AN11225

Demonstration of a 1GHz discrete VCO based on the BFR92A

Rev. 1.0 — 26 June 2012 Application note

Document information

Info	Content
Keywords	Discrete, VCO, BFR92A, EVB, Design, Evaluation, Measurements
Abstract	This document provides an example of a discrete Voltage Controlled Oscillator based on the BFR92A NPN wideband transistor. The device is oscillating on 1GHz and has a tuning range of about 100MHz. The VCO is implemented on an NXP VCO evaluation board which can be used to evaluate multiple oscillator types and configurations.

Revision history

Rev	Date	Description
1.0	20120626	Initial version

Contact information

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1. Introduction

The VCO demonstrated by this application note is a low-power single transistor common-collector Colpitts VCO with a center frequency of 1GHz and a tuning range of 100MHz. A VCO evaluation board is designed which can be used for evaluation of other VCO devices as well.

The VCO evaluation board can be used to evaluate the performance of different types of discrete LC-tank VCOs. Special attention is paid to the circuit's flexibility. The board allows the VCO to be configured either as a Colpitts oscillator or as a Clapp oscillator. Frequency tuning possibility is obtained using a varicap diode, which may be a device in a SOT323 (SC-76) package or in a SOT523 (SC-79) package. Furthermore, the board can be configured with or without an output buffer and BJT devices in both SOT23 package as well as in SOT323 package can be mounted. Also, an external bias pin is available to be able to tweak the DC bias setting of the oscillator's active device somewhat. The output of the oscillator can either be taken directly from the emitter or collector of T1 or from the emitter of the buffer stage, both ways providing enough positions for filter and impedance matching components. Even though not strictly required, all three connectors are SMA type connectors, allowing for coaxial cables to be used for the DC inputs as well, in order to reduce ambient noise coupling. Additionally, bias-T positions are available at the DC inputs for noise filtering and RF-DC isolation.

