MOTOROLA
Semiconductor Products Inc.

AN847
Application Note

TUNING DIODE DESIGN TECHNIQUES

Tuning diodes are voltage variable capacitors employing the junction capacitance of a reverse biased PN junction. This note presents a simplified theory of tuning diodes and discusses a number of considerations to be employed in designs using tuning diodes.

INTRODUCTION

Voltage variable capacitors or tuning diodes are best described as diode capacitors employing the junction capacitance of a reverse biased PN junction. The capacitance of these devices varies inversely with the applied reverse bias voltage.

Tuning diodes have several advantages over the mechanical variable capacitor. They are much smaller in size and lend themselves to circuit board mounting. They are available in most of the same capacitance values as fixed capacitors. Tuning diodes offer the designer the desirable feature of electronic tuning.

The capacitance of all tuning diodes inherently varies with temperature and may require compensation. A simple scheme is available for compensation of the temperature drift, resulting in stabilities as good as, or better than, that of air capacitors. Digital techniques effectively eliminate temperature as a problem.

SIMPLIFIED THEORY

A tuning diode is a silicon diode with very uniform and stable capacitance versus voltage characteristics when operated in its reverse biased condition. In accordance with semiconductor theory, a depletion region is set up around the PN junction. The depletion layer is devoid of mobile carriers. The width of this depletion region is dependent upon doping parameters and the applied voltage. Figure 1A shows a PN junction with reverse bias applied, while Figure 1B shows the analogy, a parallel plate capacitor. The equation for the capacitance of a parallel plate capacitor given below predicts the capacitance of a tuning diode.

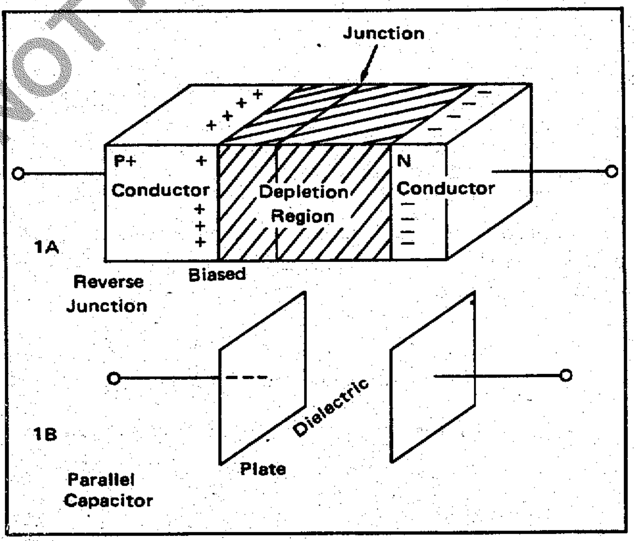


FIGURE 1 — Tuning Diode Capacitor Analogy

$$C = \frac{\epsilon A}{d} \qquad (1)$$

where ϵ = dielectric constant of silicon equal to $11.8 \times \epsilon_0$
$\epsilon_0 = 8.85 \times 10^{-12}$ F/m
A = Device cross sectional area
d = Width of the depletion layer.

The depletion layer width d may be determined from semiconductor junction theory.

The more accepted method of determining tuning diode capacitance is to use the defining formula for capacitance.

$$C = \frac{dQ}{dV} \tag{2}$$

The charge, Q per unit area, is defined as:

$$Q = \epsilon E \tag{3}$$

where E = Electric field

So we have capacitance per unit area:

$$c = \frac{C}{A} = \epsilon \frac{dE}{dV} \tag{4}$$

Norwood and Shatz[1] use these ideas to develop a general formula:

$$c = \left[\frac{q\,B\epsilon^{\,m+1}}{(m+2)\,(V+\phi)}\right]^{1/m+2} \tag{5}$$

m = Impurity exponent
c = Capacitance per unit area

Lumping all the constant terms together, including the area of the diode, into one constant, C_D, we arrive at:

$$C_J = \frac{C_D}{(V+\phi)^{\gamma}} \tag{6}$$

where γ = Capacitance Exponent, a function of impurity exponent
ϕ = The junction contact potential ($\approx$ 0.7 Volts)

The capacitance constant, C_D, can be shown to be a function of the capacitance at zero voltage and the contact potential. At room temperature we have:

$$C_D = C_o(\phi)^{\gamma} \tag{7}$$

C_o = Value of capacitance at zero voltage

The simple formula given in Eq. 6, very accurately predicts the voltage-capacitance relationship of modern tuning diodes. There are many detailed derivations[1,2,3,4,5] of junction capacitance, so further explanation is not necessary in this note.

