Zetex Variable Capacitance Diodes

Neil Chadderton

Introduction

The advent of varactor diodes has made a huge impact in many areas of electronic design, which is only too evident in todays consumer products. Formerly, where bulky or unreliable mechanical methods were used, the size, reliability and excellent tracking abilities of the varactor has led to smaller, cheaper and more elaborate circuitry, previously impossible to attain.

Zetex manufacture an extensive range of Variable Capacitance diodes that are processed using ion-implantation techniques to assure accurate doping levels, and hence produce the exacting junction profiles necessary for high performance devices. An overall capacitance range of approximately 1pF to 200pF assures a broad applications base, enabling designs operating from kHz and extending into the microwave region. Product variability within specification is comparable to, or better than, competitors devices; the Hyperabrupt series, for example, are available to 5% tolerance on nominal capacitance, due to close targeting during fabrication. Furthermore, Zetex are capable of matching (either to device type or customer specifications) or banding on capacitance parameters, as required. They are available in surface mount (SOT-23) or E-Line style packages that exhibit low inductance ensuring a wide frequency application, and assure environmental endurance and mechanical reliability.

This application note gives some basic background information, examines the important parameters and specifications for the Zetex range of devices, and suggests a few application circuit examples.

Background

The varactor diode is a device that is processed so to capitalise on the properties of the depletion layer of a P-N diode. Under reverse bias, the carriers in each region (holes in the P type and electrons in the N type) move away from the junction, leaving an area that is depleted of carriers. Thus a region that is essentially an insulator has been created, and can be compared to the classic parallel plate capacitor model. The effective width of this depletion region increases with reverse bias, and so the capacitance decreases. Thus the depletion layer effectively creates a voltage dependent junction capacitance, that can be varied between the forward conduction region and the reverse breakdown voltage (typically +0.7V to -35V respectively for the ZC830 and ZC740 series diodes).

Different junction profiles can be produced that exhibit different Capacitance-Voltage(C-V) characteristics. The Abrupt junction type for example, shows a small range of capacitance due to its diffusion profile, and as a consequence of this is capable of high Q and low distortion, while the Hyperabrupt variety allows a larger change in capacitance for the same range of reverse bias. So called Hyper-hyperabrupt, or octave tuning variable capacitance diodes show a large change in capacitance for a relatively small change in bias voltage.This is particularly useful in battery powered systems where the available bias voltage is limited.

The varactor can be modelled as a variable capacitance (Cjv), in series with a resistance (Rs). (Please refer to Figure 1).

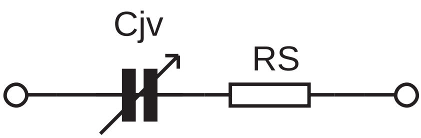

Figure 1
Common Model for the Varactor Diode.

The capacitance, Cjv, is dependent upon the reverse bias voltage, the junction area, and the doping densities of the semiconductor material, and can be described by:

$$Cjv = \frac{Cj0}{(1+V_r/\varphi)^N}$$

Where:

Cj0 = Junction capacitance at 0V
Cjv = Junction capacitance at applied bias voltage Vr
Vr = Applied bias voltage
φ = Contact Potential
N = Power law of the junction or slope factor.

The series resistance exists as a consequence of the remaining undepleted semiconductor resistance, a contribution due to the die substrate, and a small lead and package component, and is foremost in determining the performance of the device under RF conditions.

This follows, as the quality factor, Q, is given by:

$$Q = \frac{1}{2\pi f C_{jv} R_s}$$

Where:

Cjv = Junction capacitance at applied bias voltage Vr
Rs = Series Resistance
f = Frequency

So, to maximise Q, R_s must be minimised. This is achieved by the use of an epitaxial structure so minimising the amount of high resistivity material in series with the junction.

NOTE: Zetex has produced a set of SPICE models to enable designers to simulate their circuits in SPICE, PSPICE and similar simulation packages. The models use a version of the above capacitance equation and so the model parameters may also be of interest for other software packages. Information is also provided to allow inclusion of parasitic elements to the model. These models are available on request, from any Zetex sales office.

Important Parameters

This section reviews the important characteristics of varactor diodes with particular reference to the Zetex range of variable capacitance diodes.

