V_{L_1} is the fundamental component of V_L.

In Fig. 10.2*b*, C_{ce} has been replaced by C_{cem}. In Fig. 10.2*c*, C_{cb} has been replaced by C_M. In Fig. 10.2*d*, C_M in turn is replaced by C_{1M} and C_{2M}.

The method of performing these replacements is similar to that described in Section 5.5.4.2.5. The results are the following:

$$C_{cem} \approx M_{ce}C_{ce} \tag{10.1}$$

where

$$M_{ce} \approx 1 + \frac{V_{L_1}}{V_e} \tag{10.2}$$

$$C_M \approx M_{cb}C_{cb} \tag{10.3}$$

where

$$M_{cb} \approx 1 + \frac{V_{L_1}}{V_b} \tag{10.4}$$

$$C_{1M} \approx \left(1 + \frac{1}{M_M}\right)C_M \tag{10.5}$$

where

$$M_M \approx \frac{V_{be}}{V_e} \tag{10.6}$$

$$C_{2M} \approx (1 + M_M)C_M \tag{10.7}$$

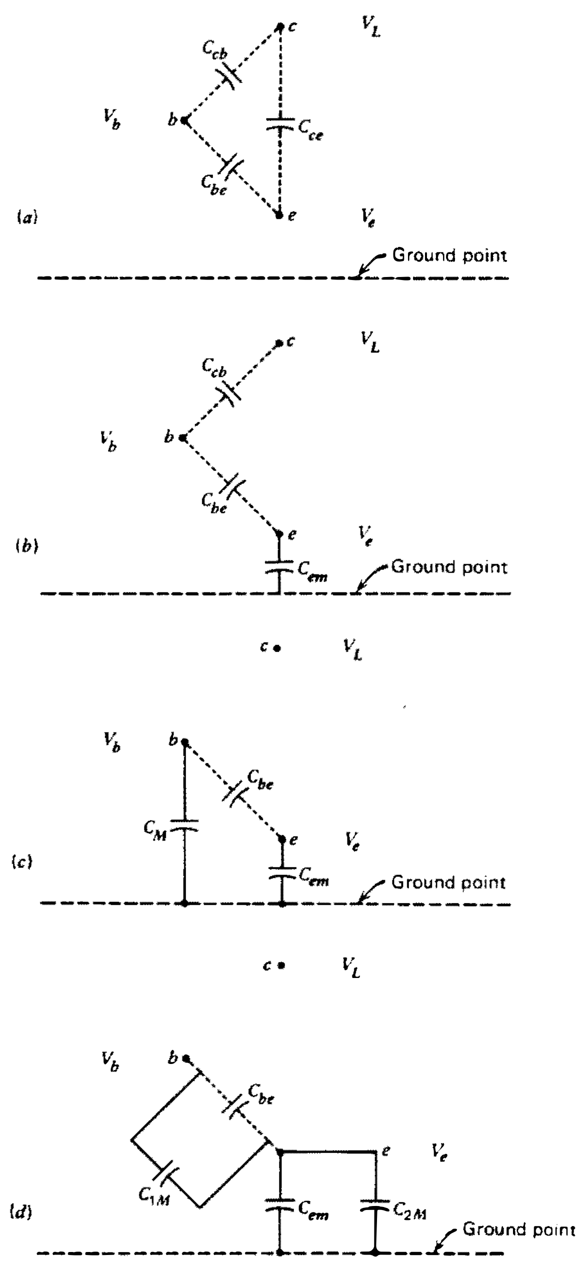


Figure 10.2 Miller effects. (a) Schematic circuit for Miller effects. (b) Replacement of C_{ce} by C_{em}. (c) Replacement of C_{be} by C_M. (d) Apportionment of C_M.

It should be noted that the above relationships are only approximate and do not take into account the Miller resistance contributions as pointed out in Section 5.5.4.2.5.

In practice, when M_{cb} is very large which, in general, is true when P_L/P_3 is very large, the Miller contributions are very important. This is particularly true when R_L is a tuned load. If R_L is changed by the environment or during the tuning procedure, large frequency shifts and amplitude variations may result and the oscillation may even be killed by the resistance contributions. Therefore, for fundamental output circuits it is necessary that M_{cb} be made very small. This results in the output being very small or the conversion efficiency being very poor. Fundamental output is not recommended for this circuit except when R_L consists of a low-value resistor.

10.2.5 Limiting

Section 6.2.2 indicates that *be* cutoff limiting is the preferred type of limiting except where the output power is a function of the resonator resistance and the application demands constancy of power output versus the resonator resistance. However, in this circuit, the power output does not depend upon the crystal resistance. Therefore *be* cutoff limiting is used.

Section 2.4 presents the theory of this type of limiting and the results are summarized in Figs. 2.12 and 2.13. Since it is very difficult to use curves in computer-aided design procedures, equations for the applicable parts of these curves will now be derived.

