HF-VHF-UHF VOLTAGE CONTROLLED OSCILLATORS USING HYPERABRUPT TUNING DIODES

INTRODUCTION

Modern systems require VCO's (voltage controlled oscillators) with stringent frequency range and linearity requirements which can only be met by the use of hyperabrupt tuning diodes such as the Narda HF, VHF, and UHF families. The purpose of this application note is to assist the VCO designer in realizing the superior performance attainable through the use of its ion implanted, hyperabrupt tuning diodes.

Voltage variable capacitance diodes are conventionally described by the equation:

$$C(V) = C_0/(1+V/\phi)^{\gamma} \quad (1)$$

A gamma of 0.5 characterizes the theoretical abrupt junction diode, but values between 0.40 and 0.48 are observed in practice. Hyperabrupt tuning diodes are characterized by gamma values greater than 0.5. Unfortunately gamma varies with the applied voltage in hyperabrupts disallowing the use of Equation 1 for design. The problem is solved through the use of devices manufactured by tightly controlled ion implantation which results in such good reproducibility of the C vs V curve that simple normalized curves can be used to predict the performance of entire families of devices at any voltage. Such normalized values are presented in Appendix I.

Along with reproducibility, ion implanted hyperabrupt tuning diodes offer high Q and linear frequency vs. voltage performance when used in LC tuned circuits, producing lower distortion and constant slope, df/dv, over part of their tuning range. This results in simpler phase locked loop design since the oscillator constant, Ko, is fixed and is not a variable as with diffused, abrupt junction tuning diodes.

DIODE SELECTION

Design begins with the selection of the optimized device from the more than 60 types available. Use of the selection guide found in the catalog is augmented by the following approach:

Let Fmax = maximum VCO frequency
and Fmin = minimum VCO frequency

$$R = \frac{F\,\max}{F\,\min} \quad (2)$$

Is R < or > 1.4?

R≤1.4	R>1.4
Use straight line frequency and possibly a fixed C in series with the diode. †(Linearity can also be traded for Q by tuning at higher voltages. (If price is important consider economy types)	Use a wideband unit having a tuning range which goes outside of the linear region.

Is VCO used in a loop or alone?

LOOP	ALONE
No fixed capacitor or trimmer needed unless acquisition time requires accurate free-running frequency	Trimmer needed for Fmax adjustment and fixed C for temperature compensation

Now estimate a value for parallel capacitance, Cp:

$$Cp = \text{fixed} + \text{active element} + \text{trimmer} + \text{stray} \quad (3)$$

The following guide may be helpful:

FREQUENCY (MHz)	APPROXIMATE ACTIVE ELEMENT AND STRAY CAPACITANCE	NOMINAL TRIMMER CAPACITANC E
†0.1 - 0.5	15 pf	10 pf
0.5 - 30	10 pf	5 pf
30 - 100	5 pf	5 pf
100 - 200	4 pf	3 pf
200 - 1000	1-3 pf	1-2 pf

The basic circuit is shown in Figure 1.

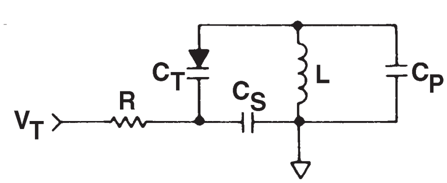

Figure 1.

Tuning diode capacitance, Ct, varies from Cmax at Vmin and Fmin to Cmin at Vmax and Fmax. Series capacitor Cs cannot be too large if the VCO is to have fast response. Since it is in series with the tuning diode it can be used as a padder to reduce the tuning range and thus residual FM arising from noise or other tuning voltage variations. Other benefits of a series padder are reduced AC voltage across the diode (especially at the critical low frequency end of the tuning range), higher tank Q, and a lower overall temperature coefficient.

Resistor R together with Cs decouples the tuning circuit from the RF circuit. Too small R value will not provide adequate decoupling while large values will produce noise modulation of the VCO by the AC components of diode leakage current. In critical applications an RF choke can replace the resistor.

Design now proceeds by calculating Cmax using R from Equation 2, Cp from Equation 3, by assuming Cs to be infinitely large, and with a value of Cmin from the diode data sheet.

$$Cmax = (R^2-1)Cp+R^2Cmin \quad (4)$$

Check to ensure that the diode maximum capacitance slightly exceeds the value given by Equation 4 to provide for a finite Cs and tendency to underestimate stray capacitance. Diode capacitances can be obtained from the typical curves found in the catalog or by using the normalized values from Appendix I.