The characteristic of prime concern to the designer is the Capacitance-Voltage relationship, illustrated by a C-V curve, and expressed at a particular voltage by Cx, where x is the bias voltage. The C-V curve summarises the range of useful capacitance, and also shows the shape of the relationship, which may be relevant when a specific response is required. Figures 2a, 2b and 2c show families of C-V curves for the ZC740-54 (Abrupt), ZC830-6 (Hyperabrupt), and ZC930 (Hyper- hyperabrupt) ranges respectively. Obviously, the choice of device type depends upon the application, but aspects to consider include: the range of frequencies the circuit must operate

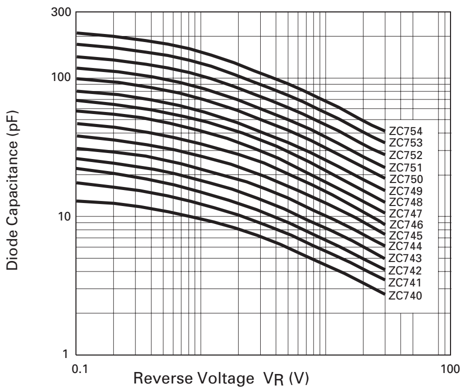

Figure 2a
Typical Capacitance-Voltage Characteristics for the ZC740-54 Range.

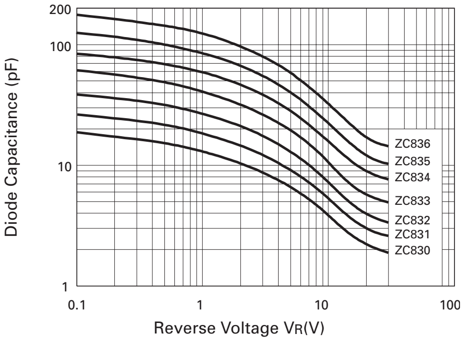

Figure 2b
Typical Capacitance-Voltage Characteristics for the ZC830-6 Range.

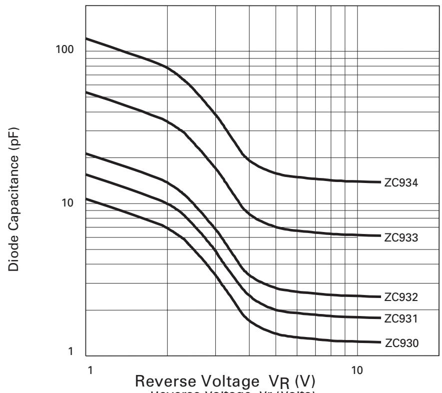

Figure 2c
Typical Capacitance-Voltage Characteristics for the ZC930-4 Range.

with, and hence an appropriate capacitance range; the available bias voltage; and the required response.

The capacitance ratio, commonly expressed as Cx/Cy (where x and y are bias voltages), is a useful parameter that shows how quickly the capacitance changes with applied bias voltage. So, for an Abrupt junction device, a C2/C20 figure of 2.8 may be typical, whereas a C2/C20 ration of 6 may be expected for a Hyperabrupt device. This feature of the Hyperabrupt variety can be particularly important when assessing devices for battery-powered applications, where the bias voltage range may be limited. In this instance, the ZC930 series that feature a better than 2:1 tuning range for a 0 to 6V bias may be of particular interest.

The quality factor, Q, at a particular condition is a useful parameter in assessing the performance of a device with respect to tuned circuits, and the resulting loaded Q.

Zetex guarantee a minimum Q at test conditions of 50MHz, and a relatively low V_R of 3 or 4V, and ranges 100 to 450 depending on device type (see Product Range Tables).

The specified V_R is very important in assessing this parameter, because as well as the C-V dependence as detailed previously, a significant part of the series resistance (Rs), is due to the remaining undepleted epitaxial layer, which is also dependant upon V_R. This Rs-V_R relationship is shown in Figure 3 for the ZC830, ZC833 and ZC836 Hyperabrupt devices, measured at frequencies of 470MHz, 300MHz and

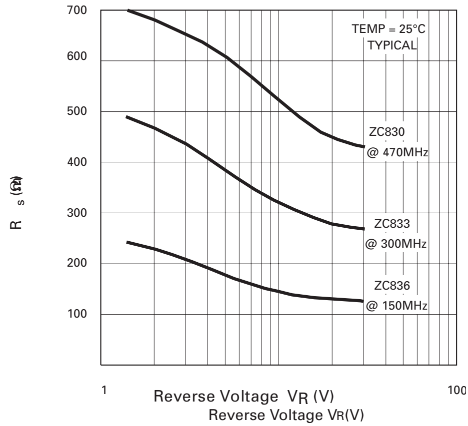

Figure 3
Typical R_S v V_R Relationship for ZC830 Series Diodes.