It is very desirable to operate in the saturated region of the γ_M curves. Therefore, α should decrease as M increases. A suitable relationship is

$$\alpha = \frac{0.3}{M} \tag{10.8}$$

From Figs. 2.12 and 2.13, it then follows that

$$\gamma_M = 1.6 - 0.2M \tag{10.9}$$

and as a special case

$$\gamma_1 = 1.4 \tag{10.9a}$$

From Eqs. (2.79) and (10.8)

$$V_{be} = 120M = \frac{36}{\alpha} \tag{10.10}$$

10.2.6 Discussion of $V_{L_{max}}$ and V_E

Since V_L is only a weak function of R_3, Eq. (9.6) can be modified to

$$V_L = 0.27BV_{CE} \tag{10.11}$$

The suitable relationship for V_E is

$$V_E = V_{BB} - 1.7V_L - 1700 \tag{10.11a}$$

The factor 1.7 is used instead of 1.4 to account for the RF voltage in the oscillator circuit.

When the calculated $V_E > V_{BB}/2$,

$$V_E = \frac{V_{BB}}{2} \tag{10.11b}$$

which is derived in the same manner as that described in Section 7.2.4.3.2.

10.2.7 Calculation of R_L

The discussion of Section 7.2.4.4 applies. However, Eq. (1.16) must be modified to

$$R_L \leqq \frac{10{,}000}{\sqrt{Mf}} \tag{10.12}$$

as the load is tuned to the harmonic of the oscillator frequency f.

Similarly, Eq. (7.30) becomes

$$V_L = \sqrt{\frac{10^7 P_L}{\sqrt{Mf}}} \tag{10.13}$$

When the output frequency is f, then $R_L \equiv R_{L_1}$, which means that it is tuned to f. However, when the output frequency is Mf, then R_L is tuned to Mf and R_{L_1} is very small and is considered to be zero, so that
for $M \neq 1$,

$$R_{L_1} = 0 \tag{10.14}$$

for $M = 1$,

$$R_{L_1} = R_L \tag{10.15}$$

Equations (10.14) and (10.15) are important for determining the Miller effects.

10.2.8 The Calculation of r_{2ac}

When Z_2 in Fig. 10.1 is a capacitor, L_N and C_{r_2} become unnecessary, and r_2 now has an ac component, r_{2ac}. Of course, r_{2ac} then contributes an ac circuit loss which must be included in the calculations. This situation exists in crystal oscillators when the crystal is operating at its fundamental overtone, in which case $N = 1$. Therefore,
for $N = 1$