The capacitance of commercial tuning diodes must be modified by the case capacitance.

The equation then becomes:

$$C = C_c + C_J \tag{8}$$

where

C_c = Case capacitance typically 0.1 to 0.25 pF
C_J = Junction capacitance given by Equation 6.

TUNING RATIOS

The tuning or capacitance ratio, TR, denotes the ratio of capacitance obtained with two values of applied bias voltage. This ratio is given by the following expression for the diode junction.

$$TR = \frac{C_J\,(V_2)}{C_J\,(V_1)} = \left[\frac{V_1+\phi}{V_2+\phi}\right]^{\gamma} \tag{9}$$

where $C_J\,(V_1)$ = Junction capacitance at V_1
$C_J\,(V_2)$ = Junction capacitance at V_2
where $V_1 > V_2$

In specifying TR, some tuning diode data sheets use four volts for V_2. However, in order to achieve larger tuning ratios, the devices may be operated at slightly lower bias levels with some degradation in the Q specified at four volts. (See the discussion of Q versus voltage in the circuit Q section, later in this note). Furthermore, care must be taken when operating tuning diodes at these low reverse bias levels to avoid swinging the diode into forward conduction upon application of large ac signals. These large signals may also produce distortion due to capacitance modulation effects.

Since the effects of ϕ and case capacitance, C_c, are usually small, Eq. 9 may be simplified to the following for most design work:

$$TR = \frac{C\,(V_{min})}{C\,(V_{max})} = \left(\frac{V_{max}}{V_{min}}\right)^{\gamma} \tag{10}$$

The frequency ratio is equal to the square root of the tuning ratio. This tunable frequency ratio assumes no stray circuit capacitance.

Another parameter of importance is γ, the capacitance exponent. Physically, γ depends on the doping geometry employed in the diode. Tuning diodes with γ values from 1/3 to 2 can be manufactured by various processing techniques. The types of junctions, their doping profiles, and resulting values of γ are shown in Figure 2. These graphs show the variation of the number of acceptors (N_A) and the number of donors (N_D) with distance from the junction.

Abrupt junctions are the easiest to manufacture and the majority of tuning diodes on the market are of this type. This type of junction gives a γ of approximately 1/2 and a tuning ratio on the order 3 with the specified voltage range. Therefore the corresponding frequency range which may be tuned is about 1.7 to 1.0. A typical example is the MV2101:

$C\,(V_2) = C_{(30\,V)} = 2.5$ pF
$C\,(V_1) = C_{(4\,V)} = 6.8$ pF
TR = 2.7
$\gamma = 0.47$

The subscripts on the capacitance refer to the bias voltage applied.

In many applications, such as tuning the television channels, or the AM broadcast band, a wider frequency range is required. In this event, the designer must use a hyper-abrupt junction tuning diode. The hyper-abrupt diode has a γ of 1 or 2, and tunes over much larger frequency ranges. Table I shows typical types of tuning diodes available, their tuning ratios, frequency ratios and junction types.

The hyper-abrupt devices are constructed with special epitaxial growth, diffusion, and ion implant techniques, which create a doping profile similar to that shown in Figures 2C and 2D. The Q of the BB105 and MV109 series hyper-abrupt diodes is as high as abrupt junction devices. Their capacitance range is from a few picofarads to 10 or 20 pF, and their major application is in television tuners. The MV1401 series are high capacitance devices for applications below 10 MHz. They are suitable for tuning elements in AM broadcast band receivers and similar low frequency applications.