Next calculate the required tank inductor from the following equation (L is in microhenries, C in pF, and F in MHz).

$$L = \frac{25{,}330}{(Cp + C\min)F\max^2} \quad (5)$$

Depending on the initial diode chosen the value of L may not be practical. If it is so small choose an alternate diode with smaller Cmin and conversely. Experience and the following guide can usually be followed to select the most suitable diode.

FREQUENCY (MHz)	L (Microhenries)
0.2 to 1.0	10 to 1500
0.5 to 2.0	10 to 1000
2 to 15	0.1 to 1000
10 to 100	0.08 to 25
50 to 200	0.04 to 0.4
200 to 1000	0.008 to 0.04 and tuned lines

TEMPERATURE COMPENSATION

Temperature compensation of the tuning diode's capacitance may not be necessary if the VCO is to be locked to a stable reference. If compensation is necessary, the designer starts by adding a silicon diode or silicon transistor emitter follower in series with the tuning voltage as shown below in order to compensate for the temperature dependence of the tuning diode's built-in junction voltage, ϕ.

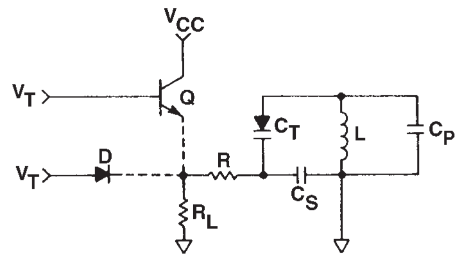

Figure 2.

Some selection of diode D (or transistor Q) and RL will be necessary with RL typically being a low TC metal film resistor in the 22 K to 150 K range. Silicon devices must be used for D (or Q), but D is otherwise a low cost device such as the 1N914 or 1N4148. Remember to increase the tuning voltage to adjust for the 0.5 to 0.7 volt drop in D (or Q). This initial compensation reduces tuning diode temperature coefficients to less than 100 ppm/°C from the initially large values of about 1200 ppm/°C of HF diodes and 300 ppm/°C of VHF and UHF diodes. Initial compensation cannot reduce the TC to zero but can make it reasonably constant across the tuning range.

This residual tuning diode temperature coefficient of capacitance arises from slight variations with temperature of the dielectric constant of silicon and other properties and can be corrected to within about 30 ppm/°C by selecting a temperature compensating capacitor for Cp or even Cs. Temperature variations in coil inductance and in active element and stray contributions to Cp may also be compensated this way.

OSCILLATOR DESIGN

Certain precautions need to be taken with oscillators using tuning diodes that can be neglected in fixed or mechanically tuned circuits. The most important precaution is to keep the AC signal level across the diode at a low level; about 300 mV rms which can be increased to 500 mV rms across each of two series connected, back-to-back diodes used as a pair. The low level not only gives low distortion but also ensures a reproducible tuning curve. The diode tuning characteristic can be altered by an AC level which is too high, producing mistracking between receiver LO and RF stages. In certain cases oscillator level control may be necessary. For example, the resonant circuit impedance of large tuning range oscillators varies greatly, and it may be necessary to maintain constant oscillator level through inclusion of automatic level control circuitry.

Low distortion levels can also be obtained with dual abrupt junction tuning diodes but the resulting tuning characteristic is very nonlinear. Back-to-back hyperabrupt tuning diodes offer both low distortion and linear tuning over part of their range.

Design Example 1: 0.6 to 2.5 MHz Wideband VCO

Fmin=0.6 MHz, Fmax=2.5 MHz,
Equation 2 gives R=4.17.

R is greater than 1.4 thus use a wideband unit.

Assume Cp=15 pF.

Select an HF diode from the catalog.

To ensure frequency coverage choose the highest capacitance KV1801 which has Cmin=C(10 V)=26.5 pF.

Equation 4 gives
Cmax=(17.36-1)15 pF+(17.36)26.5 pF=705.5 pF.

Equation 5 gives

$$L = \frac{24,330}{(15 + 26.5)6.25} = 97.7 \mu H$$

The inductor value is acceptable for the HF series, including the KV1801, C(0 V)/C(10 V) = 34.39 giving a typical C(0V) of 911.3 pF which is far greater than the required Cmax of 705.5 pF. In practice the tuning range should be 0.5 to 10 volts.