150MHz respectively, and also serves to illustrate the excellent performance of Zetex Variable Capacitance Diodes at VHF and UHF.

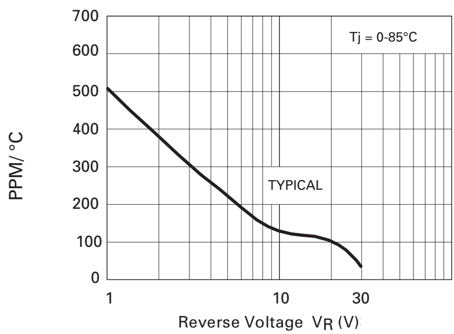

Figure 4a
Temperature Coefficient of Capacitance v V_R for the ZC740 Series.

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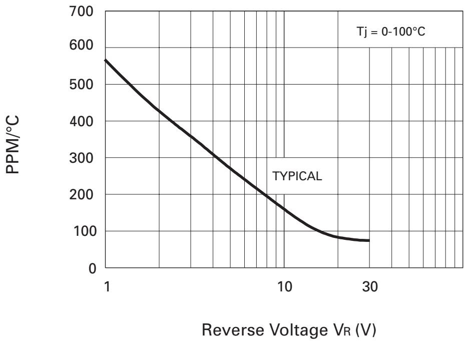

Figure 4b
Temperature Coefficient of Capacitance v V_R for the ZC830 Series.

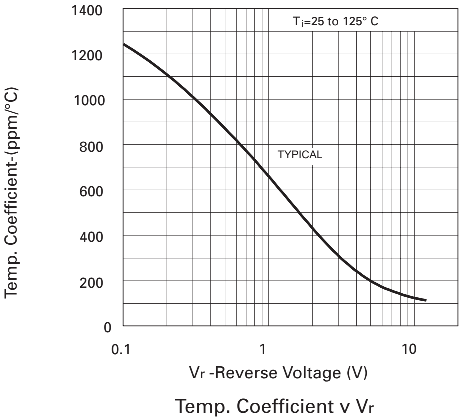

Figure 4c
Temperature Coefficient of Capacitance v V_R for the ZC930 Series.

Also of interest, with respect to stability, is the temperature coefficient of capacitance, as capacitance changes with V_R, and is shown for the three ranges in figures 4a, 4b and 4c respectively.

The reverse breakdown voltage, V(BR) also has a bearing on device selection, as this parameter limits the maximum V_R that may be used when biasing for minimum capacitance. Zetex variable capacitance diodes typically possess a V(BR) of 35V.

The maximum frequency of operation will depend on the required capacitance and the series resistance (and hence useful Q), that is possessed by a particular device type, but also of consequence are the parasitic components exhibited by the device package. These depend on the size, material, and construction of the package. For example, the Zetex SOT-23 package has a typical stray capacitance of 0.08pF, and a total lead inductance of 2.8nH, while the E-Line package shows less than 0.2pF and 5nH respectively. These low values allow a wide frequency application, for example, the ZC830 and ZC930 series, configured as series pairs are ideal for low cost microwave designs extending to 2.5GHz and above.

Applications

Variable capacitance diodes can be used in any tuned circuit application where previously mechanical methods were utilised, and provide a size, cost and performance advantage. This section briefly examines some typical examples of varactor application.

The conventional simple tuned circuit of Figure 5a can also be effected by the varactor version as in Figure 5b, where capacitor C1 isolates the DC bias. The choice of varactor for such a circuit depends on the tuning range and hence

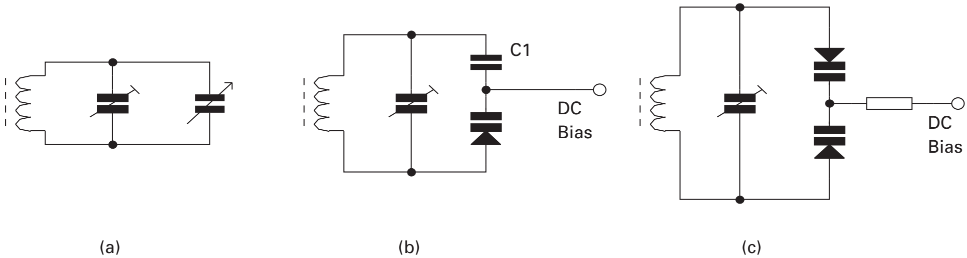

Figure 5
Basic Tuned Circuits.

