# APN1013: A Differential VCO Design for GSM Handset Applications
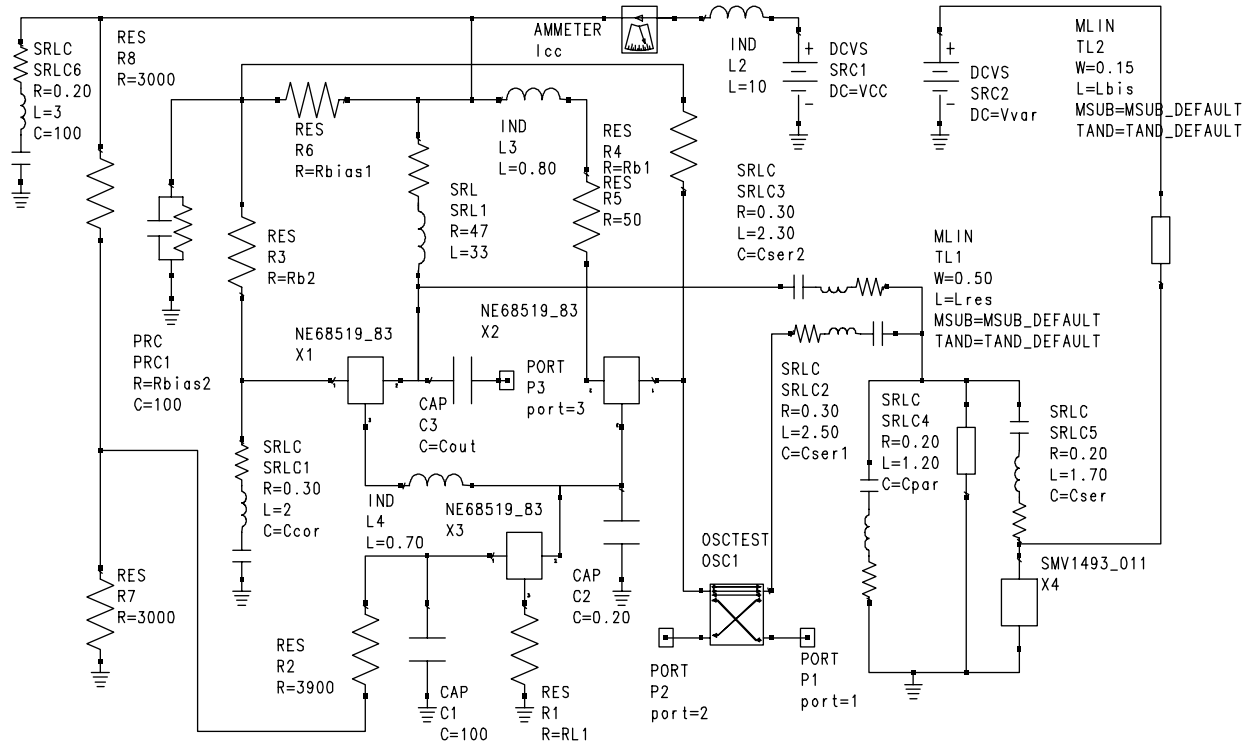
## Introduction

The differential pair of bipolar transistors is the common building block in modern RF integrated circuits. An advantage of this architecture is its high loop gain making it popular for differential Voltage Controlled Oscillator (VCO) designs in RFICs. Designers of discrete (or hybrid) VCO circuits usually use the more traditional Colpitts design, avoiding the added complexity of the differential VCO configuration.

Because of its primary usage in proprietary RFICs, only limited differential VCO design and modeling information has been made available. In this application note, we will attempt to build a bridge toward better understanding of the differential VCO by describing a design covering 910–980 MHz which is appropriate for use in GSM handsets. This design will also demonstrate how the SMV1493-079 varactor diode, an essential element in this VCO, may be used advantageously in designs aimed at other wireless applications including AMPS, CDMA, and PCS.

## The VCO Model

In the circuit in Figure 1 the transistor pair $X_1$ and $X_2$ form a differential configuration with $X_3$ as a current source. All of the transistors are NEC NE68519 with 12 GHz $f_T$. We chose this transistor for this demonstration because it is commonly used in many VCO applications and its SPICE parameters are available. The RF signal from collector of $X_1$ is fed through the coupling capacitor SRLC3 to the resonator. The resonator is formed by the parallel connection of capacitive branches SRLC4 and SRLC5/$X_4$, and the inductive branch formed by microstrip line $TL_1$. The output signal from the resonator is fed through the coupling capacitor SRLC2 to the base of transistor $X_2$, which is in differential feedback with $X_1$. There it closes the feedback path. Ideally, the phase shift between the base of $X_2$ and the collector of $X_1$ in the differential stage is 0°, and the oscillation should occur at the exact parallel resonance of the tank circuit. In reality, however, the phase shift in the differential pair is not 0°, because of unavoidable transit times and parasitic reactances.