The wide frequency range leads to very large impedance changes of the tuned circuit. For example use a loaded Q of 80 for the tuned circuit which then has resonant impedances of 29,000 ohms at 0.6 MHz and 123,000 ohms at 2.5 MHz. Some form of automatic level control must be used to maintain the AC level across the diode at less than 300 mV rms. The complete circuit including level control is shown in Figure 3.

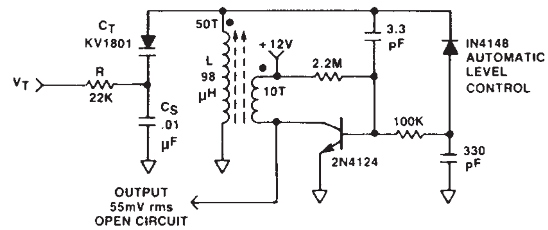

Figure 3.

Measured results:

V_T(Vdc)	FREQ (MHz) ACTUAL	CALC.	
0	0.5501	0.547	Output Level
1	0.6923	0.693	Variation Approx.
2	0.8630	0.865	±1 dB Over Entire
3	1.2106	1.170	Range.
4	1.7984	1.700	
5	2.1193	2.040	Second Harmonic
6	2.3033	2.230	>22 dB Below
7	2.4327	2.370	Fund.
8	2.5312	2.470	
9	2.6116	2.560	Third Harmonic
10	2.6781	2.630	>40 dB Below
			Fund.

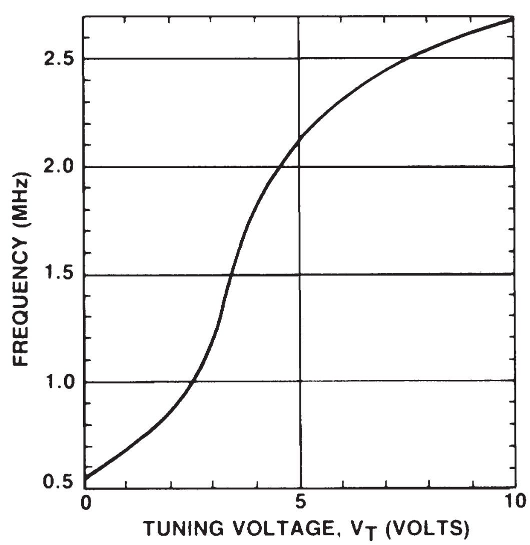

Figure 4.

Design Example 2: 40.7 to 60.7 MHz Synthesized Receiver L.O.

Fmin=40.7 MHz, Fmax=60.7 MHz,

Equation 2 gives R=1.491.

R is near enough to 1.4 to use straight line tuning which results in a fixed oscillator constant and simpler loop design. No trimmer is required thus assume Cp=6 pF. A VHF hyperabrupt diode tuned over the 4 to 8 volt region is appropriate. We will use the KV2201 which is a good choice for this frequency range.

Cmin=C(8V)=19.5 pF.

Eq. 4 gives
Cmax=(2.223-1)6 pF+(2.223)19.5 pF=50.7 pf.

Eq. 5 gives $L = \frac{25,330}{(6+19.5)60.7^2} = 0.2\ \mu H$

The Cmax and L values are acceptable, particularly since the KV2201 achieves Cmax near V_T=4 Vdc.

Other devices such as the KV2301 or KV2401 may be substituted for the KV2201 simply by changing the inductor. The KV2201 offers highest circuit Q and impedance but performance is sensitive to changes in stray capacitance. Usage of the KV2301 or KV2401 lessens this sensitivity at the cost of lower Q.

The following circuit employs the KV2201 but illustrates the alternate use of back-to-back KV2301 diodes to achieve low harmonic content with no other circuit changes.

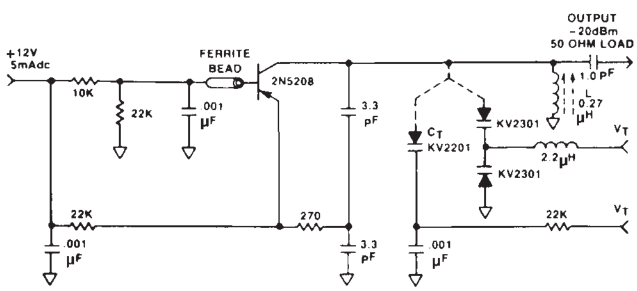

Figure 5.