capacitance, with particular attention being paid to the C-V region approaching 0V, as this may introduce non-linearity and poor Q. Another similar approach is to use the series configuration shown in Figure 5c which, while allowing a lower apparent diode capacitance, also prevents RF rectification at low values of diode bias therefore inhibiting generation of intermodulation products, and also simplifies bias requirements.

A practical front-end for an FM receiver is shown in Figure 6, with each stage being tuned by it's own diode. Multi-stage units are therefore possible without the severe tracking errors, and the massive size penalty inherent to mechanical mechanisms.

As the tuning is now controlled by a voltage, the inevitable inclusion of the microprocessor and memory in many modern receivers has allowed

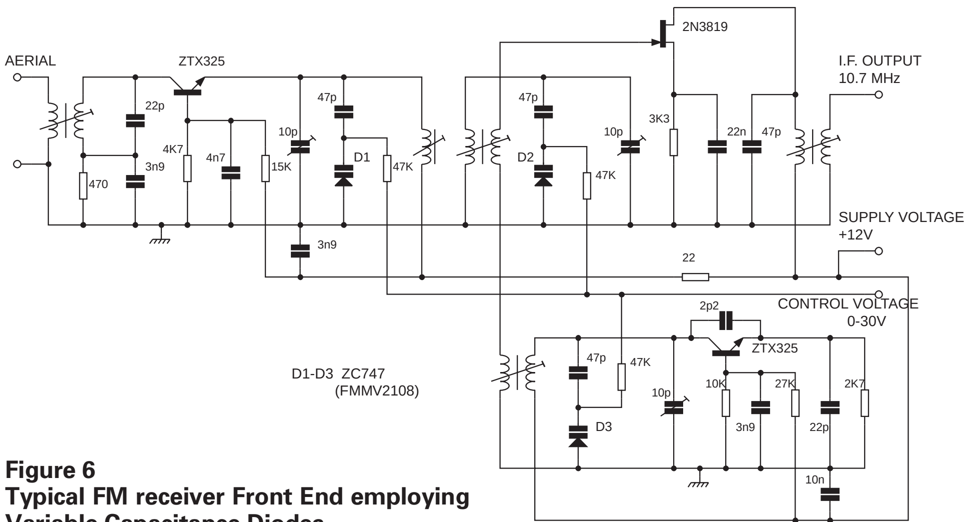

Figure 6
Typical FM receiver Front End employing Variable Capacitance Diodes.

band-scanning and station storage by producing the control voltage automatically. It is noteworthy that the control voltage of any system must possess good voltage and temperature stability.

Perhaps the largest effect on consumer products due to the varactor has been the development of varactor based VHF and UHF tuners for televisions. These have enabled solid state non-mechanical designs that are smaller, more reliable and allow elaborate features such as remote control and station searching. Figure 7 shows a typical circuit of a UHF tuner incorporating varactor diodes. Stage matching is effected by the bias trimmers RV1-5, and allows adjustment remote from the actual tuning element; the mechanical equivalent being to add padding capacitance, or to bend the vanes on an air-spaced capacitor.

Such a tuner can, using the large capacitance range of Hyperabrupt varactor diodes, tune the whole channel range of bands IV and V (470MHz-850MHz).

Another common application for the varactor is as the frequency controlling element in a Voltage Controlled Oscillator (VCO). There are many applications for such circuits, either as stand alone units or as part of a phase locked loop in a frequency synthesiser. This latter method is commonly utilised in radio telecommunications and for the tuning stages in satellite receivers. Closely allied to these are functions such as frequency pulling on crystal oscillators, narrow band FM and temperature compensation of frequency within an oscillator, all of which can benefit from a varactor diode based design.