For example, the phase shift in this loop changes from -50° to -100° in the frequency range of 0.8–1.5 GHz. To compensate this (capacitive) phase shift, the resonator should be inductive and provide an opposite phase shift. It is interesting to note that compared to the Colpitts VCO configuration, the resonant frequency may be set at the exact oscillation frequency. The Colpitts design cannot be used at the natural resonance frequency of the resonator due to losses in the feedback path. Therefore, the differential design has the advantage of both high phase slope at resonance and low loss in the feedback path.

SRLC
SRLC6
R=0.20
L=3
C=100
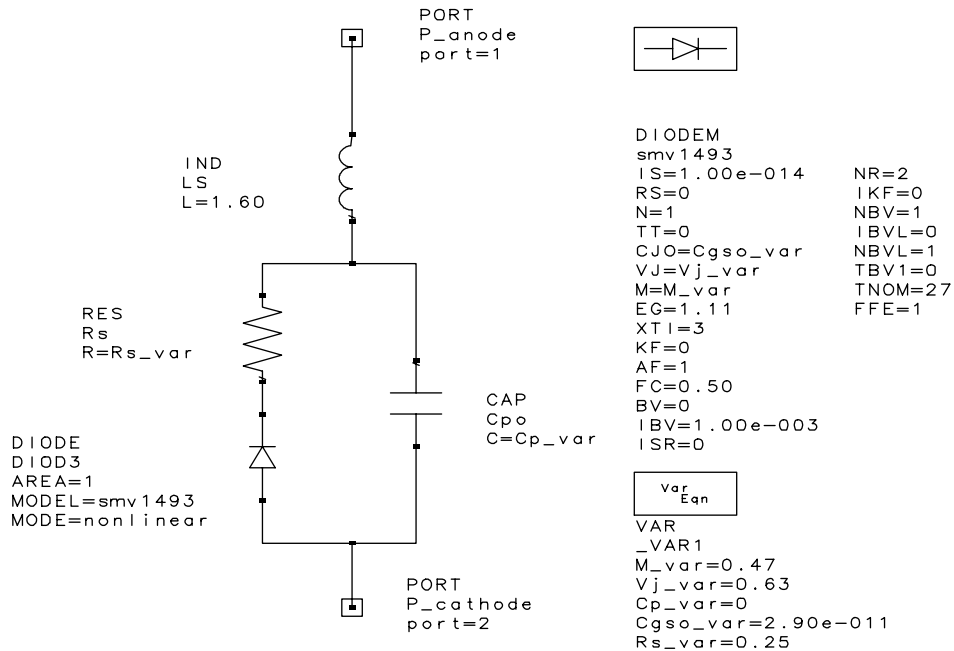
RES
R8
R=3000

AMMETER
Icc

IND
L2
L=10

+  DCVS
   SRC1
-  DC=VCC

+  DCVS
   SRC2
-  DC=Vvar

MLIN
TL2
W=0.15
L=Lbis
MSUB=MSUB_DEFAULT
TAND=TAND_DEFAULT

RES
R6
R=Rbias1

IND
L3
L=0.80

RES
R4
R=Rb1
RES
R5
R=50

SRLC
SRLC3
R=0.30
L=2.30
C=Cser2

SRL
SRL1
R=47
L=33

MLIN
TL1
W=0.50
L=Lres
MSUB=MSUB_DEFAULT
TAND=TAND_DEFAULT

RES
R3
R=Rb2

PRC
PRC1
R=Rbias2
C=100

NE68519_83
X1

NE68519_83
X2

CAP
C3
C=Cout

PORT
P3
port=3

SRLC
SRLC2
R=0.30
L=2.50
C=Cser1

SRLC
SRLC4
R=0.20
L=1.20
C=Cpar

SRLC
SRLC5
R=0.20
L=1.70
C=Cser

SRLC
SRLC1
R=0.30
L=2
C=Ccor

IND
L4
L=0.70

NE68519_83
X3

CAP
C2
C=0.20

OSCTEST
OSC1

SMV1493_011
X4

RES
R7
R=3000

RES
R2
R=3900

CAP
C1
C=100

RES
R1
R=RL1

PORT
P2
port=2

PORT
P1
port=1

**Spice Model for SMV1493-079**

PORT
P_anode
port=1

IND
LS
L=1.60

DIODEM
smv1493
IS=1.00e-014        NR=2
RS=0                IKF=0
N=1                 NBV=1
TT=0                IBVL=0
CJO=Cgso_var        NBVL=1
VJ=Vj_var           TBV1=0
M=M_var             TNOM=27
EG=1.11             FFE=1
XTI=3
KF=0
AF=1
FC=0.50
BV=0
IBV=1.00e-003
ISR=0