Measured results follow, illustrating (1) the tendency for Cp to be higher than expected as evidenced by the actual 3.7 to 8.3 volt tuning range; (2) the low harmonic content achieved using back-to-back diodes; (3) the large achievable frequency range over which output and distortion changes are small.

V_T(Vdc)	FREQ. (MHz)
2	36.6
3	39.1
4	41.7
5	44.8
6	48.9
7	54.1
8	59.1
9	63.5
10	67.0
11	69.8
12	71.9
13	74.1
14	75.7
15	77.0
16	78.1
17	79.4
18	80.4
19	81.4
20	82.2

Using one KV2201
fundamental – 29 dBm
2nd harm. 25 dB below fund.
3rd harm. 36 dB below fund.

Using two KV2301
fundamental – 23 dBm
2nd harm. 42 dB below fund.
3rd harm. 52 dB below fund.

Replacing diodes with a 22 pF fixed capacitor
fundamental – 20 dBm
2nd harm. 42 dB below fund.
3rd harm. 47 dB below fund.

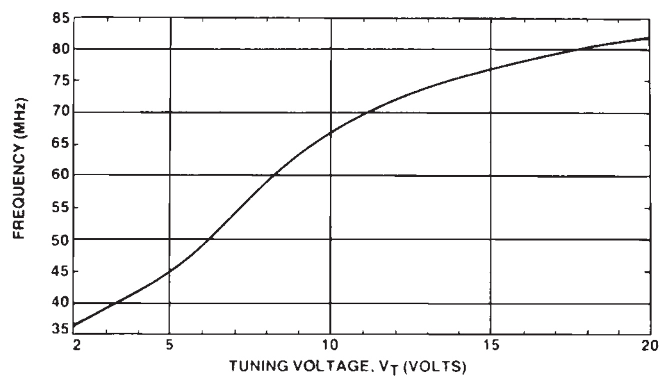

Figure 6.

Design Example 3: 200 to 400 MHz VCO

Octave coverage at high frequencies necessitates very low stray capacitances. Select the KV2101 UHF diode for its high Q. To ensure octave coverage use the data sheet minimum value for C(3 V) = 10.5 pF and the specified maximum C(20 V) = 2.3 pF. Tune the device from zero to twenty volts and make the tuning diode part of the capacitive divider. The series padder is chosen to be Cs=39 pF which is selected by trial and error in the actual circuit. It is also the smallest value which allows the diode to cover the required frequency range.

Cmax=C(0 V)=2.003(10.5 pf)=21.03 pF worst case.

As stated above, worst case
Cmin=2.3 pF and Cs=39 pF.

The following circuit may be used if care is exercised in construction to avoid unwanted resonances. Nonetheless, oscillations may cease when the oscillator is tuned below one volt where tuning diode Q is low.

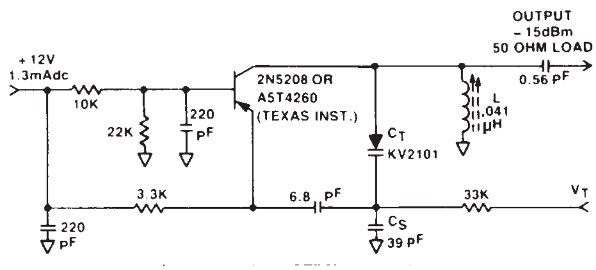

Figure 7.

Measured results:

V_T(Vdc)	FREQ (MHz) ACTUAL	CALC.	V_T(Vdc)	FREQ (MHz) ACTUAL	CALC.
0.32	200	201.9	8.41	320	
1.72	220		9.64	340	344.5
3.28	240	244.5	11.30	360	
4.81	260		13.99	380	
6.10	280		19.85	400	411.1
7.24	300	307.0			

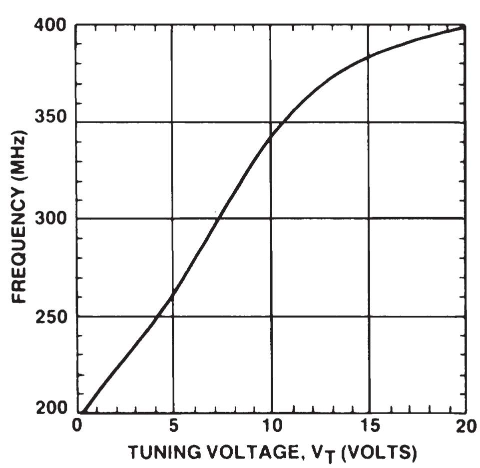

Figure 8.