$$r_{2ac} = r_2 \tag{10.16}$$

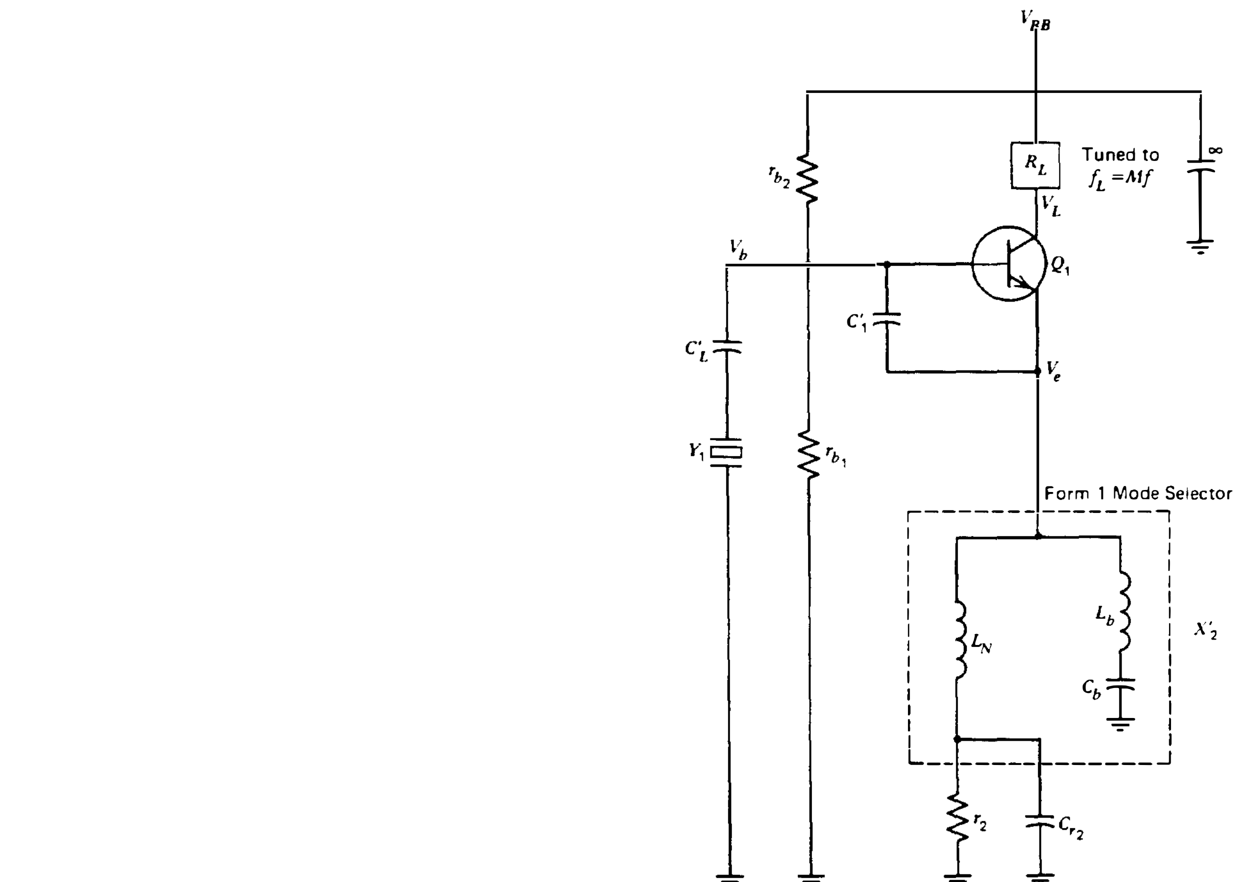


Figure 10.3 Semi-isolated Colpitts oscillator for SC-cut crystals with form 1 mode selector. *Note*: For $N = 1$, $L_N = C_{r_2} = 0$.

for $N \neq 1$

$$r_{2ac} \rightarrow \infty \tag{10.17}$$

since r_2 is then isolated by C_{r_2} and L_N.

10.2.9 Overtone and Mode Selection

Figures 10.3 and 10.4 show the oscillator configured for using the SC-cut crystal with either the form 1 or form 2 mode selector. (See Section 5.6.5.4.)

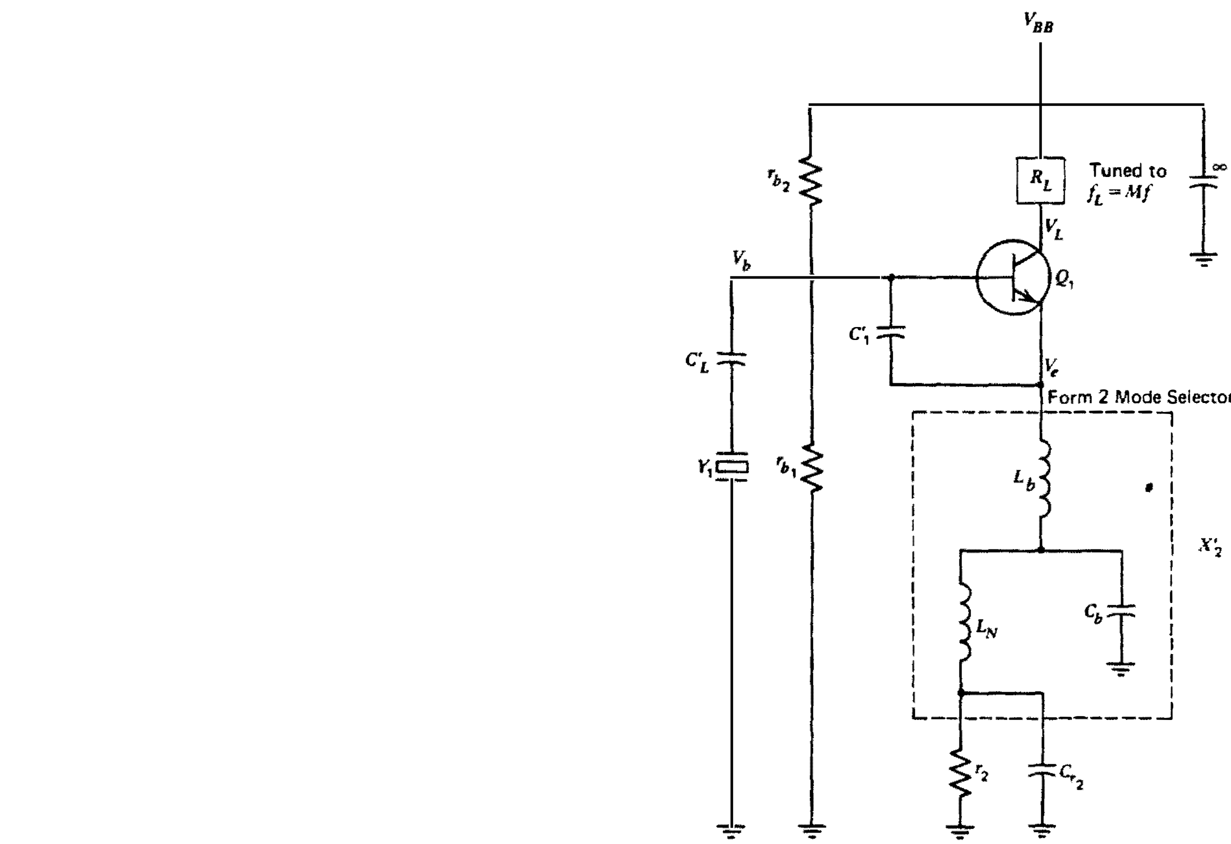


Figure 10.4 Semi-isolated Colpitts oscillator for SC-cut crystals with form 2 mode selector.