RES
Rs
R=Rs_var

CAP
Cpo
C=Cp_var

DIODE
DIOD3
AREA=1
MODEL=smv1493
MODE=nonlinear

Var
Eqn

VAR
_VAR1
M_var=0.47
Vj_var=0.63
Cp_var=0
Cgso_var=2.90e-011
Rs_var=0.25

PORT
P_cathode
port=2

**Figure 1. VCO Model Schematic**

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Capacitors SRLC2 and SRLC3 are used to obtain the required phase shift at the center of the tank circuit resonant frequency. By changing the values of these capacitors, optimum phase noise may be achieved.

Resistor $R_5$ suppresses higher frequency oscillation modes caused by the parasitic resonance between SRLC4 and varactor branch SRLC5/$X_4$. A resistance of 20–50 $\Omega$ is normally enough to perform this function without serious degradation of loop power and phase noise.

The differential stage bias is set by voltage dividers $R_6$/PRC1 and $R_8$/$R_7$. The base currents are limited by $R_3$ and $R_5$ for the differential pair and $R_2$ for the current source. In this case, the 3 V, $V_{CC}$ current is set to about 7 mA.

In the VCO model test bench in Figure 2 we define open loop gain, Ku = $V_{OUT}$/$V_{IN}$, as the ratio of voltage phasors at the input and output ports of an OSCTEST component. Defining the oscillation point is a technique to balance input (loop) power to provide zero gain for a zero loop phase shift. Once the oscillation point is defined, the frequency and output power may be "measured." We do not recommend the use of the OSCTEST2 component for closed loop analysis, since it may not converge and does not allow clear insight to VCO behavior.
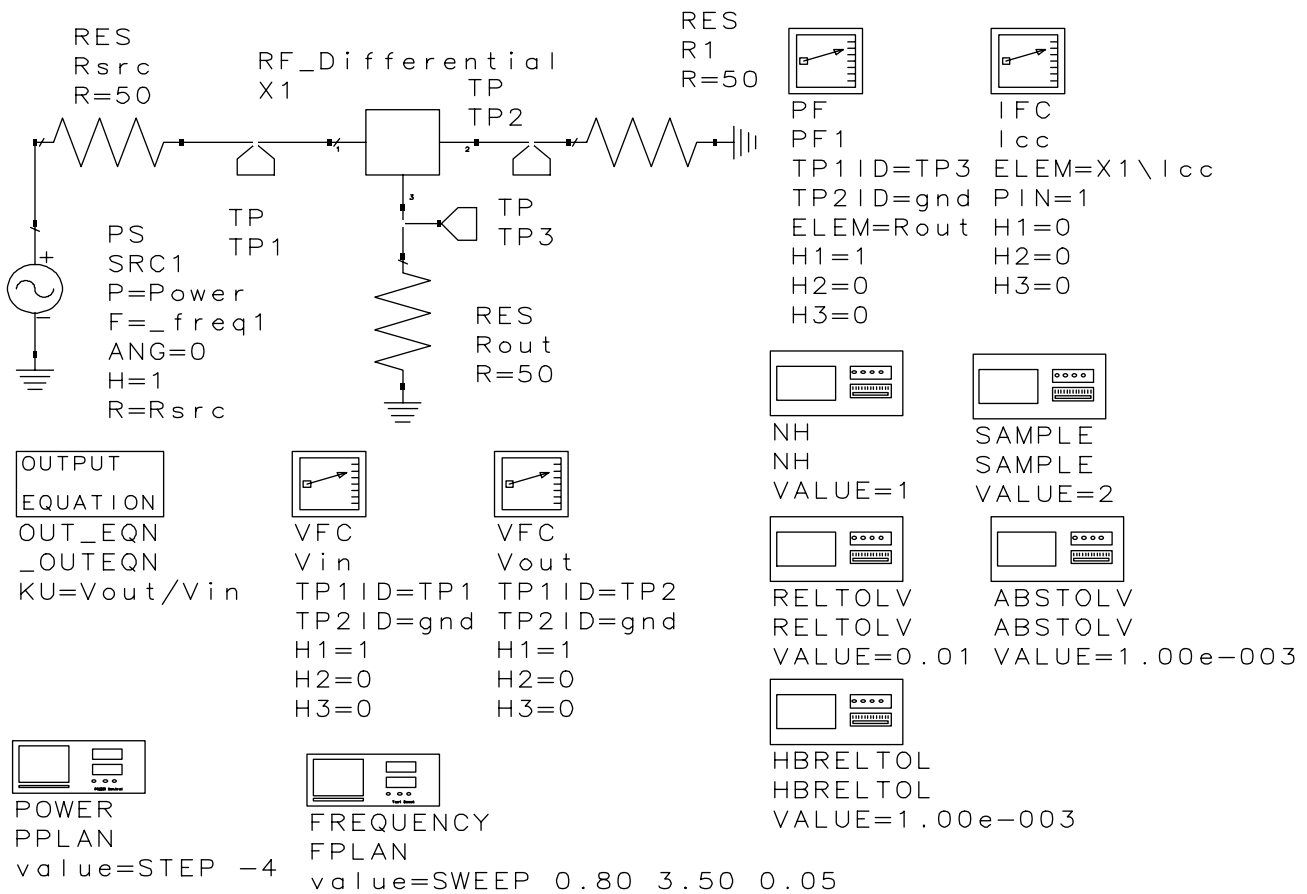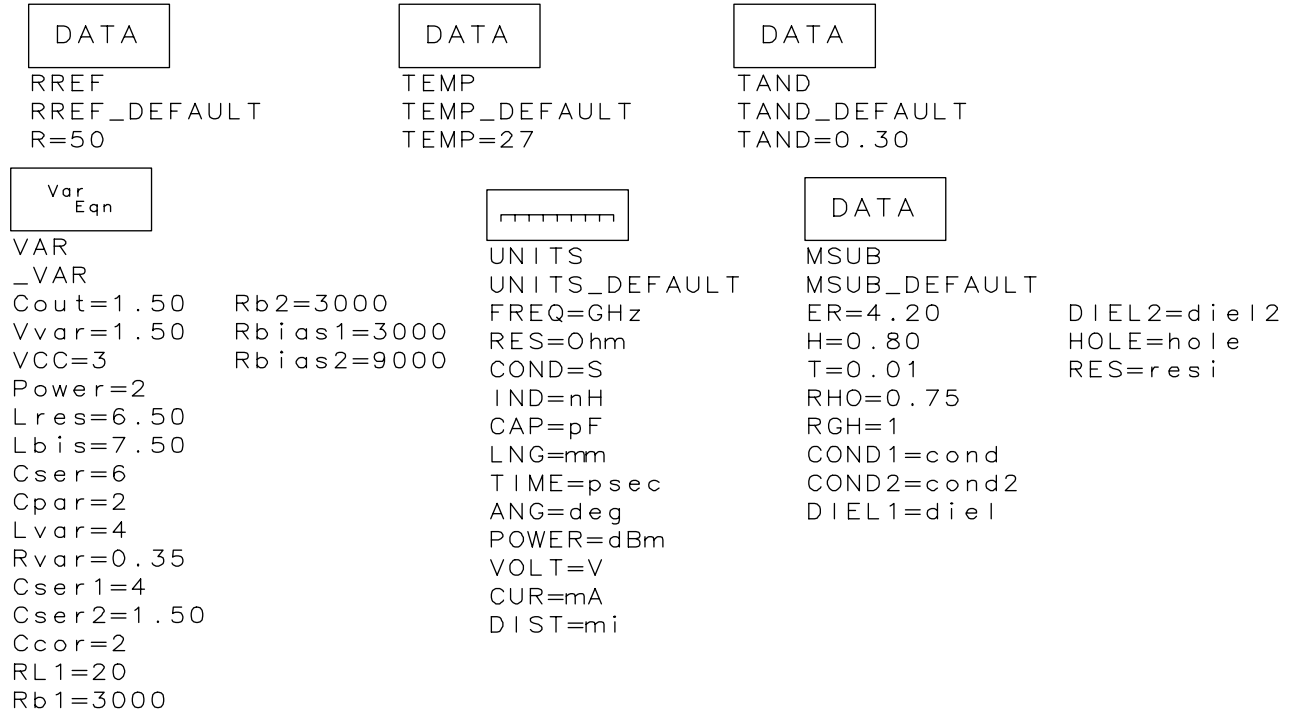