TABLE I SAMPLE TUNING DIODE TYPES

Device Series	Capacitances Available	Tuning Ratio	γ	Frequency Ratio	Junction Type
1N5139	47–6.8 pF	2.7–3.4	0.47	1.6–1.8	Abrupt
MV2101	100–6.8 pF	1.6–3.3	0.47	1.6–1.8	Abrupt
BB105	10 pF	4.0–6.0	1.0	2.0–2.4	Hyper-Abrupt
MV1401	550–120 pF	10–14	2.0	3.2–3.7	Hyper-Abrupt
MV109	30 pF	5.0–6.5	1.0	2.2–2.5	Hyper-Abrupt

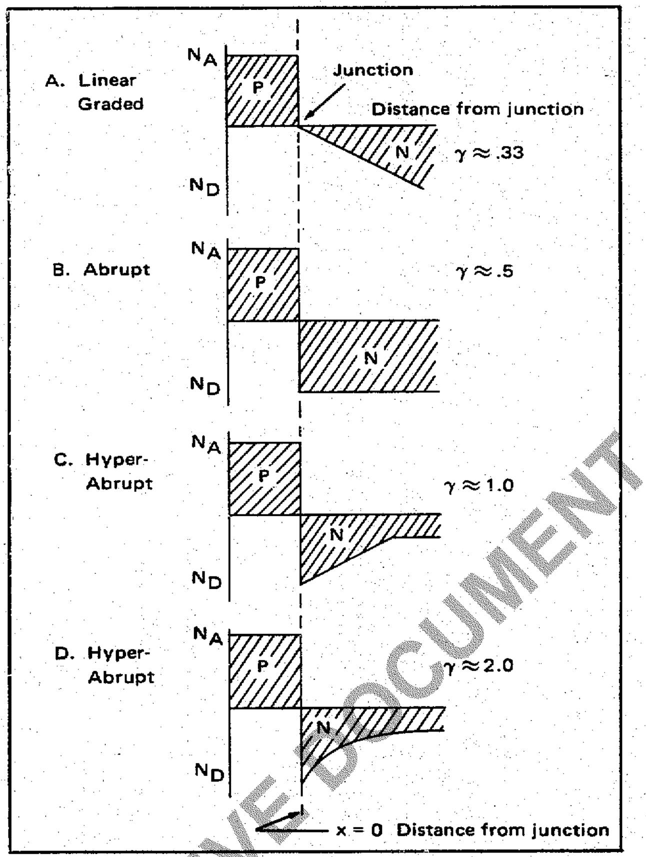


FIGURE 2 — Doping Profiles and Capacitance Exponent for Some Common Tuning Diode Types

CIRCUIT Q

Popular types of mechanical tuning capacitors often have Q's on the order of a thousand or greater. The Q of tuned circuits using these capacitors is generally dependent only on the coil. When using a tuning diode, however, one must be conscious of the tuning diode Q as well. The Q of the tuning diode is not constant, being dependent on bias voltage and frequency. The Q of tuning diode capacitors falls off at high frequencies, because of the series bulk resistance of the silicon used in the diode. The Q also falls off at low frequencies because of the back resistance of the reverse-biased diode.

The equivalent circuit of a tuning diode is often described as shown:[7]

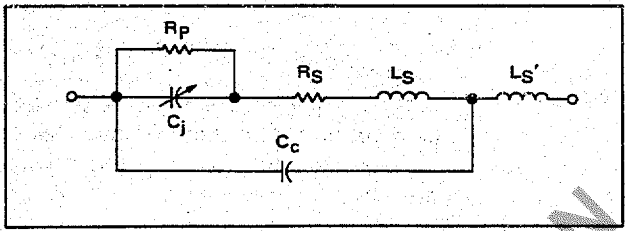


FIGURE 3 — Equivalent Circuit of Tuning Diode

where

R_P = Parallel resistance or back resistance of the diode
R_S = Bulk resistance of the silicon in the diode
L_S' = External lead inductance
L_S = Internal lead inductance
C_C = Case capacitance

Normally we may neglect the lead inductance and case capacitance. This results in simplified circuit of Figure 4.

