AN-178A
Technical Information Note

EPICAP TUNING DIODE THEORY AND APPLICATION

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This report gives the basic theory for the Epicap tuning diode. General considerations for electric tuning are discussed in which the important parameters such as Q, tuning range and temperature stability are introduced. The equivalent circuit of PN junctions used for Epicap voltage variable capacitors is developed from a physical description of the junction and associated package. Equations describing the electrical characteristics of these PN junctions versus voltage and frequency are given.

The Motorola Epicap series is introduced, Epicaps with 4 volt capacities from 6.8 to 47 pf and 60 volt breakdowns are now available. The Epicaps are superior to competitive devices with regard to Q, leakage current, and temperature stability.

A brief section is included on application of Epicaps as a prelude to circuit application reports now being prepared.

MOTOROLA Semiconductor Products Inc.

EPICAP TUNING DIODE THEORY AND APPLICATION

INTRODUCTION

Epicaps are voltage-variable capacitors, based on semiconductor junction phenomena, which can be used for electric tuning applications. This note is intended to explain how Epicaps function, summarize the parameters of available Epicaps, and introduce important application possibilities.

It is felt that these Epicaps will become important circuit components because electric tuning offers many advantages over mechanical tuning. Electrically and electronically tuned circuits are small, reliable and extremely fast acting. However, electric tuning in the HF, UHF and VHF regions had not been extensively applied because the quality factors of the available tuning elements were poor, such as 100 at 50 mc. This situation is changed with the introduction of the Epicap tuning diode series where Q's exceed 200 at 50 mc. Further with Epicaps many of the important electric tuning parameters, such as temperature stability and leakage current are improved.

Generally for electric tuning it is desired to vary capacitance or inductance as a function of voltage or current. For HF through UHF frequencies the most practical electric means is to vary capacitance with voltage. The rate of change of capacity with voltage is, of course, of fundamental importance, the greatest rate being most desirable. Except for experimental hyper-abrupt semiconductor junctions the best devices approach a capacity varying inversely with the square root of applied voltage. This is discussed further in the section on how Epicaps work.

The most significant parameter in using tunable capacitors is Q or quality factor. For a capacitor with series resistance.

$$Q_S = \frac{1}{\omega C R_S} \qquad (1)$$

where

Q is the quality factor

ω is the frequency in radians/sec

C is the capacitance in farads

R_S is the series resistance in ohms

When the resistance is in parallel with the capacitance

$$Q_P = \omega C R_P \qquad (2)$$

where

R_P is the parallel resistance.

If both series and parallel resistances are present the following is a simple formula for Q

$$\frac{1}{Q} = \frac{1}{Q_S} + \frac{1}{Q_P} \qquad (3)$$

where Q_S and Q_P are calculated by equations 1 and 2 respectively. For most circuit applications loaded circuit Q's exceeding 20 and often 100 or more are needed. Therefore, the low unloaded Q's of previously available voltage-variable capacitors limited their use.

Tuning range is another important parameter. With voltage-variable devices, this means how great a capacitance swing can be achieved while maintaining acceptable capacitor characteristics. For PN junctions, the usual allowable voltage swing is from a few volts negative to the maximum reverse working voltage. Capacity swing is calculated from voltage swing by the inverse half-power relation between capacity and voltage. For large tuning ratios the maximum to minimum voltage ratio should obviously be large.

For most applications the temperature stability of all the capacitor parameters are important. Epicap stability does not equal the stability of the best air capacitors, but a high level of parameter stability has to be maintained either by the device itself or with some sort of compensating mechanism. An example of the deficiency of previously available devices is the relatively high leakage currents occurring at elevated temperatures.

Not to be neglected when considering devices for electric tuning is the package for the voltage-variable capacitor. Package parasites such as lead inductance or case capacity could alter the device impedance beyond use. Especially for higher frequencies previously available packages exhibited too high an inductance which degraded circuit performance.

Both the previously available devices and Epicaps are based on PN junction theory. The difference stems from the way the junctions are formed; allowing for the previous devices and diffusion into epitaxially grown layers for the Epicaps. Before explicit performance parameters and comparisons are made, the physics of both types of devices will be briefly described.