**Figure 2. VCO Model Test Bench**

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| DATA | | DATA | | DATA | |
|---|---|---|---|---|---|
| RREF | | TEMP | | TAND | |
| RREF_DEFAULT | | TEMP_DEFAULT | | TAND_DEFAULT | |
| R=50 | | TEMP=27 | | TAND=0.30 | |

| Var<br>Eqn | | | | DATA | |
|---|---|---|---|---|---|

VAR
_VAR
Cout=1.50    Rb2=3000
Vvar=1.50    Rbias1=3000
VCC=3        Rbias2=9000
Power=2
Lres=6.50
Lbis=7.50
Cser=6
Cpar=2
Lvar=4
Rvar=0.35
Cser1=4
Cser2=1.50
Ccor=2
RL1=20
Rb1=3000

UNITS
UNITS_DEFAULT
FREQ=GHz
RES=Ohm
COND=S
IND=nH
CAP=pF
LNG=mm
TIME=psec
ANG=deg
POWER=dBm
VOLT=V
CUR=mA
DIST=mi

MSUB
MSUB_DEFAULT
ER=4.20          DIEL2=diel2
H=0.80           HOLE=hole
T=0.01           RES=resi
RHO=0.75
RGH=1
COND1=cond
COND2=cond2
DIEL1=diel

**Figure 3. VCO Model Default Bench**

Figure 3 shows the default bench where some circuit variables were defined in the "Variables and Equations" component for the convenience of "tuning" during performance analysis and optimization

## SMV1493-079 SPICE Model

SMV1493-079 is a low series resistance, hyperabrupt junction varactor diode. It features the industry's smallest plastic package SC-79 with a body size of 47 x 31 x 24 mm (the total length with leads is 62 mm).

The SPICE model for the SMV1493-079 varactor diode, defined for the Libra IV environment, is shown in Figure 1 with a description of the parameters employed.

Table 1 describes the model parameters. It shows default values appropriate for silicon varactor diodes that may be used by the Libra IV simulator.

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| Parameter | Description | Unit | Default |
|---|---|---|---|
| IS | Saturation current (with N, determine the DC characteristics of the diode) | A | 1e-14 |
| $R_S$ | Series resistance | Ω | 0 |
| N | Emission coefficient (with IS, determines the DC characteristics of the diode) | - | 1 |
| TT | Transit time | S | 0 |
| $C_{JO}$ | Zero-bias junction capacitance (with $V_J$ and M define nonlinear junction capacitance of the diode) | F | 0 |
| $V_J$ | Junction potential (with $V_J$ and M define nonlinear junction capacitance of the diode) | V | 1 |
| M | Grading coefficient (with $V_J$ and M define nonlinear junction capacitance of the diode) | - | 0.5 |
| $E_G$ | Energy gap (with XTI, helps define the dependence of IS on temperature) | eV | 1.11 |
| XTI | Saturation current temperature exponent (with $E_G$, helps define the dependence of IS on temperature) | - | 3 |
| KF | Flicker noise coefficient | - | 0 |
| AF | Flicker noise exponent | - | 1 |
| FC | Forward bias depletion capacitance coefficient | - | 0.5 |
| $B_V$ | Reverse breakdown voltage | V | Infinity |
| $I_{BV}$ | Current at reverse breakdown voltage | A | 1e-3 |
| ISR | Recombination current parameter | A | 0 |
| NR | Emission coefficient for ISR | - | 2 |
| IKF | High injection knee current | A | Infinity |
| NBV | Reverse breakdown ideality factor | - | 1 |
| IBVL | Low-level reverse breakdown knee current | A | 0 |
| NBVL | Low-level reverse breakdown ideality factor | - | 1 |
| $T_{NOM}$ | Nominal ambient temperature at which these model parameters were derived | °C | 27 |
| FFE | Flicker noise frequency exponent | - | 1 |

**Table 1. Silicon Diode Default Values in Libra IV**

According to the SPICE model, the varactor capacitance, $C_V$, is a function of the applied reverse DC voltage, $V_R$, and may be expressed as follows:

$$C_V = \frac{C_{JO}}{\left(1 + \frac{V_{VAR}}{V_J}\right)^M} + C_P$$

This equation is a mathematical expression of the capacitance characteristic. The model is accurate for abrupt junction varactors (like the SMV1408). For hyperabrupt junction varactors, the model is less accurate because the coefficients are dependent on the applied voltage. To make the equation work better for the hyper-abrupt varactors, the coefficients were optimized for the best capacitance vs. voltage fit as shown in Table 2 and Figure 4.