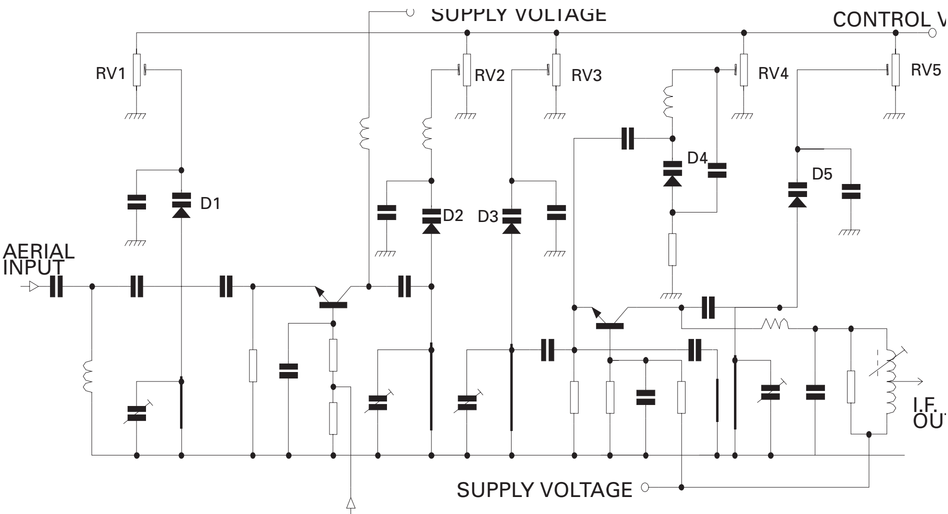

Figure 7
Typical UHF Variable Capacitance Diode Tuner Module.

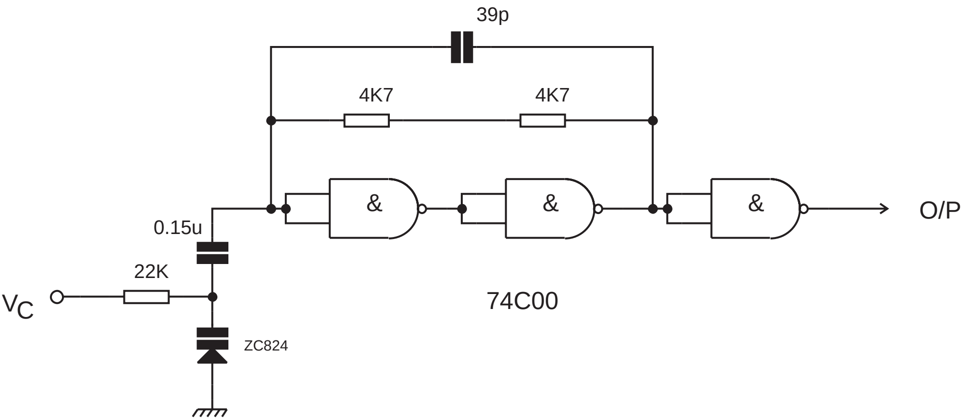

Figure 8
Basic Form of VCO using Logic Gates.

In it's basic form, and for a square wave output, a common method of providing a VCO is to use logic gates coupled as shown in Figure 8; this particular design giving a 1 to 1.25MHz range. For a transistor design, a VCO can be realised by modifying the Clapp configuration as shown in Figure 9. For this example, the frequency can be varied over a 75 to 150MHz range for a 0-30V control voltage.

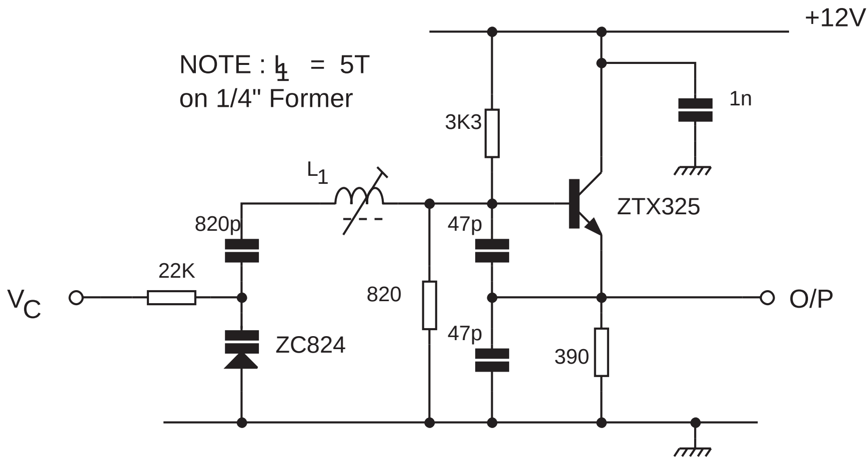

Figure 9
Transistor Effected VCO using Clapp Configuration.