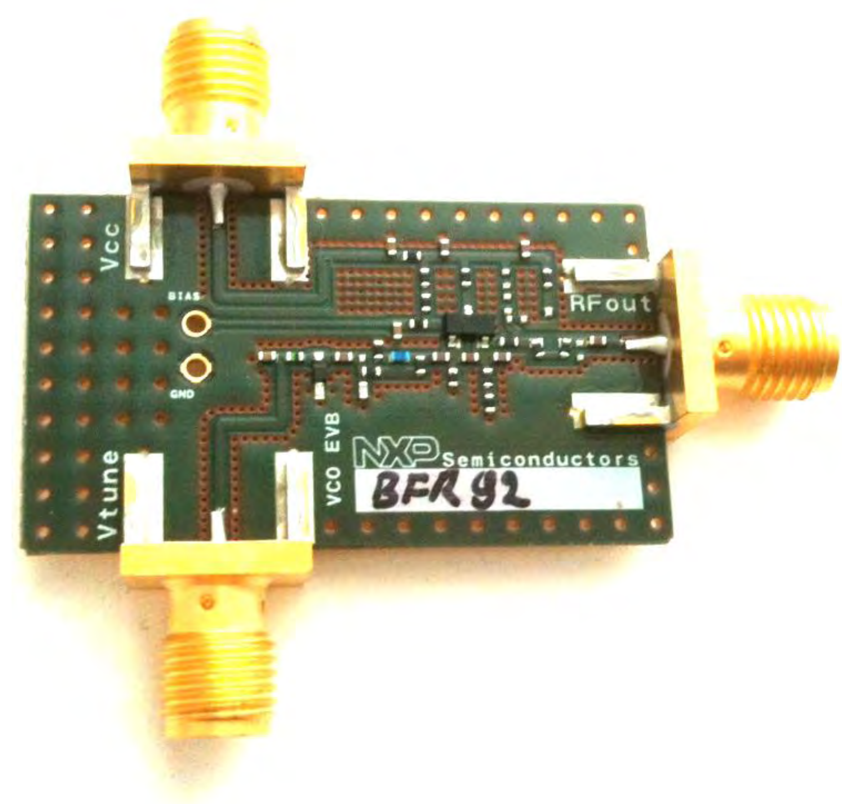


Fig 1. VCO evaluation board with NXP's BFR92A NPN wideband transistor

2. General board schematic

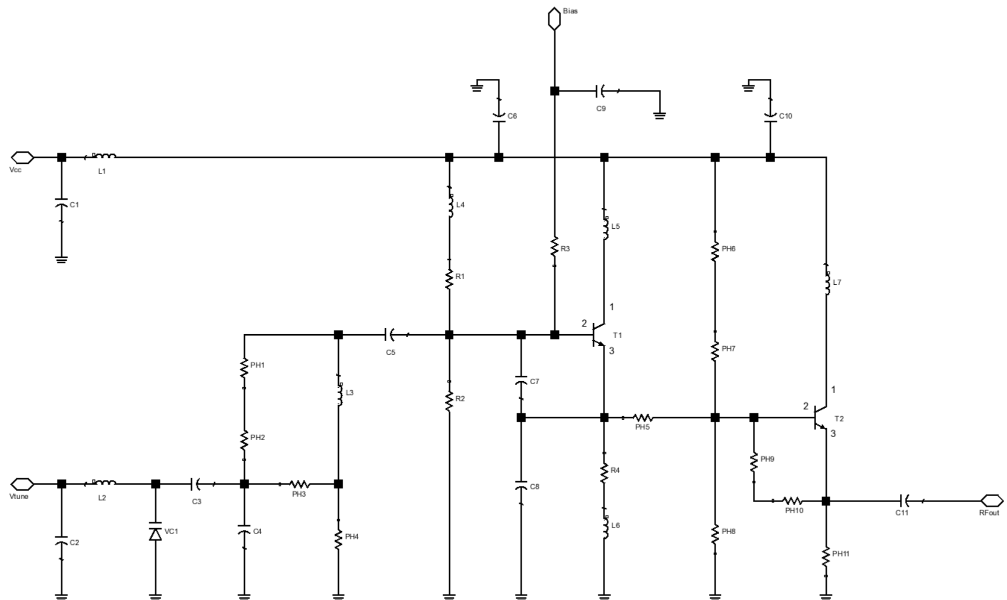


Fig 2. Schematic of VCO EVB

3. Board layout

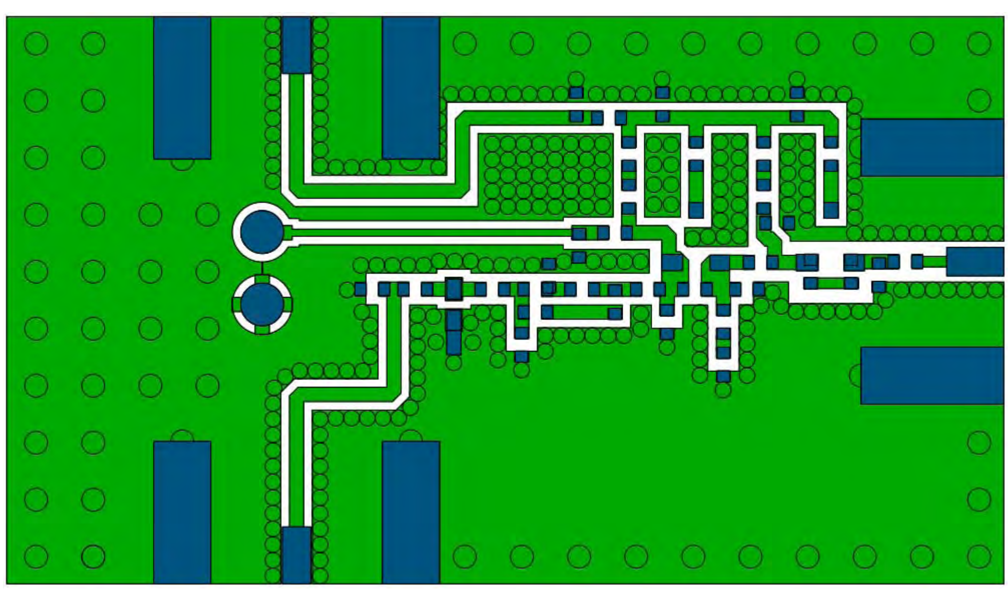