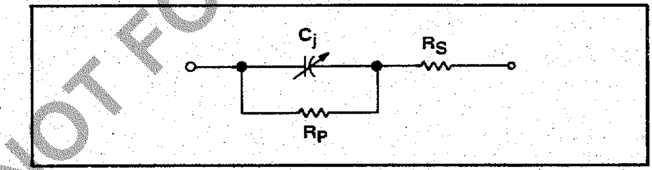


FIGURE 4 — Simplified Equivalent Circuit of Tuning Diodes

The tuning diode Q may be calculated with Equation 11.

$$Q = \frac{2\pi f C\, R_p^2}{R_s + R_p + (2\pi f C)^2 R_s R_p^2} \qquad (11)$$

This rather complicated equation is plotted in Figure 5 for $R_S = 1.0$ ohm, $R_p = 30 \times 10^9$ ohms, at V = 4 volts and C = 6.8 pF, typical for a 1N5139 diode at room temperature.

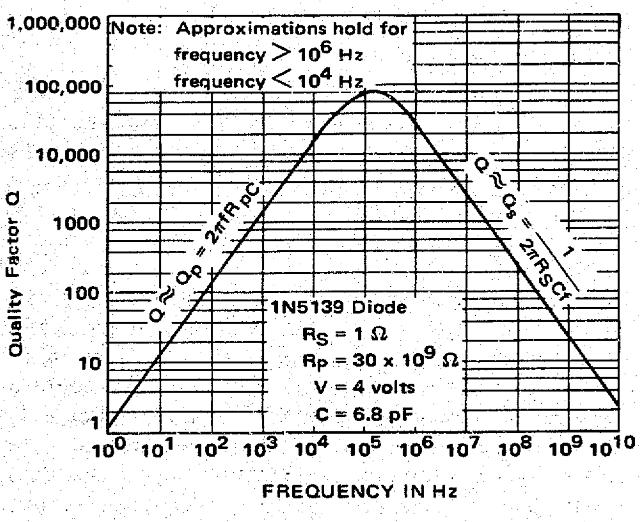


FIGURE 5 — Graph of Q versus Frequency

At frequencies above several MHz, the Q decreases directly with increasing frequency by the simpler formula given below:

$$Q \approx Q_S = \frac{1}{2\pi f C R_s} \text{ (High frequency Q)} \qquad (12)$$

The emphasis today is on decreasing R_s so better high frequency Q can be obtained. At low frequencies Q increases with frequency since only the component resulting from R_p, the back resistance of the diode, is of consequence.

$$Q \approx Q_p = 2\pi f C R_p \text{ (Low frequency Q)} \qquad (13)$$

Q is also dependent on voltage and temperature. Higher reverse bias voltage yields a lower value of capacitance, and also since R_s decreases with increasing bias voltage, the Q increases with increasing voltages. Similarly, low reverse bias voltages accompany larger capacitances, and lower Q's. Increasing temperature also lowers the Q of tuning diodes. As the junction temperature increases, the leakage current increases, lowering R_p. There is also a slight decrease in R_s with increasing temperature, but the effects of the decreasing R_p are greater and this causes the Q to decrease. The effects of temperature and voltage on the Q of a 1N5139 at 50 MHz are plotted in Figure 6.