Note, that in the Libra model above, $C_P$ is given in picofarads, while $C_{GO}$ is given in farads to comply with the default unit system used in Libra.

| Part Number | $C_{JO}$ (pF) | M | $V_J$ (V) | $C_P$ (pF) | $R_S$ (Ω) | $L_S$ (nH) |
|---|---|---|---|---|---|---|
| SMV1493-079 | 29 | 0.47 | 0.63 | 0 | 0.25 | 1.7 |

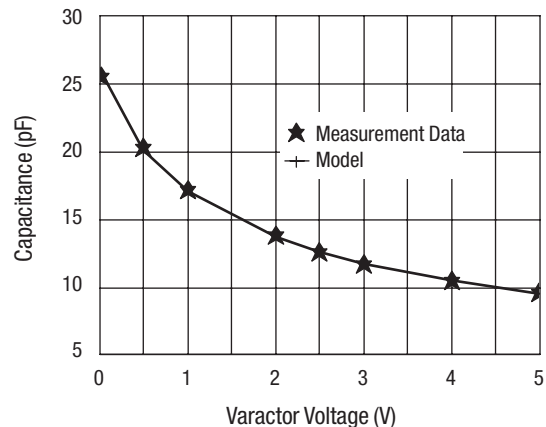**Table 2. SPICE Parameters for SMV1493-079**



**Figure 4. SMV1493-079 $C_V$ Curve**

## VCO Design, Materials, Layout and Performance

The differential VCO schematic diagram appropriate for an RFIC in many wireless or cordless applications is shown in Figure 5. This circuit is supplied from the 3 V voltage source. The $I_{CC}$ current is established at approximately 8 mA, and the RF output signal is fed from the VCO through capacitor $C_4$ (1 pF).

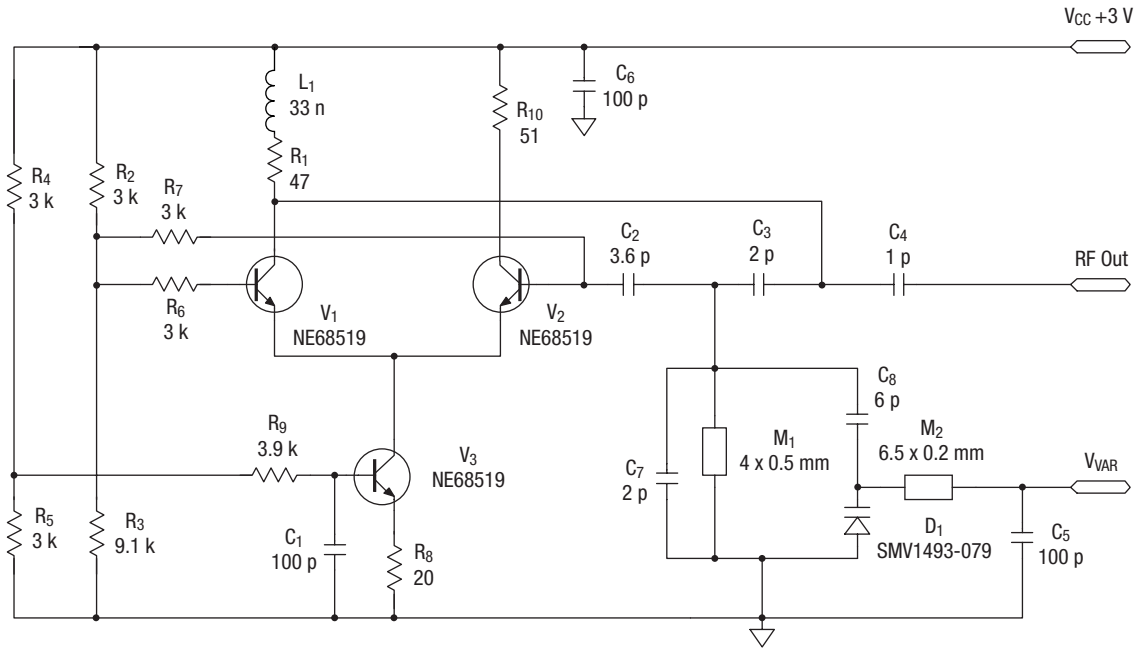The PCB layout is shown in Figure 6. The board is made of standard 30 mil thick FR4 material.