HOW EPICAPS WORK

Epicaps are voltage-variable capacitors based on PN junction theory. Conventionally speaking, when we refer to a semiconductor diode we normally visualize a 2-

terminal p-n junction operated in the forward conduction region (as a rectifier) or in the reverse avalanche region (as a zener diode). From this standpoint, the word diode applied to a Epicap is actually a misnomer – for while the Epicap is indeed a 2-terminal PN junction, it operates neither as a rectifier, nor as an avalanche device. Rather, it operates principally in the region between forward conduction and reverse breakdown – the very region in which a conventional diode is considered to be cut off.

In this operating region the PN junction can be represented by a capacitor in series with a resistor,

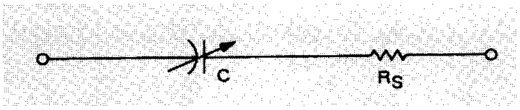


FIGURE 1

The capacitance, known as junction capacitance, is inherently associated with all PN junctions and, while it represents an undesirable parasitic in conventional diode operation, it is the specific mechanism that permits the device to function as an Epicap, or voltage-variable capacitor (VVC). This is true because the capacitance value, as will be seen later, actually varies as a function of applied voltage. This factor cannot only be used for electric tuning but also for harmonic generation and parametric amplification.

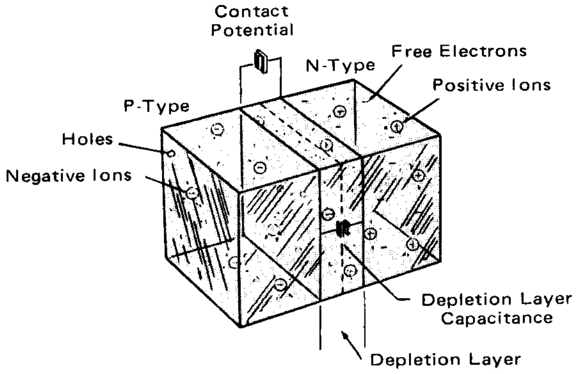
The resistor is the result of bulk and contact resistance of the semiconductor material. In Epicap operation this resistance is the primary parasitic affecting Epicap quality. Great pains are taken in Epicap design, therefore, to hold this resistance value to an absolute minimum.

The cause and behavior of the junction capacitance can be determined from basic semiconductor theory, as follows:

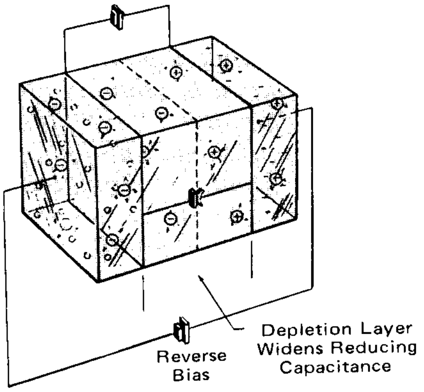
When a junction is formed between n-type and p-type material, there is a cross-migration of charges across the junction. Electrons from the n-region cross the junction to neutralize positive carriers near the junction in the p-region, and "holes" from the p-region cross the junction to neutralize the "excess" electrons near the junction in the n-region. As a result of this migration, all free charged particles are swept out of the immediate vicinity of the junction area. And, in the process, a contact potential or space charge (about 0.5 V for silicon) appears across the junction, Fig. 2a.

This structure acts very much like a slightly charged capacitor, with the depletion layer representing the dielectric and the semiconductor material adjacent to the depletion layer representing the two conductive plates.

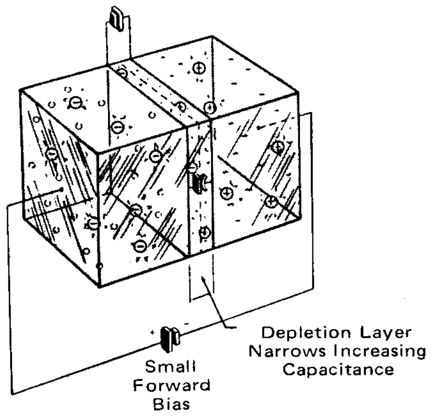
If an external voltage is connected across the p-n junction so as to reinforce the contact potential (reverse bias), the depletion layer increases, resulting in a capacitance decrease, Fig. 2b. If a forward voltage is applied, the depletion layer decreases, Fig. 2c. However, if the external forward voltage is made large enough to overcome the contact potential, forward conduction occurs and the capacitance effect is destroyed.