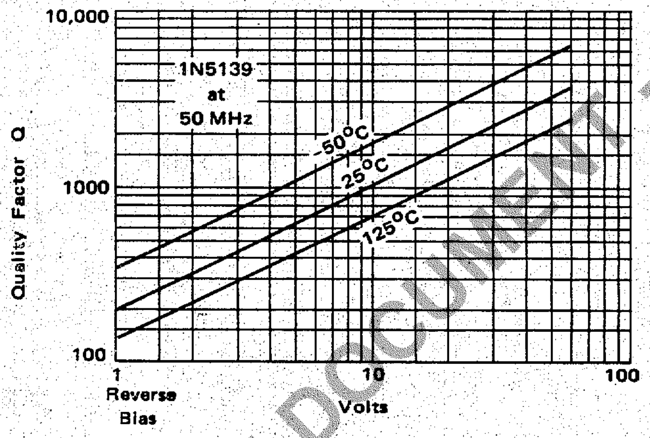


FIGURE 6 — Q versus Reverse Bias and Temperature

TEMPERATURE

The Q and tuning ratio of tuning diodes are parameters that every design engineer must be aware of in his circuits. Another equally important characteristic of tuning diodes is their temperature coefficient. A typical example of the capacitance versus temperature drift is shown in Figure 7.

The temperature coefficient, T_C, is a function of applied bias. Figure 8 shows T_C for a typical tuning diode. Note that for low bias levels, on the order of a volt or two, the T_C is as high as +600 parts per million per degree centigrade (ppm/°C). This represents a frequency change of -300 ppm/°C which at 100 MHz means a frequency shift of 30 kHz per degree. It is obvious that a temperature compensation scheme is desirable for any frequency control not using feedback techniques.

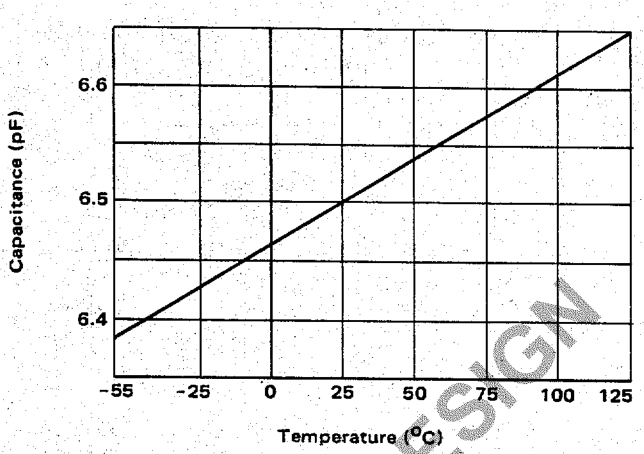


FIGURE 7 — Capacitance versus Temperature for a MV2101 Diode Biased at 4.0 Volts

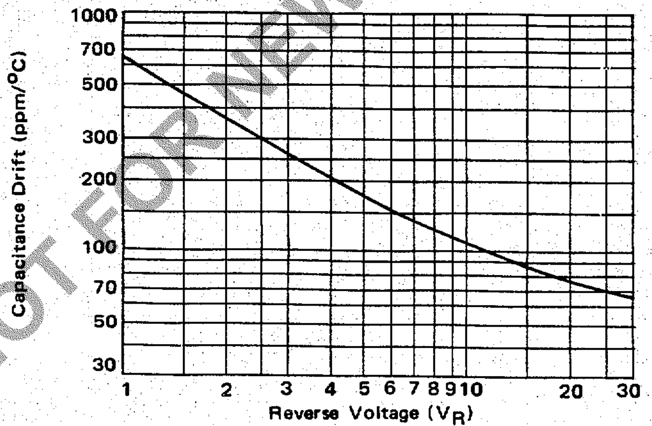
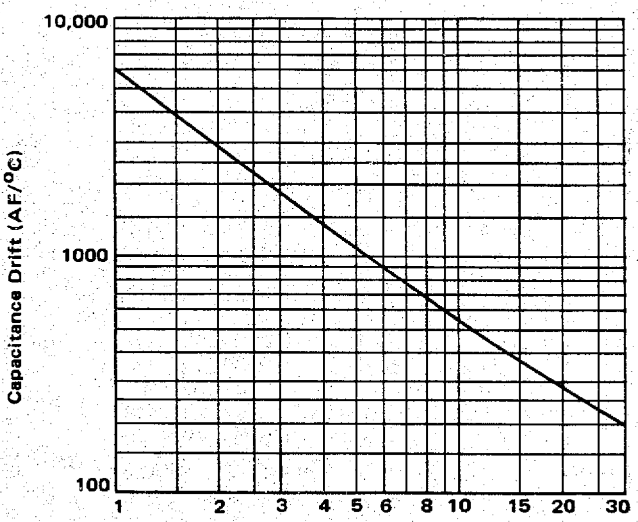


FIGURE 8 — Capacitance Drift in ppm/°C versus Voltage MV2101 Diode

In Figure 9, the actual capacitance drift of a MV2101 per degree centigrade is plotted. The graph illustrates that a simple negative temperature coefficient compensating capacitor will not compensate for the tuning diode T_C because the change in capacitance is not constant with voltage.