Table 3 lists the bill of materials.



Figure 5. VCO Schematic Diagram
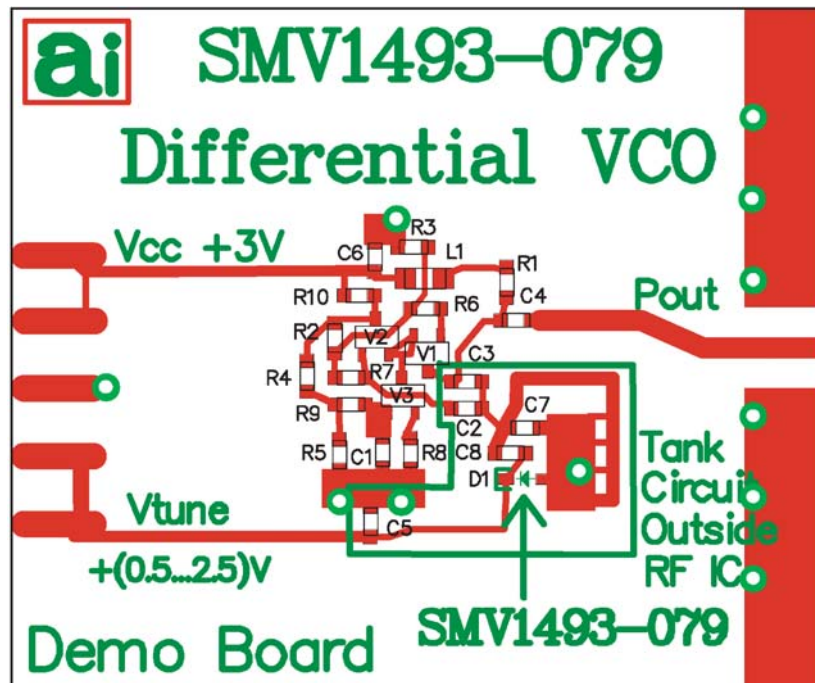


Figure 6. Differential VCO PC Board Layout

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| Designator | Value | Part Number | Footprint | Manufacturer |
|---|---|---|---|---|
| $C_1$ | 100 p | 0603AU101JAT9 | 0603 | AVX |
| $C_2$ | 3.6 p | 0603AU3R6JAT9 | 0603 | AVX |
| $C_3$ | 2 p | 0603AU2R0JAT9 | 0603 | AVX |
| $C_4$ | 1 p | 0603AU1R0JAT9 | 0603 | AVX |
| $C_5$ | 100 p | 0603AU101JAT9 | 0603 | AVX |
| $C_6$ | 100 p | 0603AU101JAT9 | 0603 | AVX |
| $C_7$ | 2 p | 0603AU2R0JAT9 | 0603 | AVX |
| $C_8$ | 6 p | 0603AU6R0JAT9 | 0603 | AVX |
| $D_1$ | SMV1493-079 | SMV1493-079 | SOD-323 | Skyworks Solutions |
| $L_1$ | 33 n | 0603CS-33NX_BC | 0603 | Coilcraft |
| $M_1$ | 4 x 0.5 mm | MSL | 4 x 0.5 mm | |
| $M_2$ | 6.5 x 0.2 mm | MSL | 6.5 x 0.2 mm | |
| $R_1$ | 47 | CR10-470J-T | 0603 | AVX |
| $R_{10}$ | 51 | CR10-510J-T | 0603 | AVX |
| $R_2$ | 3 k | CR10-302J-T | 0603 | AVX |
| $R_3$ | 9.1 k | CR10-912J-T | 0603 | AVX |
| $R_4$ | 3 k | CR10-302J-T | 0603 | AVX |
| $R_5$ | 3 k | CR10-302J-T | 0603 | AVX |
| $R_6$ | 3 k | CR10-302J-T | 0603 | AVX |
| $R_7$ | 3 k | CR10-302J-T | 0603 | AVX |
| $R_8$ | 20 | CR10-200J-T | 0603 | AVX |
| $R_9$ | 3.9 k | CR10-392J-T | 0603 | AVX |
| $V_1$ | NE68519 | NE68519 | SOT-416 | NEC |
| $V_2$ | NE68519 | NE68519 | SOT-416 | NEC |
| $V_3$ | NE68519 | NE68519 | SOT-416 | NEC |

**Table 3. VCOs Bill of Materials**

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The measured performance of this circuit and the simulated results obtained with the model are shown in Figure 7.