Design Example 4: 750 to 950 MHz VCO

Design at UHF with lumped elements requires some trial and error in circuit construction, especially since the external dimension of the packaged tuning diode approached the length of the tuning inductor which is normally a short piece of PC board foil. The simplicity of the following circuit provides an initial design.

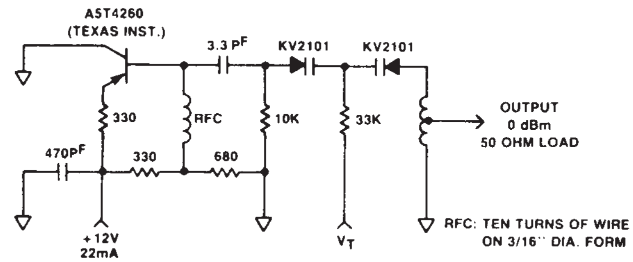

Figure 9.

Measured results:

V_T(Vdc)	FREQ (MHz)	OUTPUT(dBM)	V_T(Vdc)	FREQ (MHz)	OUTPUT(dBm)
0	720	-2	9.32	900	0
2.10	750	-1	10.42	925	0
5.73	800	-2	11.74	950	0
7.61	850	-2			

As noted in Design Example 4, UHF circuits are quite sensitive to layout and problems may be encountered with spurious oscillations or cessation of oscillations at points in the tuning range. The problem most frequently occurs at very low tuning voltages where the tuning diode Q is lowest. Solutions are selection of high ft transistors, increased inductor Q, or avoidance of low tuning voltages. Occasionally oscillations may cease in the middle of the tuning range because of spurious resonances in the circuit layout or in chokes and capacitors. Such spurious resonances must then be isolated and corrected.

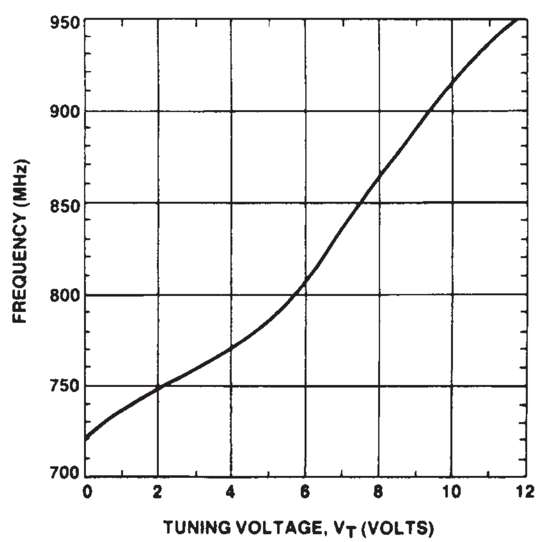

Figure 10.

APPENDIX I

NORMALIZED CAPACITANCE – VOLTAGE VALUES

HF SERIES	VHF SERIES	UHF SERIES
KV1401	KV2001	KV2101
KV1501	KV2201	KV2801
KV1601	LV2301	
KV1701	KV2401	
KV1801	KV2501	
	KV2601	
	KV2701	

V (VOLTS)	C (NORM.)	C (NORM.)	C (NORM.)
0	2.6960	2.495	2.003
0.5	2.0310	2.033	1.642
1.0	1.6110	1.766	1.432
1.5	1.2840	1.570	1.286
2.0	1.0000	1.422	1.173
2.5	0.7420	1.300	1.081
3.0	0.5230	1.192	1.000
3.5	0.3440	1.094	0.928
4.0	0.2300	1.000	0.862
4.5	0.1770	0.909	0.797
5.0	0.1500	0.817	0.735
5.5	0.1330	0.725	0.673
6.0	0.1210	0.635	0.612
6.5	0.1110	0.555	0.555
7.0	0.1040	0.487	0.502
7.5	0.0980	0.433	0.458
8.0	0.0928	0.390	0.421
8.5	0.0882	0.354	0.390
9.0	0.0848	0.326	0.363
9.5	0.0813	0.302	0.341
10.0	0.0784	0.282	0.322
11.0	—	0.251	0.292
12.0	—	0.229	0.269
13.0	—	0.212	0.246
14.0	—	0.199	0.231
15.0	—	0.188	0.219
16.0	—	0.179	0.209
17.0	—	0.171	0.200
18.0	—	0.164	0.193
19.0	—	0.157	0.186
20.0	—	0.152	0.180