(a) A representative P-N junction. The battery represents the contact potential which must be overcome before current can flow. Current carriers act as a capacitor plates and the depletion layer is the dielectric.



(b) Reverse voltage forces carriers away from junction. This widens the depletion layer and reduces capacitance.



(c) Forward voltage forces carriers closer to junction or across junction again changing capacitance.

FIGURE 2

It is obvious, therefore, that the value of the junction capacitance is a function of the externally applied voltage, so long as the junction itself remains reverse biased. This relationship is:

$$C = \frac{C_o}{(1 + V/\Phi)^\gamma} + \frac{\Phi^\gamma C_o}{(\Phi + V)^\gamma} \tag{4}$$

where:

C = capacitance at voltage V

C_o = capacitance at zero bias

V = voltage across the diode (reverse bias)

Φ = contact potential

γ = power law of the junction, determined by impurity gradient.

The exponent is a function of the impurity gradient of the PN junction. It may vary from approximately 1/2, for step junctions, to about 1/6 for specially graded junctions. For electric tuning the greatest capacity-voltage variation is desired so the step junction is generally used.

All PN junctions have to be protected from the corrosive effects of the atmosphere; therefore, packages or housings are used. Associated with the package and the internal connections to the junctions are parasitic reactances. The complete equivalent circuit of a packaged PN junction operated in the reverse voltage region for electric tuning, is shown in Fig. 3. The voltage-variable capacitance is C_J; R_s is the series resistance; R_p is the junction shunt resistance which generally can be neglected; L_s is the lead inductance and C_c is the case capacitance.

The admittance of an Epicap including all parameters of Fig. 3 is:

$$y = j\omega C_c + \frac{1}{R_s + j\omega L_s + \frac{1}{\frac{1}{R_p} + j\omega C_J}} \tag{5}$$

where

R_p is high enough to be neglected

$$y = j\omega C_c + \frac{j\omega C_J}{1 - \omega^2 L_s C_J + j\omega C_J R_s} \tag{6}$$

Inherent junction Q is defined as:

$$Q = \frac{1}{\omega C_J R_s} \tag{7}$$

If Q is high compared to $1-\omega^2 L_s C_J$ the Epicap has a capacitance given by

$$C_{eq} = C_c + \frac{C_J}{1 - \omega^2 L_s C_J} \tag{8}$$

Equation 8 shows how equivalent capacity can be modified by L_s and C_c.

Usually operation is well below the self-resonant frequency $\omega_o = 1/L_s C_J$ so that the total capacity is given by

$$C_{eq} \approx C_c + C_J \tag{9}$$

and in terms of voltage

$$C_{eq} \approx C_c + \frac{C_o}{\left(1 + \frac{V_R}{\Phi}\right)^\gamma} \tag{10}$$

where:

$\gamma = 0.5$ for step junction

$\Phi = 0.5$ volts

The total Q is then

$$Q = \frac{1}{\omega C_t R_s} \tag{11}$$

The important device information is given by eqs. (10) and (11) with eq. (8) being significant at frequencies approaching self-resonance.

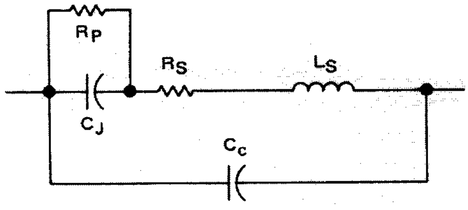


FIGURE 3 – Equivalent Circuit Epicap

APPLICATION OF EPICAPS

Epicaps can be applied to almost every part of the receiver circuit and many parts of the transmitter circuit. Some places these devices can be used are rf preselectors, rf filters, rf phase shifters, rf amplifiers, local oscillator tuning, automatic frequency control, if amplifiers, video filters and delay lines, fm modulators, and harmonic power generators. With Epicaps these circuits can be rapidly and accurately tuned either individually or concurrently. Of particular interest is that these tuning functions can be controlled from remote location. Usable frequencies are from audio to 2000 mc.