Fig 3. Board layout

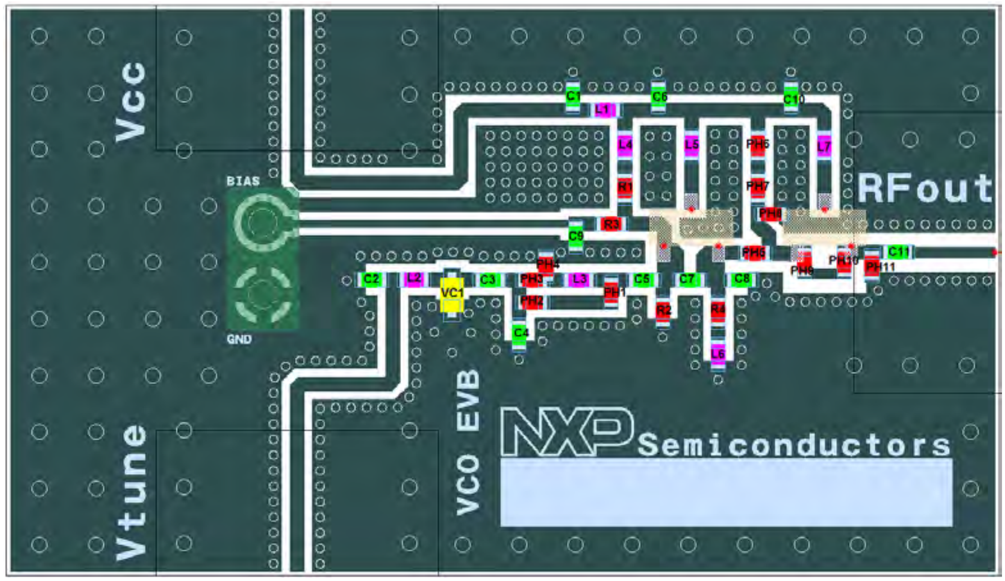


Fig 4. Board layout with components

4. PCB stack

The material that has been used for the EVB is FR4 using the stack shown in Fig 5.

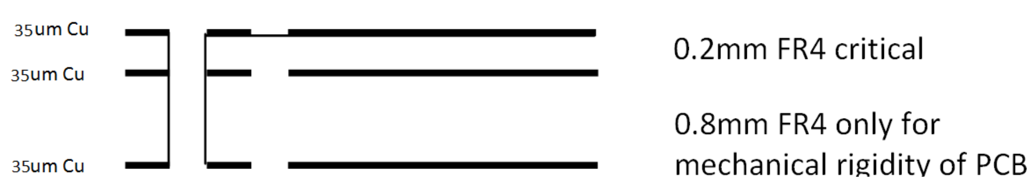
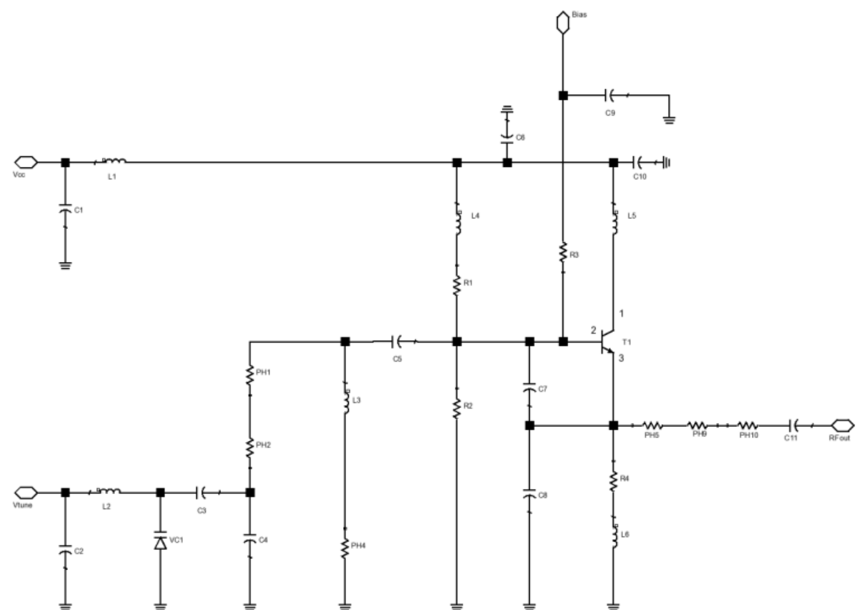