10.3 FREQUENCY VARIATIONS DUE TO EXTERNAL FACTORS

The material in Section 7.3 is applicable except that, as pointed out in Section 10.2.3, the effect of changes in external load is much less, especially for harmonic output circuits.

10.4 THE DESIGN PROCEDURE

The design procedure is very straightforward and is principally determined by the output power, the harmonic number M, and the crystal characteristics. Again, the algorithms are prepared for crystal resonators, but other types of resonators may also be used with slight modifications of the algorithms. The algorithms are prepared for all crystal cuts and include both forms of SC mode selectors, as shown in Figs. 10.3 and 10.4. In this connection, it should be noted that this oscillator circuit is normally used for low crystal drive applications where C_1' is very small and mode selection in the base emitter circuit therefore becomes impractical.

10.5 THE DESIGN ALGORITHM AND DESIGN EXAMPLES

10.5.1 The Design Algorithm (Algorithm 12.6)

The user has to supply the information requested in Sections a, b, c, and d. It will be noted that Items c7, c9, c10, and c11 are not in the algorithm, but checks should be made after the design to make sure that these values are not exceeded.

The comments in Section 7.5.1 about replacement of the crystal networks by other types of networks and about replacing the calculated value of R_L by another R_L apply equally well here.

10.5.2 Design Examples 10.1 to 10.6

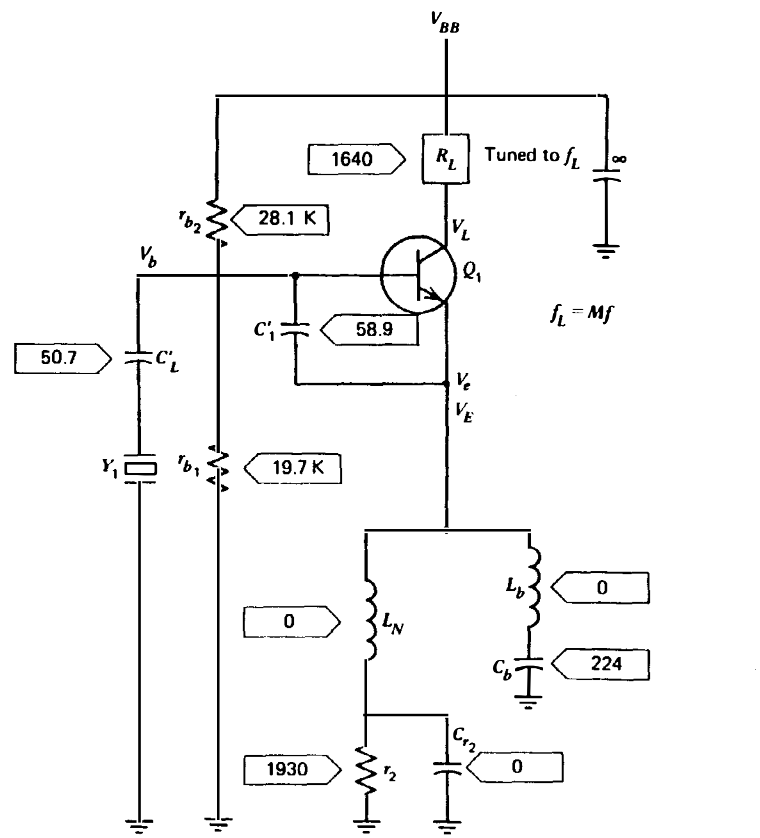
There are six design examples; three for $M = 1$ and three for $M = 2$.

For $M = 1$, R_L is fixed by the BV_{CE} of the transistor in accordance with Eq. (10.10). For $M = 2$, R_L is fixed by the maximum realizable load in accordance with Eq. (10.12).

$(P_L/P_x)_{\max}$ is fixed by the maximum realizable load in accordance with Eq. (10.12).

All the design examples have the same P_L and P_x. P_L/P_x is very high, namely, 200.