Attofarads = (pF x 10^{-6})

FIGURE 9 — Capacitance Drift in Attofarads/°C versus Voltage for the MV2101 Tuning Diode

THEORY OF TEMPERATURE CHANGE

Before proceeding further with schemes to correct the temperature drift, it is informative to investigate the physical mechanisms responsible for the changing capacitance. Equations 6 and 8 may be combined to give the basic expression for capacitance below:

$$C = \frac{C_d}{(V + \phi)^{\gamma}} + C_c \qquad (14)$$

We can pinpoint the terms in Eq. 14 that may account for capacitance changes. The contact potential, ϕ, is a strong function of temperature, varying on the order of -2.0 mV/°C. C_d is a function of geometric dimensions which can change with temperature and ϵ which changes with temperature. Case capacitance also changes with temperature. For this analysis we will assume the only terms not temperature dependent are the supply voltage V, and the capacitance exponent, which is a function only of the slope of the doping profile.

The contact potential, ϕ, is readily calculated from semiconductor theory, and the equations predict a large change with temperature. This change in ϕ will produce a much larger change in capacitance for lower voltages than for higher voltages, and therefore accounts for the majority of capacitance change in tuning diode temperature drift. See Table II.

TABLE II

Calculated capacitance change versus applied voltage in ppm/°C for:

$$\frac{d\phi}{d_T} = -2\ \text{mV/°C}$$

$$C = \frac{C_d}{(V + \phi)^{\gamma}} + C_c$$

Applied Bias Voltage (Volts)	Capacitance Drift In (ppm/°C)
1	587
2	261
4	204
10	88.7
20	45.6
30	30.7

Comparing Table II with Figure 8, we see that a +40 to +50 ppm/°C temperature drift still remains. Therefore ϕ is not the only mechanism responsible for temperature drift and others must be sought. There is a change with temperature in physical dimensions in any material which has an affect on the order of 1 ppm/°C for a tuning diode. However, this change is too small to be of any significance. Another possibility is a change in dielectric constant. Silicon, depleted of its charge carriers, forms a dielectric layer with a relative dielectric constant of 11.8. The dielectric constant of silicon has a temperature coefficient of +35 ppm/°C.[1] These effects change the value of C_d with temperature. The case capacitance also varies slightly with temperature. See Table III.

TABLE III Effect Of Case Capacitance Changes On 1N5139 And 1N5148 Diodes

Bias Voltage (Volts)	1N5139 Capacitance (pF)	1N5139 Changes attributable to case capacitance (ppm/°C)	1N5148 Capacitance (pF)	1N5148 Changes attributable to case capacitance (ppm/°C)
2.0	8.9	3.4	61	0.5
4.0	6.4	4.7	47	0.6
10.0	4.8	6.3	32	1.0
30.0	3.0	10.0	19	1.6
60.0	2.2	14.0	13	2.3

In summary, the largest changes are caused by the change in contact potential. This effect is most noticeable at low voltage, high capacitance levels. The change in silicon dielectric is the next most important factor providing a change that is uniform for all devices and voltages. Case capacitance changes are most noticeable in the low capacitance, high voltage range, and may be neglected for all devices except those low capacitance devices.

TEMPERATURE COMPENSATION

A popular method of temperature compensating tuning diodes involves the use of a forward biased diode. The voltage drop of a forward biased diode decreases as the temperature rises, thus applying a changing voltage to the tuning diode. In the network shown in Figure 10, an increase in temperature will result in a decrease of the diode voltage V_{DIODE} to perhaps 0.5 V.