Fig 5. PCB stack

5. Example board configurations

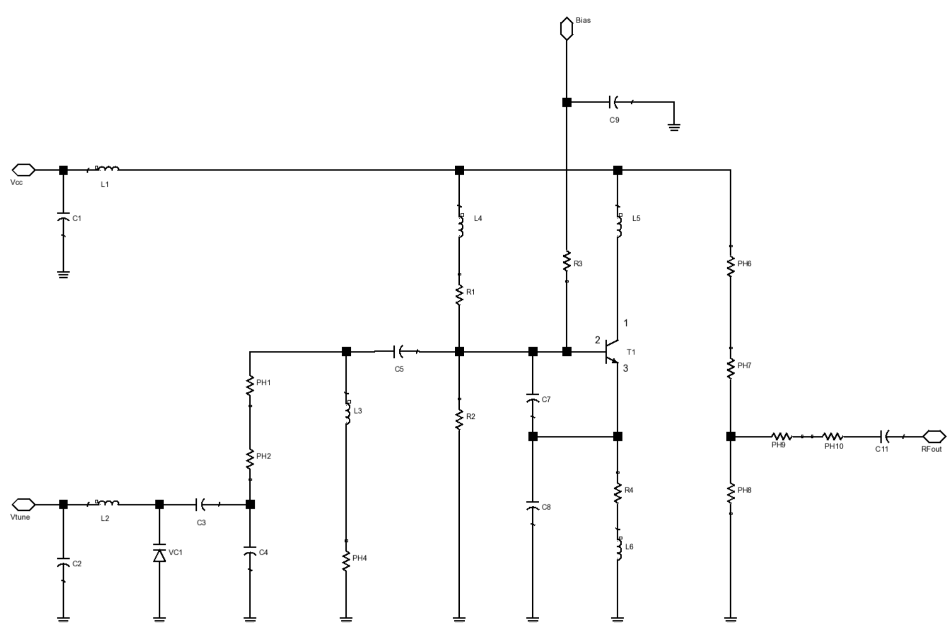
5.1 Configuration 1 - Colpitts emitter out



(1) Simple output coupling through capacitor

Fig 6. Colpitts emitter out

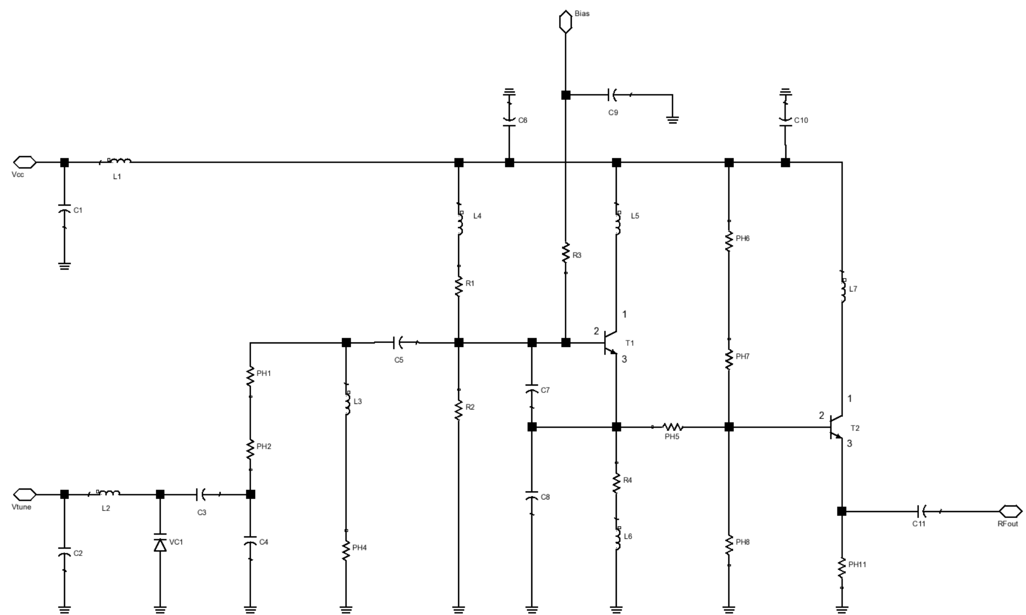
5.2 Configuration 2 – Colpitts Collector out