A surprising result is the relatively high conversion efficiency of the circuits: 43% for $M = 1$ and 36% for $M = 2$. This, of course, is diminished by the losses

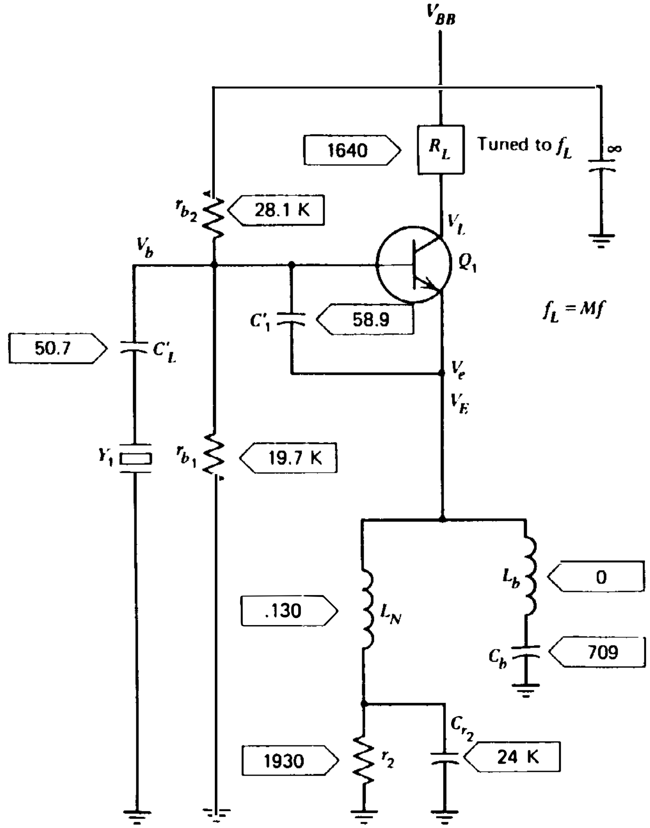


Design Example 10.1 Semi-isolated Colpitts oscillator. *Note*: For $N = 1$, $L_n = C_{r_2} = 0$.

All units in

℧ MHz Ω mW pF µH
mA, mV dc or rms

	Item	Value
Oscillator Performance	f	20
	P_L	10
	P_x	0.05
	V_{BB}	12,000
	M	1
Principal Crystal Data	R_{df}	20
	I_x	1.58
	Cut	AT
	N	1
	C_L	32
Transistor Data	β_o	30
	f_T	700
	BV_{CE}	15,000
	C_{cb}	1
	C_{bel}	2
	C_{ce}	2
	P_{dis}	
	Type	2N918
Circuit Parameters	α	0.3
	γ_1	1.4
	γ_m	
	V_{be}	120
Calculated Data	I_{BB}	2.04
	g_m	0.020
	V_E	3410