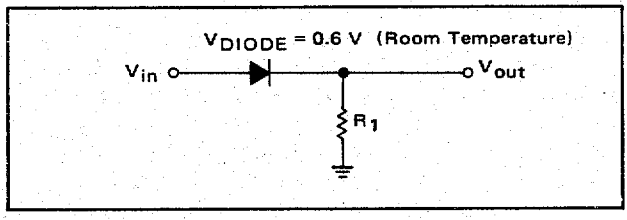


FIGURE 10 — Simple Temperature Compensating Network

If V_{in} is maintained constant, the available output voltage V_{out} will rise by 0.1 V. This increase in output voltage will lower the capacitance of the tuning diode and partially offset the initial capacitance increase caused by the temperature change. Obviously, for the above circuit to be effective, the compensating diode must be thermally coupled to the varactor to be corrected.

Frequently, the varactor is part of a feedback loop which controls the frequency of oscillation by digital techniques. In this case, the temperature effects are generally accounted for in the digital feedback loops, so that diode compensation is not required.

THE POWER SUPPLY

We previously assumed that the supply voltage did not change with temperature. This is rarely the case, and special consideration must be given to this part of the design. All our efforts to temperature compensate the tuning diode may be in vain if the power supply has a large T_C or is otherwise unstable. Figure 11 shows the common method of supplying voltage to a tuning diode.

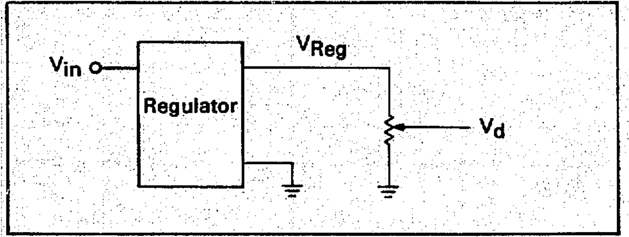


FIGURE 11 — Common Means of Supplying Bias Voltage to a Tuning Diode

The regulator is the most critical part of the circuit in Figure 11. It must be extermely stable in order to achieve good varactor tuning stability. The full drift of the power supply as expressed in ppm/°C will appear at V_d regardless of the setting of the potentiometer. For example, if V_{Reg} is 40 volts with a drift of 100 ppm/°C (4 mV/°C), V_d may be 10 V, but will still have a drift of 100 ppm/°C (1 mV/°C). A 50 ppm/°C stability figure in V_d translates into a 25 ppm/°C stability of capacitance, when the capacitance exponent is 0.5. For hyper-abrupt junctions we realize capacitance stabilities of 50 and 100 ppm/°C for exponents of 1 and 2 respectively.

There are many differing power supply regulators available to the designer. Zener diodes are relatively inexpensive, but have a poor temperature coefficient. Temperature compensated zeners are very expensive and have a limited voltage range. The LM117, a monolithic integrated circuit voltage regulator, has excellent temperature characteristics, 37 volt output capability, and wide temperature range.

The MC7800 fixed output voltage regulators are extremely simple to use in that they have only input, output and ground terminals and require no external components other than possibly a high frequency bypass capacitor. (The latter item is generally required with all IC regulators to prevent high frequency oscillations).

The MVS460 is a two leaded IC regulator expecially designed for use with tuning diodes. It represents a simple, inexpensive solution to the voltage regulator problem. Table IV contains a summary of available power supply regulators.

VARIABLE RESISTOR

The variable resistor is considerably less critical. Since it is being used as a voltage divider, all that is required is that the resistive material be uniform so any change in resistance is uniform throughout the potentiometer. Wire wound, and special high quality cermet film variable resistors are suitable for these applications. Generally speaking, a linear potentiometer should have a T_C of ±150 ppm/°C or better. Special taper potentiometers should have a T_C of ±50 ppm/°C or better.