Fairly good compliance of frequency response vs. varactor tuning voltage confirms the validity of the varactor model for predicting the frequency behavior of the VCO. However, the power response simulation indicates more variation of power in the tuning range than the measured response. This may be due to the transistor modeling accuracy or the accuracy of the overall VCO model. For example, simulations show that the power may strongly depend on high order harmonics which may not be accurately described by the VCO model.
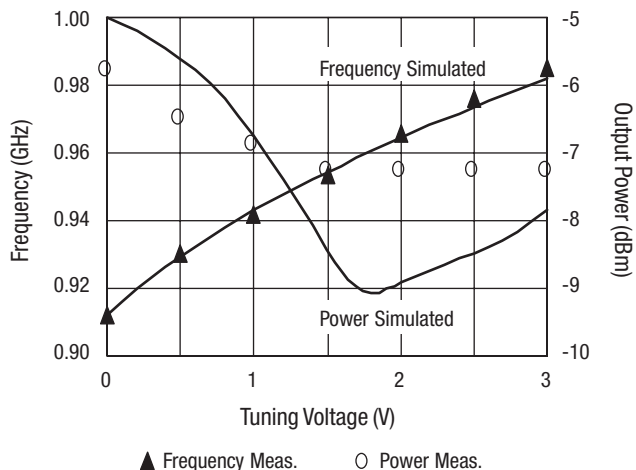


Figure 7. Measured and Simulated Frequency and Power Responses of the Differential VCO

Figure 8 shows the phase noise of the VCO measured in the range of 100 Hz to 8 MHz offset from the carrier. This measurement was made using the Aeroflex PN9000 Phase Noise Test Set with a 40 ns delay line. The best phase noise occurred with circuit components very close to the originally established values in the preliminary simulation. Only small changes were introduced such as: $C_2$ from its original 4 pF to 3.6 pF, $C_3$ from 1.5 pF to 2 pF and $C_4$ from 1.5 pF to 1 pF.

Phase noise was approximately -93 dBc/Hz at a 10 kHz offset, which is about 5–10 dB poorer than a typical Colpitts low noise VCO having similar bias condition. The reason for the poorer phase noise may be that the resonator in a differential VCO works at its resonance frequency (or very near to it). This results in high reactive currents in the resonator, causing high power losses, causing much higher phase noise sensitivity to resonator component losses. This was confirmed by replacing the resonator circuit components with similar ones having less loss. For

example, after exchanging the varactor with a lower loss discrete ceramic capacitor, the phase noise was improved by 5–6 dB. In another example, increasing the solder thickness on the microstrip line improved phase noise as much as 3 dB. In comparison, typically there is less phase noise sensitivity to circuit components in a Colpitts VCO design, where the oscillation frequency is always below the resonance frequency of the resonator.
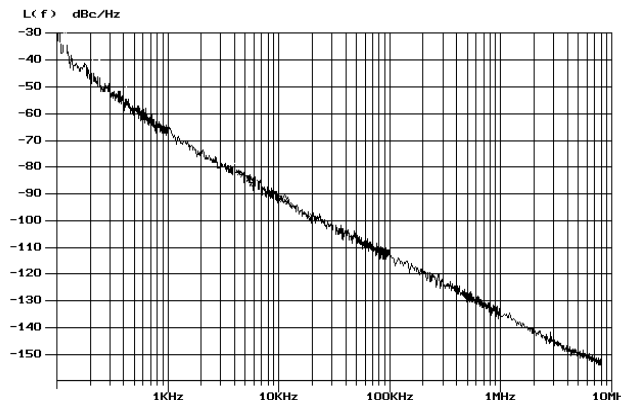


Figure 8. The VCO Phase Noise vs. Carrier Offset Frequency

## List of Available Documents

The Differential RF VCO Simulation Project Files for Libra IV.

The Differential RF VCO Circuit Schematic and PCB Layout for Protel EDA Client, 1998 Version.

The Differential RF VCO PCB Gerber Photo-plot Files.

## VCO Related Application Notes

APN1004, "Varactor SPICE Models for RF VCO Applications."

APN1006, "A Colpitts VCO for Wideband (0.95– 2.15 GHz) Set-Top TV Tuner Applications."

APN1005, "A Balanced Wideband VCO for Set-Top TV Tuner Applications."

APN1007, "Switchable Dual-Band 170/420 MHz VCO for Handset Cellular Applications."

"An RF VCO Design for Wireless and Broadband Applications."

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