The introduction of the Epicaps series permits voltage tuning in relatively sensitive circuits. For example, low insertion loss filters requiring high Q components could only sparingly use voltage tunable capacitors. As a result only limited electric tuning range was possible. Now with Epicaps tuning ranges approaching an octave level can be considered. A possible filter circuit using voltage tuning is shown in Fig. 4.

THE EPICAP VVC-TUNED RESONANT CIRCUIT

Most Epicap VVC resonant circuits take the form of Fig. 5 for the parallel circuit, or Fig. 6 for the series circuit. In either case the equations and graphs of this report apply. The effective circuit inductance is given by L, al-

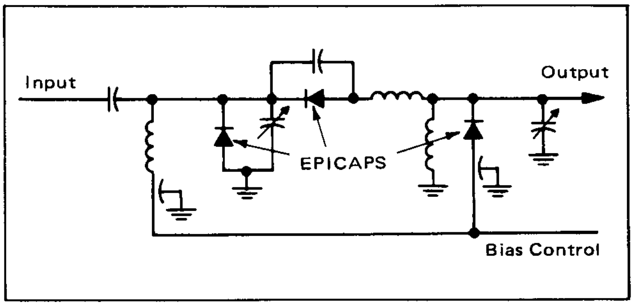


FIGURE 4 – Possible Filter Configuration Using Epicaps

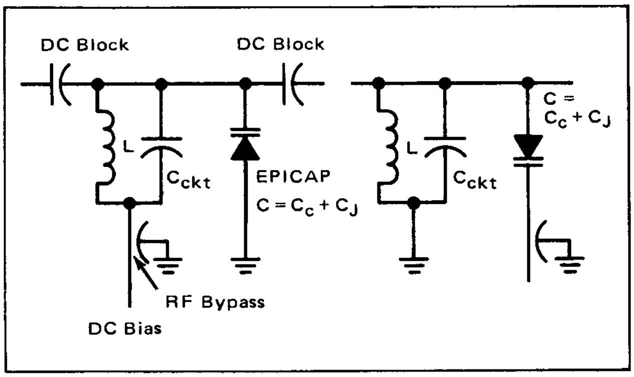


FIGURE 5 – Two EPICAP VVC Tuned Parallel Resonant Circuits

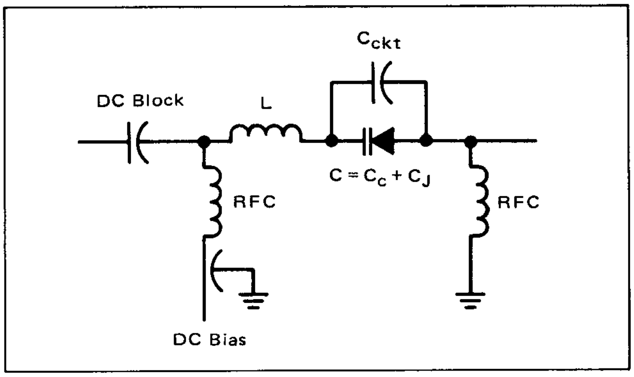


FIGURE 6 – EPICAP VVC Tuned Series Resonant Circuit

though in some cases for biasing purposes there are additional RF chokes which, if properly chosen, have negligible effect on the resonant frequency. Circuit capacity shunting the varactor is given by C_{ckt}. The Epicap VVC capacity is given by $C_c + C_J$, the sum of case and junction capacitances. For this note it is assumed that the resonant frequencies are well below diode self-resonant frequency so the Epicap VVC inductance can be neglected. A short discussion of the effect of this inductance, however, is included.

In the design of electrically tuned circuits, a major concern is the tuning range. A graph has been developed from which tuning range can be predicted using the voltage tunable capacitance and external circuit parameters. The development, discussion and use of that graph is the major thesis of the applications section of this report.