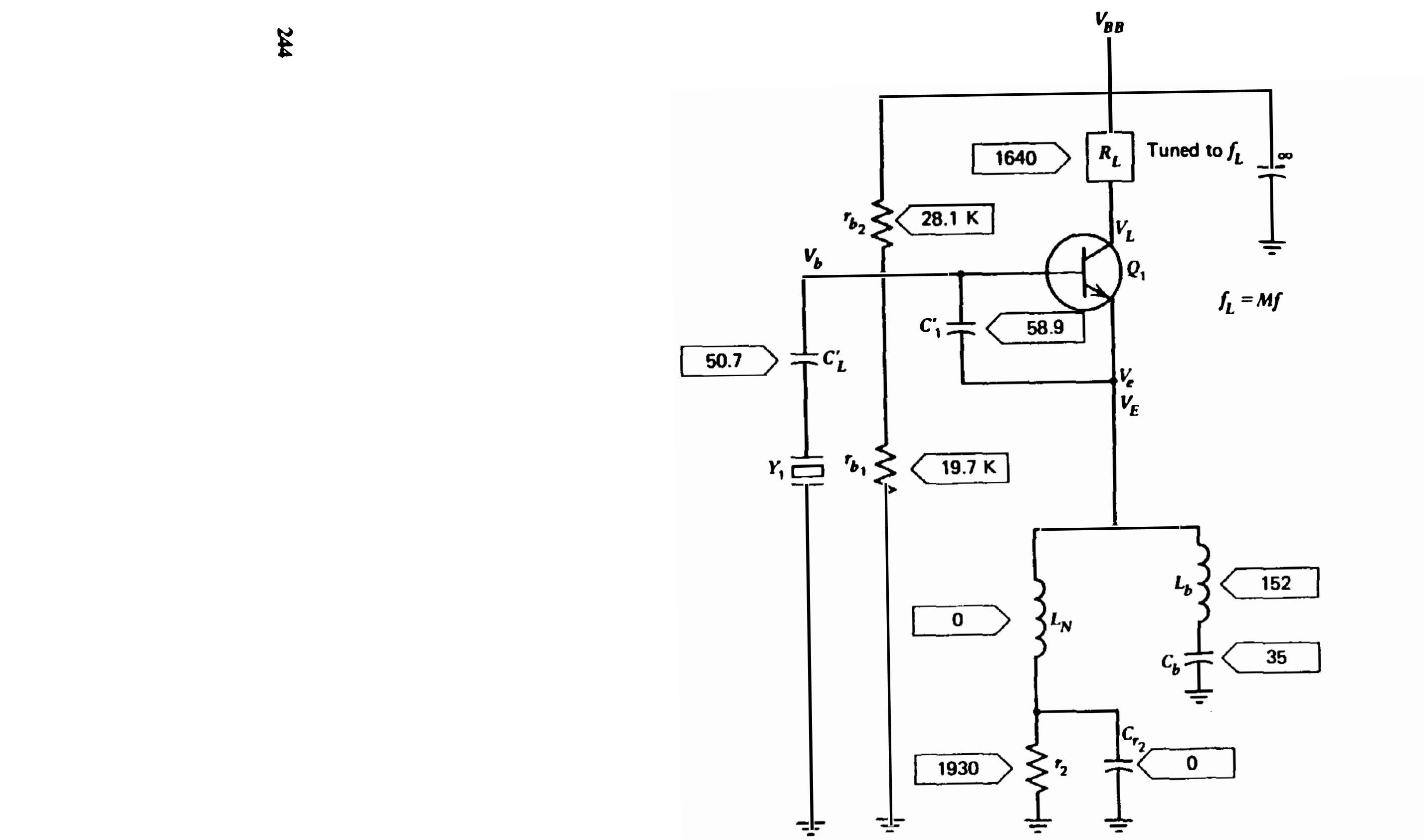


Design Example 10.2 Semi-isolated Colpitts oscillator. *Note*: For $N = 1$, $L_N = C_{r_2} = 0$.

All units in .

℧ MHz Ω mW pF μH
mA, mV dc or rms

	Item	Value
Oscillator Performance	f	20
	P_L	10
	P_x	0.05
	V_{BB}	12000
	M	1
Principal Crystal Data	R_{df}	20
	I_x	1.58
	Cut	AT
	N	5
	C_L	32
Transistor Data	β_o	30
	f_T	700
	BV_{CE}	15000
	C_{cb}	1
	C_{bet}	2
	C_{ce}	2
	P_{dis}	
	Type	2N918
Circuit Parameters	a	0.3
	γ_1	1.4
	γ_M	1.4
	V_{be}	120
Calculated Data	I_{BB}	2.04
	g_m	0.02
	V_E	3410

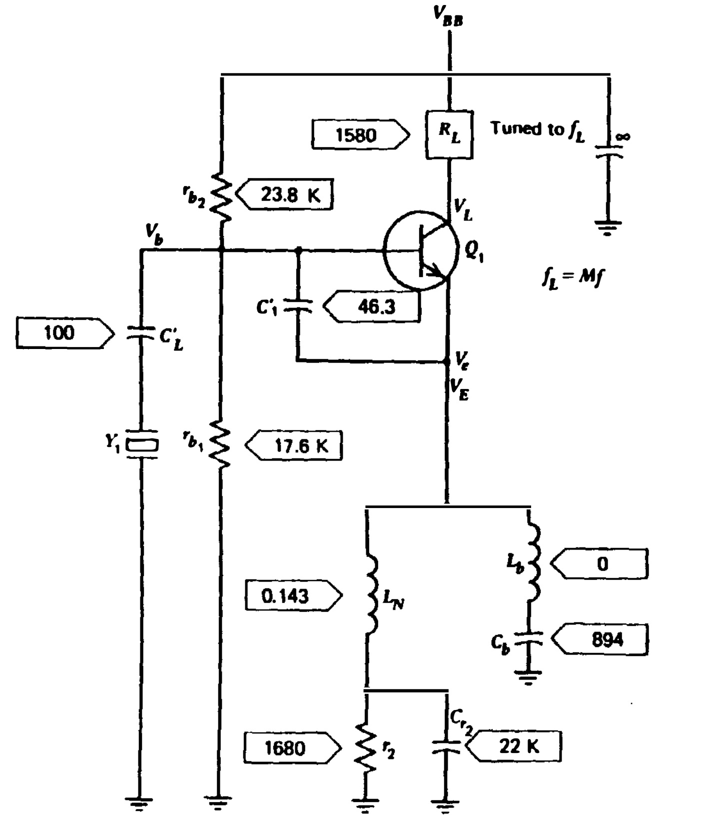


All units in

℧ MHz Ω mW pF μH
mA, mV dc or rms

	Item	Value
Oscillator Performance	f	20
	P_L	10
	P_x	0.05
	V_{BB}	12,000
	M	1
Principal Crystal Data	R_{df}	20
	I_x	1.58
	Cut	SC
	N	1
	C_L	32
Transistor Data	β_o	30
	f_T	700
	BV_{CE}	15000
	C_{cb}	1
	C_{bei}	2
	C_{ce}	2
	P_{dis}	
	Type	2N918
Circuit Parameters	α	0.3
	γ_1	1.4
	γ_M	1.4
	V_{be}	120
Calculated Data	I_{BB}	2.04
	g_m	0.0203
	V_E	3410

Design Example 10.3 Semi-isolated Colpitts oscillator. *Note*: For $N = 1$, $L_N = C_{r_2} = 0$.