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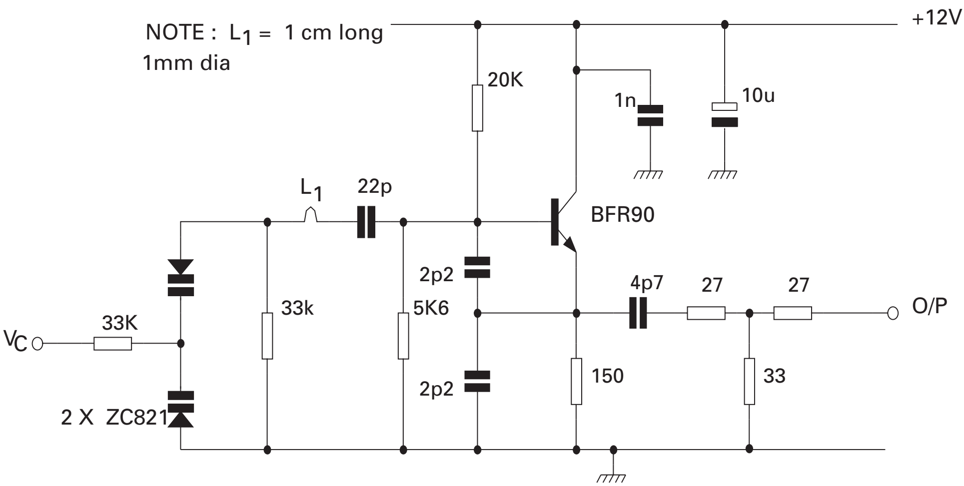


Figure 10
1GHz VCO Producing -5dBm with a 10dB PAD into 50Ω .

Figure 10 shows a similar configuration for a 1GHz VCO. Obviously at this frequency, circuit construction is critical and capable of producing large tuning range changes. For this example, the transistor was mounted in a slot in a small ground plane configured board, and the other components supported by short leads. This produced a signal level of -5dBm with a 10dB PAD into 50 ohms. The second harmonic was observed at -35dB down from the fundamental.

Other techniques using lumped components and Zetex variable capacitance diodes are capable of output at 1.5-2.5GHz, typically for tuning units for satellite receivers; one such design is included in Plessey's *"Satellite, Cable and TV Handbook"* as an alternative to the costly commercial VCO modules.

Low Phase Noise Capability

Due to the geometric features employed in the Zetex range of variable capacitance diodes, these products exhibit extremely low values of leakage current (typically less than 200 pA, and less for low capacitance options) which enables excellent low phase noise performance within VCXO circuitry.

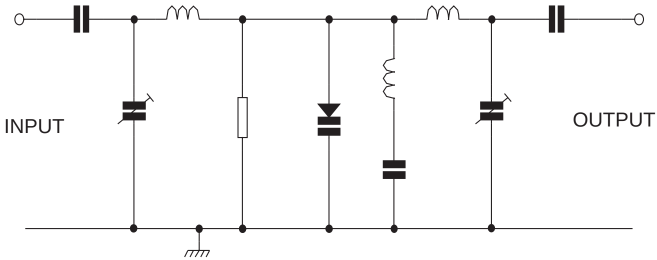
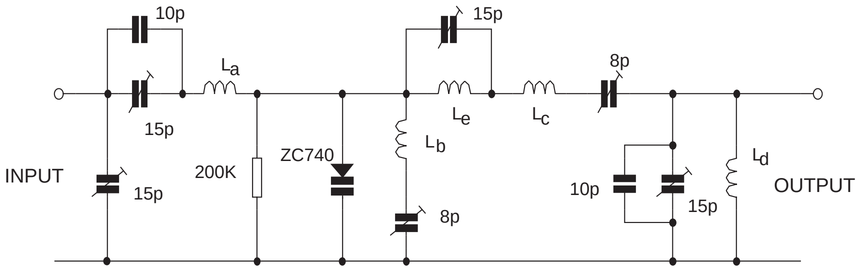


Figure 11a
Varactor Tripler with Matching Input and Output Stages.