The expression for resonant frequency is given by

$$f_o = \frac{1}{2\pi(LC_T)^{1/2}} \tag{12}$$

where

$$C_T = C_{ckt} + C_J + C_c$$

$$C_J = \frac{C_o}{(1 + V/\Phi)^{\gamma}} = \frac{C_o}{(1 + 2V)^{1/2}} \tag{13}$$

where

γ the law of the diode = 0.5 for Epicap VVC's

C_o is the zero bias capacity

Φ the contact potential = 0.5 volts

V is the magnitude of the reverse voltage

The maximum junction capacity occurs when the minimum bias voltage is applied and vice versa for the minimum capacity.

$$C_{J\,max} = \frac{C_o}{\left(1 + \frac{V_{min}}{\Phi}\right)^{1/2}} \tag{14}$$

$$C_{J\,min} = \frac{C_o}{\left(1 + \frac{V_{max}}{\Phi}\right)^{1/2}} \tag{15}$$

The mean capacity between C_{max} and C_{min} is usually chosen to resonate the circuit at the design center frequency

$$C_{cf} = (C_{J\,max}\,C_{J\,min})^{1/2} \tag{16}$$

From eqs. (14) and (15)

$$C_{J\,min} = C_{J\,max}\frac{(\Phi + V_{min})^{1/2}}{(\Phi + V_{max})^{1/2}} \tag{17}$$

hence

$$C_{J\,cf} = C_{J\,max}\frac{(\Phi + V_{min})^{1/4}}{(\Phi + V_{max})^{1/4}} \tag{18}$$