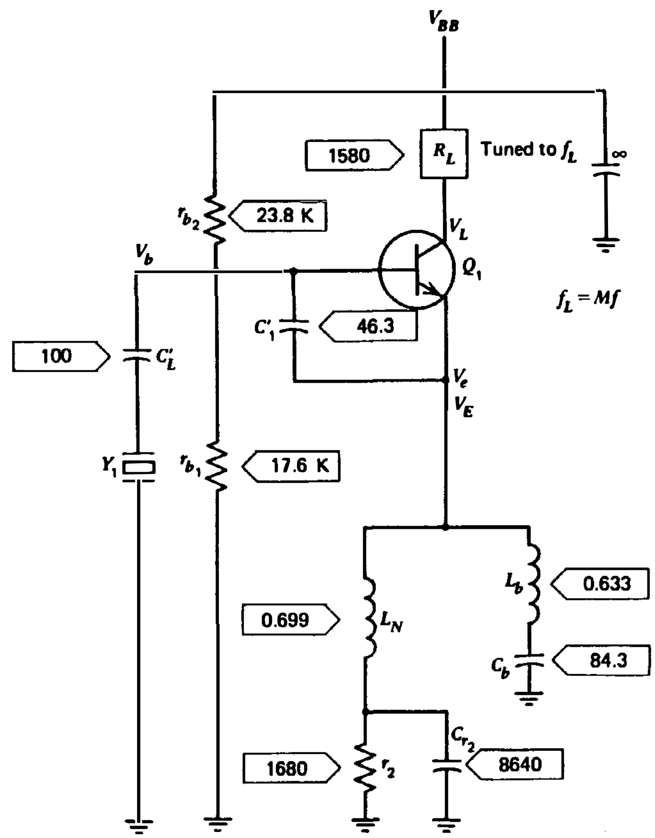


All units in

℧ MHz Ω mW pF μH
mA, mV dc or rms

	Item	Value
Oscillator Performance	f	20
	P_L P_x V_{BB}	10 0.05 12,000
	M	2
Principal Crystal Data	R_{df}	20
	I_x	1.58
	Cut	AT
	N	5
	C_L	32
Transistor Data	β_o	30
	f_T	700
	BV_{CE}	15,000
	C_{cb}	1
	C_{bei}	2
	C_{ce}	2
	P_{dis}	
	Type	2N918
Circuit Parameters	a	0.15
	γ_I	1.4
	γ_M	1.2
	V_{be}	240
Calculated Data	I_{BB}	2.42
	g_m	0.012
	V_E	3540

Design Example 10.4 Semi-isolated Colpitts oscillator. *Note*: For $N = 1$, $L_N = C_{r_2} = 0$.

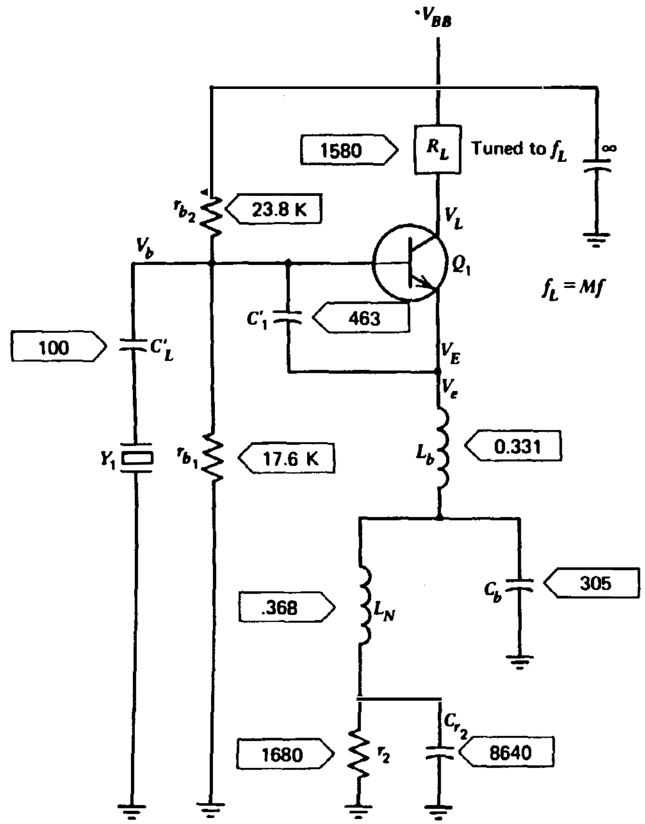


Design Example 10.5 Semi-isolated Colpitts oscillator. *Note*: For $N = 1$, $L_N = C_{r_2} = 0$.