Figures11b
Varactor Tripler with Bandpass Filtered Output and a Trap for the Fundamental.

Coil winding data: La 5¼ turns 16swg tinned copper ½" dia. Lb 3½ turns 18 swg tinned copper ⅜" dia.	Lc 3½ turns 16 swg tinned copper ⅜" dia. Ld ½ turn 16 swg tinned copper ½" dia. Le 7 turns 18swg tinned copper ⅜ "dia.

The varactor diode also enables frequency multipliers to be produced that exhibit very high conversion efficiency, a zero DC power requirement, and low component count. Figure 11a shows the general appearance of a varactor tripler, and consists of input and output matching, and a trap for the unwanted second harmonic. Figure 11b shows a similar circuit for a 100-300MHz tripler using a ZC740, and includes a bandpass filtered output and a trap for the fundamental.

Appendix

Zetex Variable Capacitance Diode Product Range.

The tables presented within this Appendix illustrate the standard abrupt, hyperabrupt and hyper-hyperabrupt ranges available with respect to datasheet characteristics and package style. In addition, Zetex can also supply to competitors' type numbers and customers' specific requirements.

HIGH PERFORMANCE HYPERABRUPT

Package		Nominal Capacitance(pF) (V_R=2V, f=1MHz)	Cap. ratio C2/C20 (f=1MHz)		Figure of Merit, Q Minimum (V_R =3V, f=50MHz)
E-Line	SOT 23		Min.	Max.	
ZC820	ZC830	10	5 (4.5)	6.5 (6)	300
ZC821	ZC831	15	5 (4.5)	6.5 (6)	300
ZC822	ZC832	22	5	6.5	200
ZC823	ZC833	33	5	6.5	200
ZC824	ZC834	47	5	6.5	200
ZC825	ZC835	68	5	6.5	100
ZC826	ZC836	100	5	6.5	100
		See note 1	See note 2		

HIGH PERFORMANCE HYPER-HYPERABRUPT

Package	Nominal Capacitance (pF)			Minimum Cap. ratio C1/C4 (f=1MHz)	Figure of Merit Q Minimum (V_R =4V, f=50 MHz)
SOT23	Min.	Max.	at V_R		
ZC930	4.3	5.5	2.5	3	350
ZC931	6.5	7.8	2.5	3.6	300
ZC932	8.5	10.5	2.5	3.1	200
ZC933	18	27	2.5	3.5	150
ZC934	40	65	2.5	3.8	80

Note 1: Available with 5% (suffix B), 10% (suffix A) and 20% tolerance on nominal capacitance.
2: SOT-23 figure in parenthesis when different.

HYPERABRUPT

Package SOT-23	Nominal Capacitance (pF) (f=1MHz)			Cap.ratio C3/C25 (f=1MHz)		Figure of Merit, Q Minimum (V_R=3V, f=50MHz)
	Min.	Max.	at V_R	Min.	Max.	
BBY31	1.8	2.8	25	5 (typ)		-
BBY40	26	32	3	5	6.5	-
	4.3	6	25	-	-	-
FMMV105G	1.8	2.8	25	4	6	350
FMMV109	26	32	3	5	6.5	250
FMMV3102	20	25	3	4.5	-	300

ABRUPT

Package		Nominal Capacitance (pF) (V_R=4V, f=1MHz)	Minimum Cap. ratio C2/C30 (f=1MHz)		Figure of Merit, Q Minimum (V_R=4V, f=50MHz)
E-Line	SOT-23		E-Line	SOT-23	
ZC740	FMMV2101	6.8	2.7	2.5	450
ZC741	FMMV2102	8.2	2.7	2.6	450
ZC742	FMMV2103	10	2.7	2.6	400
ZC743	FMMV2104	12	2.8	2.6	400
ZC744	FMMV2105	15	2.8	2.6	400
ZC745	FMMV2106	18	2.8	2.7	350
ZC746	FMMV2107	22	2.8	2.7	350
ZC747	FMMV2108	27	2.8	2.7	300
ZC748	FMMV2109	33	2.8	2.7	200
ZC749		39	2.8		150
ZC750		47	2.8		150
ZC751		56	2.8		150
ZC752		68	2.8		150
ZC753		82	2.8		100
ZC754		100	2.8		100
		See note 3			

Note 3: 10% tolerance on nominal capacitance.

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