Defining

$$\frac{(\Phi + V_{min})^{1/2}}{(\Phi + V_{max})^{1/2}} = X \tag{19}$$

$$C_{J\,min} = X\ C_{J\,max} \tag{20}$$

$$C_{J\,cf} = X^{1/2}\,C_{J\,max} \tag{21}$$

The maximum, minimum, and center resonant frequencies

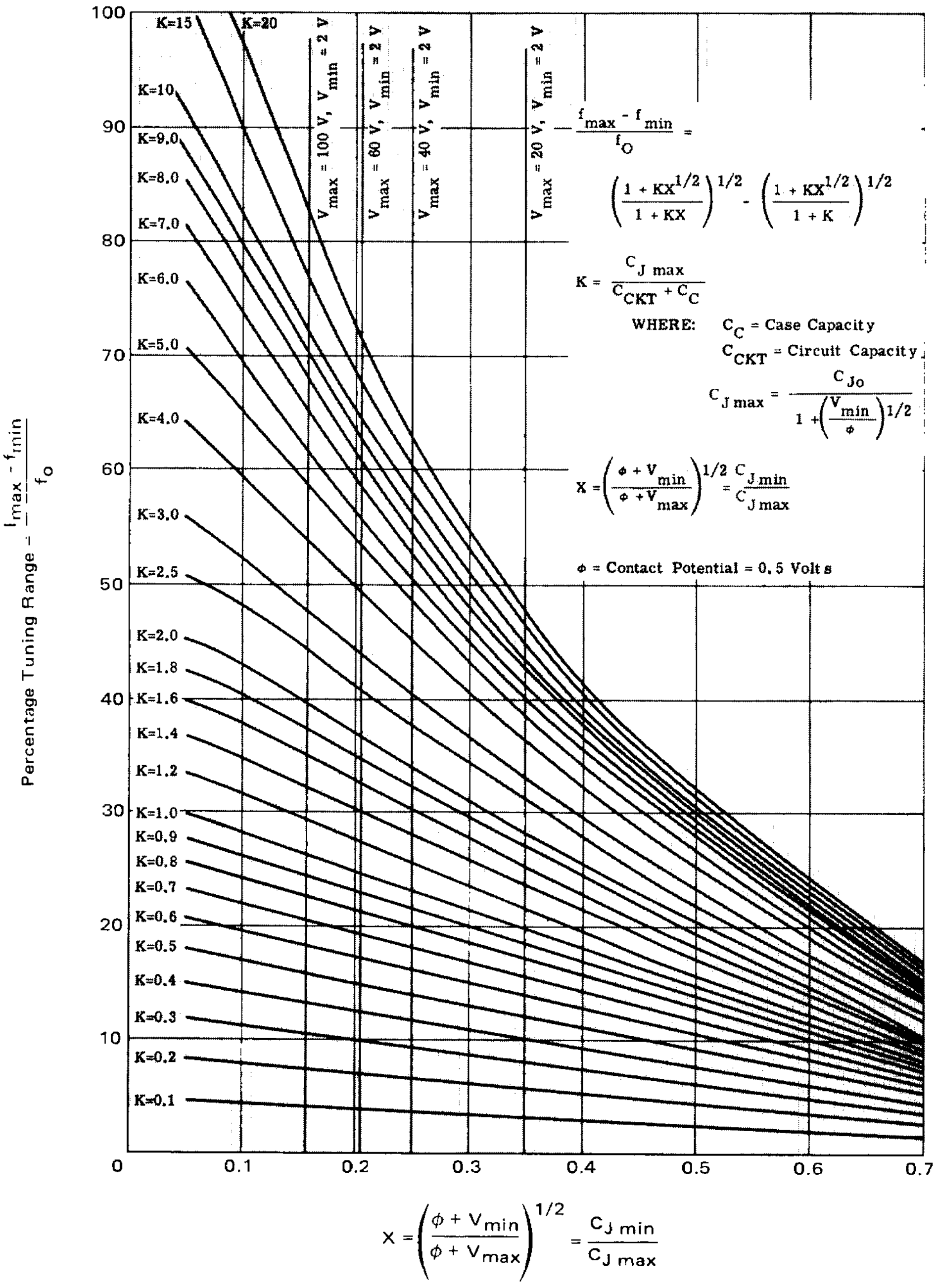


FIGURE 7 – Percentage Resonant Circuit Tuning Range

are given by

$$f_{max} = \frac{1}{\left[L(C_{ckt} + C_c + C_{J\,min})\right]^{1/2}}$$

$$= \frac{1}{\left[L(C_{ckt} + C_c + X\,C_{J\,max})\right]^{1/2}} \qquad (22)$$

$$f_{min} = \frac{1}{\left[L(C_{ckt} + C_c + C_{J\,max})\right]^{1/2}} \qquad (23)$$

$$f_o = \frac{1}{\left[L(C_{ckt} + C_c + C_{J\,cf})\right]^{1/2}}$$

$$= \frac{1}{\left[L(C_{ckt} + C_c + X^{1/2}\,C_{J\,max})\right]^{1/2}} \qquad (24)$$

Tuning range percentage is

$$\frac{f_{max} - f_{min}}{f_o} = \left[\frac{C_{ckt} + C_c + X^{1/2}\,C_{J\,max}}{C_{ckt} + C_c + X\,C_{J\,max}}\right]^{1/2} - \left[\frac{C_{ckt} + C_c + X^{1/2}\,C_{J\,max}}{C_{ckt} + C_c + C_{J\,max}}\right]^{1/2} \qquad (25)$$

Defining

$$K = \frac{C_{J\,max}}{C_{ckt} + C_c}$$

eq. (25) can be simplified to

$$\frac{f_{max} - f_{min}}{f_o} = \left(\frac{1 + K X^{1/2}}{1 + K X}\right)^{1/2} \left(\frac{1 + K X^{1/2}}{1 + K}\right)^{1/2} \qquad (26)$$

Equation (26) is plotted versus $X = \frac{C_{J\,min}}{C_{J\,max}}$ for several $K = \frac{C_{J\,max}}{C_{ckt} + C_c}$ as parameters in Fig. 7. Using Fig. 7, circuits can be designed and Epicap VVC's specified. Actually Fig. 7 can be used for any variable capacitor as long as the abcissa is kept in terms of the minimum to maximum capacity ratio. Using Epicap VVC's, the abcissa is also given in terms of minimum and maximum voltage.

USE OF THE TUNING RANGE DESIGN GRAPH

To illustrate the use of Fig. 7 (design graph) a sample design is given.

Assume a tuning range is desired between 60 and 90 MHz with a fixed circuit capacity of 10 pF present. (This might be due to collector capacity.) The percentage tuning range is $\frac{90 - 60}{(90 \times 60)^{1/2}} \times 100\% = 41\%$. With Epicap VVC's MV1864B through 1N5148 the maximum usable voltage is 60 volts. Voltage breakdown determines this upper voltage limit. The lower voltage limit is determined by temperature stability and/or intermodulation effects because the junction capacity varies sharply at low voltages. Temperature dependence enters via the contact potential which is more significant with low applied bias voltages. It is generally accepted that a lower limit of two volts is to be used for most applications. Therefore, for $V_{max} = 60$ V, $V_{min} = 2$ V and tuning range = 41% the minimum allowable K is 2.5, or $C_{4\,V} > 26$ pF/1.34 = 19.4 pF.