All units in

℧ MHz Ω mW pF μH
mA, mV dc or rms

	Item	Value
Oscillator Performance	f	20
	P_L	10
	P_x	0.05
	V_{BB}	12,000
	M	2
Principal Crystal Data	R_{df}	20
	I_x	1.58
	Cut	SC
	N	5
	C_L	32
Transistor Data	β_o	30
	f_T	700
	BV_{CE}	15,000
	C_{cb}	1
	C_{bet}	2
	C_{ce}	2
	P_{dis}	
	Type	2N918
Circuit Parameters	α	0.15
	γ_1	1.4
	γ_M	1.2
	V_{be}	240
Calculated Data	I_{BB}	2
	g_m	0.012
	V_E	3540



Design Example 10.6 Semi-isolated Colpitts oscillator.

All units in

℧ MHz Ω mW pF μH
mA, mV dc or rms

	Item	Value
Oscillator Performance	f	20
	P_L	10
	P_x	0.05
	V_{BB}	12,000
	M	2
Principal Crystal Data	R_{df}	20
	I_x	1.58
	Cut	SC
	N	5
	C_L	32
Transistor Data	β_o	30
	f_T	700
	BV_{CE}	15,000
	C_{cb}	1
	C_{bet}	2
	C_{ce}	2
	P_{dis}	
	Type	2N918
Circuit Parameters	α	0.15
	γ_1	1.4
	γ_M	1.2
	V_{be}	240
Calculated Data	I_{BB}	2.42
	g_m	0.012
	V_E	3540

in the various circuit elements, except the load, transistor, and the crystal. The distortion of the output signal is a function of the Q of the load circuit, R_L.

Because of the high value of P_L/P_x, the Miller effects in the $M = 1$ circuits are very large, and considerable difficulty will be encountered in tuning R_L. For example, in Design Example 10.1, C_1' is 59 pF, while the Miller effects provide an additional 45 pF. Similarly C_2' is 709 pF, and the Miller effects provide an additional 289 pF. These examples are, of course, deliberately made to be extreme to show the importance of the Miller effects. It is recommended that, if M must be 1, P_L/P_x be made as small as possible.

For $M = 2$, the total contribution of the Miller effect and the transistor transition and diffusion capacitances is only 6 pF to C_1', which is 46 pF. The similar contribution to C_2, which is effectively 460 pF, is only 8 pF, so that for all practical purposes C_2 may be considered equal to C_2'.

Design Example 10.3 is the same as Design Example 10.1 except for the crystal cut. The emitter circuits are modified accordingly.

Design Example 10.2 is the same as Design Example 10.1 except for the crystal overtone. This also requires modification in the emitter circuitry.

Design Example 10.4 is the same as Design Example 10.2 except for M. The circuits are similar except for the tuning of R_L and the values of the components.

Design Examples 10.5 and 10.6 are identical except for the form of the mode selector circuit, which is necessary because of the SC-cut crystal. In this case both forms 1 and 2 are realizable, but there are many cases where one form is much more realizable than the other, and the choice becomes self-evident.

The values of g_m are given on the design examples to check the adequacy of β_o and f_T in accordance with Steps c2 and c3 of the algorithm.

10.5.3 Trimming for Algorithm 12.6

See Algorithm Figures 12.6.1 and 12.6.2.

10.5.3.1 Introduction

See Section 7.5.3.1.

10.5.3.2 Basis of the Trimming Procedure

The trimming is based upon the following relations:

1. $$I_e \approx 1.4 I_E$$
2. α decreases as X_1 increases.
3. γ_M increases slightly as α decreases ($M \neq 1$).
4. $$I_{e_M} = \gamma_M I_E$$
5. $$V_L = I_{e_M} R_L$$

6 $$1000P_L = \frac{V_L^2}{R_L} \approx \frac{I_{e_M}^2 R_L}{1000}$$

7 $$I_3 \approx I_{e_1}\frac{(X_2)}{R_T}$$

8 $$V_{be} \approx I_3 X_1$$

9 Section 7.5.3.2, item 5 is applicable here.

Note: For a crystal resonator $I_3 = I_x$.

10.5.3.3 Typical Trimming Steps

The following describes the action required to increase a given characteristic. Obviously, the opposite action decreases the same characteristic.

10.5.3.3.1 Output Power P_L

Item 6 states that increasing I_{e_M} and/or R_L will increase the power. I_{e_M}, in turn, can be increased by increasing I_E and/or γ_M as stated in item 4. I_E is increased by adjusting the bias circuit. γ_M is increased by increasing X_1 but when γ_M reaches 1.2 it has almost reached saturation, and further efforts will result in little improvement.

For $M = 1$ great caution should be exercised in increasing R_L because that will increase frequency instability.

10.5.3.3.2 Current I_3

Item 7 states that I_3 increases as I_{e_1} and/or X_2 are increased. Increasing X_2 is accomplished as described in Sections 5.6.4 and 5.6.5. I_{e_1} is increased by increasing I_E which will also increase P_L.

It is interesting to note that changing X_1 will have little effect upon I_3.

Item 7 also states I_3 increases as R_{df} decreases so that if a new crystal with lower R_{df} is used, the current increases.