The variable resistance cannot be made too large or there will be appreciable voltage drop as the reverse current in the diode increases. The reverse current in a silicon diode generally doubles every 10°C so this becomes an important problem at temperatures above 50°C. If the temperature is expected to run as high as 70°C, one must limit the variable resistor to 50 kΩ or the effect will be a greater than 5 ppm/°C capacitance change. If 50°C is the upper temperature limit, the resistance may be upped to 150 kΩ. These values apply to all of Motorola's tuning diode series. When the tuning diodes are used in applications where temperature will greatly exceed 70°C, the divide resistance should be kept below 10 kΩ. This low value requires large power supply currents and would be undesirable in some applications. However, since the Motorola LM117 is the recommended power source at these temperatures, voltage control may be accomplished using the regulator without relying on an external divider potentiometer, as shown in Figure 12. The LM117's low output impedance of 0.05 ohms will easily and reliably handle the change in current demanded by the tuning diode as it heats up.

HYPER-ABRUPT TEMPERATURE DRIFT

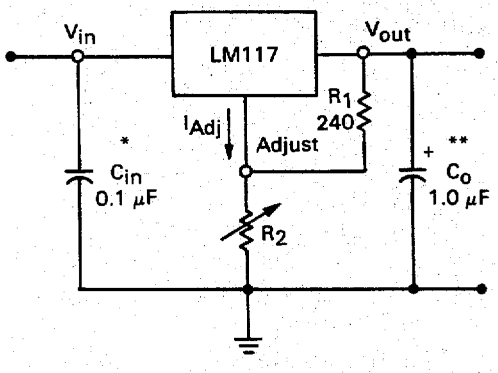
The hyper-abrupt tuning diode is more sensitive than other types to temperature variations resulting in a greater need for temperature compensation. Also their drift with temperature is not as uniform as abrupt junction tuning diodes. Their drift factors expressed in ppm/°C run as high as 800 to 1200 for the units with a γ of 2. Units having a γ of 1 typically show 300 to 400 ppm/°C capacitance changes. These higher drift rates are caused by the hyper-abrupt tuning diode's greater

TABLE IV Summary of Power Regulators

Device	Voltage Range	Temperature Range	Voltage ppm/°C Max T_C	Voltage ppm/°C Typical T_C	Capacitance ppm/°C Typical $\gamma = 0.5$	Relative Cost
1N5260 Zener	33	−65 +200°C	975	975	475	Low
1N4752 Zener	33	−65 +200°C	850	850	425	Low
1N3157 Temperature Compensated Zener	8.4	−50 +125°C	10	10	5	High
LM117 Regulator	37	−55 +125°C		50	25	Low
MC7800 Fixed Voltage Regulators	28	0° +125°C		40–60	20–30	Low
MVS460 TO-92 Regulator	31 V	0 +70°C	−100 +50	−25	12	Low

Notes:
1) See Figure 12 for some typical circuit connections
2) To compute frequency change (ppm/°C), divide capacitance (ppm/°C) change by 2.

sensitivity to changes in voltage, and the fact that the majority of capacitance change is caused by the change in contact potential, ϕ. This greater sensitivity to voltage changes means that power supply and other instabilities will also have a larger effect than with regular abrupt junction tuning diodes.



* = C_{in} is required if regulator is located an appreciable distance from power supply filter

** = C_o is not needed for stability, however it does improve transient response.

$$V_{out} = 1.25\ V\ (1 + \frac{R_2}{R_1}) + I_{Adj}\ R_2$$

Since I_{Adj} is controlled to less than 100 µA, the error associated with this term is negligible in most applications.

FIGURE 12 — High Stability Regulator -50 to +125°C

SUMMARY

Voltage variable capacitors have replaced air variable capacitors in most applications. These devices offer many advantages over previous variable capacitors, such as the ability to employ remote tuning. By carefully considering the proper design conditions, such as temperature drift, and designing accordingly, tuning diodes can replace air capacitors in virtually all but high power applications. The designer must be aware of the tuning range and Q limitation in order to use these devices effectively. Temperature drift ceases to be an issue when proper compensation schemes, or digital feedback loops are used.

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