All Epicap VVC's are identified by a four volt capacity value. The two volt value which corresponds to C_{Jmax} is simply obtained by multiplying $C_{4\,V}$ by 1.34 which is obtained from the ratio of capacity at 2 V to the capacity at

$$4\ V = \left(\frac{1 + 4/0.5}{1 + 2/0.5}\right)^{1/2} = 1.34$$

With $C_{ckt} = 10$ pF and $C_c = 0.3$ for the glass diode $C_{J\,max}$ must be greater than K_{min} $(C_{ckt} + C_c)$ or $C_{J\,max} > 2.5$ $(10.3) = 26$ pF.

Any Epicap VVC having a -4 V capacity over 19.4 pF would tune the desired range; however, usually the lower the capacity value the higher the Q so that the lowest capacity device should be selected (where Q is important). For this problem the recommended Epicap VVC is the 1N5144 which has a 22 pF 4 volt capacity. This allows for a standard tolerance of ±10% in the Epicap VVC capacity.

Where the best temperature stability is desired the minimum voltage should be as high as possible. In that case the X is reduced so that the minimum tolerable K is increased. Larger Epicap VVC's, e.g., the 1N5148 with $C_{4\,V} = 47$ pF, would have to be used. Similar conditions would prevail if the maximum control voltage is limited.

Completing the circuit design, for tuning 22 pF x 1.34 + 10 pF + 0.3 pF = 39.8 pF at 60 MHz a coil of 0.179 μH is needed. To account for variations of ±2.2 pF in the Epicap VVC tolerance, it is recommended that this coil be tunable by insertion of a ferrite slug. The ferrite core is the simplest possible trimming in this frequency range. For considerably higher frequencies, capacity trimming would have to be selected.

The maximum voltage needed can be calculated from

$$K = \frac{22 \times 1.34}{10 + 0.3} = 2.85$$

From Fig. 7 with a 41% tuning range and K = 2.85 the required X is 0.24 or

$$V_{max} = \frac{(2.5)}{(0.24)^2} - 0.5 = 43\ V$$

In the worst case where the 22 pF value is at the lower limit of 19.8 pF,

$$K = \frac{19.8 \times 1.34}{10.3} = 2.55$$

Then the full 60 volts would be needed for V_{max}.

For cases where V_{min} and V_{max} have to remain fixed no matter what the circuit and Epicap VVC values are (within the prescribed tolerances) the circuit has to be designed around a constant K value. This means $\frac{C_{J\,max}}{C_{ckt} + C_c}$ has to be fixed no matter what $C_{J\,max}$ or C_{ckt} are. Also for tuning the proper frequency $C_{J\,max} + C_{ckt} + C_c$ has to remain constant.

$$L(C_{J\,max} + C_{ckt} + C_c) = \frac{1}{(2\pi f_{min})^2} \qquad (27)$$

$$\frac{C_{J\,max}}{C_{ckt} + C_c} = K \qquad (28)$$

By placing a trimmer capacitor in the circuit in addition to a variable inductance the conditions of eqs. (27) and (28) can be maintained. In the example above with $C_{J\,max}$ - 19.8 x 1.34 = 25.5 pF $f_{min} = 60$ MHz, K = 2.5, $C_c = 0.3$ pF.

$$L(C_{ckt} + 26.8 \times 10^{-12}) = \frac{1}{(2\pi\ 60 \times 10^6)^2}$$

$$C_{ckt} = \frac{C_{J\,max}}{K} - C_c = \frac{26.5}{2.5} - 0.3 = 10.3\ pF$$

$$L = 0.192\ \mu H$$

If $C_{J\,max} = 24.2 \times 1.34 = 32.5$ pF, $f_{min} = 60$ MHz, K = 2.5, $C_c = 0.3$.

$$C_{ckt} = \frac{32.5}{2.5} - 0.3 = 12.7 \text{ pF}$$

$$L = 0.156\ \mu\text{H}$$

Hence to maintain constant tuning voltage within the standard Epicap VVC tolerances, the circuit inductance has to be tunable from 0.156 μH to 0.192 μH, and a trimmer capacity adjustable from 0.3 pF to 2.7 pF has to be added to the 10 pF circuit capacity. A summary of this design procedure is given in the following.

SUMMARY OF EPICAP VVC RESONANT CIRCUIT DESIGN

If f_{max}, f_{min}, C_{ckt}, V_{max}, and V_{min} are given,

1. From f_{max} and f_{min} determine $f_o = (f_{max} f_{min})^{1/2}$
2. Obtain percentage bandwidth $= \dfrac{f_{max} - f_{min}}{f_o}$
3. Determine $X = \left(\dfrac{0.5 + V_{min}}{0.5 + V_{max}}\right)^{1/2} = \dfrac{C_{J\,min}}{C_{J\,max}}$
4. Using Fig. 7 find $K = \dfrac{C_{J\,max}}{C_{ckt} + C_c}$ at the intersection of constant percentage bandwidth and X lines.
5. Knowing C_{ckt} (use maximum value possible) and 0.3 pF for C_c if glass Epicap VVC is used (1.0 pF for large pill and 0.3 for small pill or pill with prong Epicap VVC) determine a trial $C_{max} = C'_{max}$.
6. The Epicap VVC selected must have a four volt capacity

$$C_{4\,V\,DC} > 1.1 \times \left(\frac{0.5 + V_{min}}{4.5}\right)^{1/2} C_{J\,max}.$$

   The 1.1 is to allow for standard 10% Epicap VVC tolerance (1.05 for a 5% tolerance unit).

7. Once an Epicap VVC is selected assume the minimum possible $C_{4\,V\,DC}$ and calculate $C_{J\,max} = \left(\dfrac{4.5}{0.5 + V_{min}}\right)^{1/2} C_{4\,V\,DC}$.
   a. Using K from step 4 calculate a new C_{ckt}. The difference between this new C_{ckt} and that of the circuit has to be positive; otherwise a higher capacity Epicap VVC has to be selected. The capacity difference is the minimum value required for a trimmer capacitor placed in parallel with the Epicap VVC.
   b. Determine inductance from

$$L = \frac{1}{(2\pi f_{min})^2 \, (C_{J\,max} + C_{ckt} + C_c)}$$

   where C_{ckt} includes, the trimmer value, this L is the maximum value of the variable L.

8. Assume the maximum possible $C_{4\,V\,DC}$ and calculate a corresponding

$$C_{J\,max} = \left(\frac{4.5}{0.5 + V_{min}}\right)^{1/2} C_{4V\,DC}$$

   a. Using K from step 4, calculate a new C_{ckt}. The difference between this new C_{ckt} and that of the circuit is the maximum value required to the trimmer capacity.
   b. Determine inductance as in step 7b only, using the C_{ckt} and C_{max} for this step. This L is the minimum value of the variable L.

9. Check the calculations by determining f_{max} using V_{max} for both upper and lower Epicap VVC tolerances

$$C_{J\,min} = C_{J\,max}\left(\frac{0.5 + V_{min}}{0.5 + V_{max}}\right)^{1/2}$$

$$f_{max} = \frac{1}{2\pi(C_{J\,min} + C_{ckt} + C_c)^{1/2} (L)^{1/2}}$$

   Be sure to use a consistent set of values for $C_{J\,min}$, C_{ckt}, and L in one case from step 7 and in the other case from step 8.

EPICAP VVC-USAGE NEAR THE SELF-RESONANT FREQUENCY

If Epicap VVC inductance has an appreciable reactance compared to the junction reactance the design procedure has to be altered. An equivalent capacitance can be calculated but it is now a function of frequency.

$$Y = j\omega C_{eq} = \frac{j\omega C_J}{1 - \omega^2 L_s C_J} \qquad (29)$$

or

$$C_{eq} = \frac{C_J}{1 - (2\pi f)^2 L_s C_J} \qquad (30)$$

For the glass Epicap VVC's an L_s = 5 nH can be assumed with 1/16" leads and for the pill Epicap VVC's L_s = 0.4 nH. Using the proper inductance value with minimum and maximum frequencies and junction capacities, limits on C_{eq} can be obtained. From the C_{eq} limits an X can be calculated and using Fig. 7 a percentage bandwidth obtained.

In general, operation near self resonance is not recommended because the design procedures are not as definitive and the device Q is degraded.

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