(1) Output coupling with LC-filter positions for harmonic suppression

Fig 7. Colpitts collector out

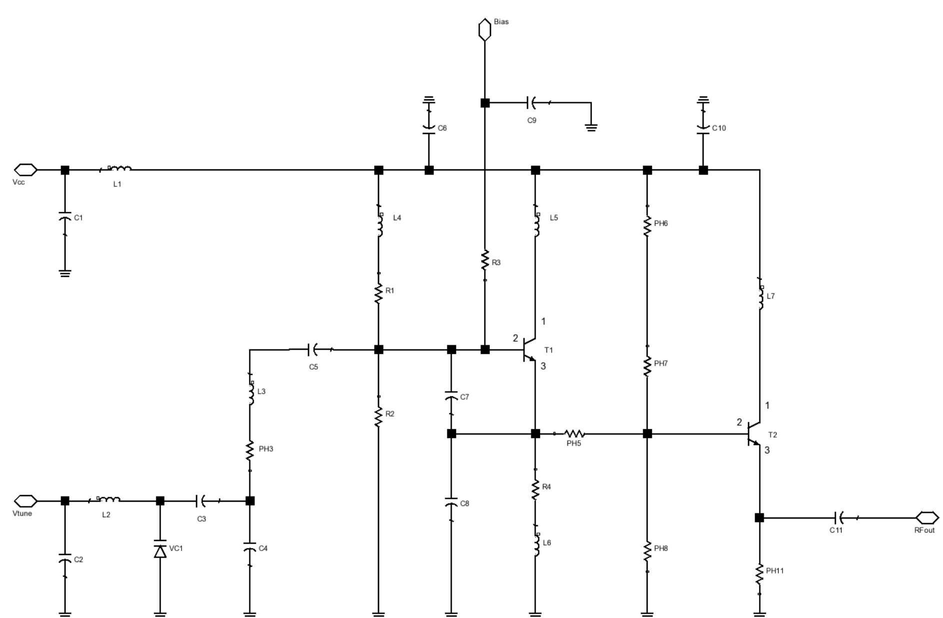
5.3 Configuration 3 – Colpitts emitter out with buffer stage



(1) Coupling from emitter of sustaining stage to base of buffer stage

Fig 8. Colpitts emitter out with buffer stage

5.4 Configuration 4- Clapp emitter out with buffer stage



(1) Coupling from emitter of sustaining stage to base of buffer stage

Fig 9. Gouriet-Clapp emitter out with buffer stage

Table 1. Example of mounted components and functions

Mounted component types: C=capacitor, L=inductor, R=resistor, T=transistor, VC=varicap diode, NM= not mounted

ID	Configuration 1		Configuration 2		Configuration 3		Configuration 4	
	Type	Function	Type	Function	Type	Function	Type	Function
C1	C	Decoupling	C	Decoupling	C	Decoupling	C	Decoupling
C2	C	Decoupling	C	Decoupling	C	Decoupling	C	Decoupling
C3	C	Varactor scaling	C	Varactor scaling	C	Varactor scaling	C	Varactor scaling
C4	C	Varactor scaling	C	Varactor scaling	C	Varactor scaling	C	Varactor scaling
C5	C	DC block	C	DC block	C	DC block	**R**	**Short**
C6	C	Decoupling	**NM**	**Open**	C	Decoupling	C	Decoupling
C7	C	Feedback	C	Feedback	C	Feedback	C	Feedback
C8	C	Feedback	C	Feedback	C	Feedback	C	Feedback
C9	C	Decoupling	C	Decoupling	C	Decoupling	C	Decoupling
C10	C	Decoupling	**NM**	**Open**	C	Decoupling	C	Decoupling
C11	C	Output coupling	C	Output coupling	C	Output coupling	C	Output coupling
L1	**R**	**Short**	L	DC feed	**R**	**Short**	**R**	**Short**
L2	L	DC feed	L	DC feed	L	DC feed	L	DC feed
L3	L	Tank inductance	L	Tank inductance	L	Tank inductance	L	Tank inductance
L4	**R**	**Short**	**R**	**Short**	**R**	**Short**	**R**	**Short**
L5	**R**	**Short**	**R**	**Short**	**R**	**Short**	**R**	**Short**
L6	L	RF block	L	RF block	L	RF block	L	RF block
L7	**NM**	**Open**	**NM**	**Open**	**R**	**Short**	**R**	**Short**
R1	R	Transistor bias	R	Transistor bias	R	Transistor bias	R	Transistor bias
R2	R	Transistor bias	R	Transistor bias	R	Transistor bias	R	Transistor bias
R3	R	Bias tweak	R	Bias tweak	R	Bias tweak	R	Bias tweak
R4	R	Transistor bias	R	Transistor bias	R	Transistor bias	R	Transistor bias
PH1	**R**	**Short**	**R**	**Short**	**R**	**Short**	**NM**	**Open**
PH2	**R**	**Short**	**R**	**Short**	**R**	**Short**	**NM**	**Open**
PH3	**NM**	**Open**	**NM**	**Open**	**NM**	**Open**	**R**	**Short**
PH4	**R**	**Short**	**R**	**Short**	**R**	**Short**	**NM**	**Open**
PH5	L	Low-pass filter	**NM**	**Open**	C	DC block/coupling	C	DC block/coupling
PH6	**NM**	**Open**	**R**	**Short**	**R**	**Short**	**R**	**Short**
PH7	**NM**	**Open**	L	Low-pass filter	R	Transistor bias	R	Transistor bias
PH8	C	Low-pass filter	C	Low-pass filter	R	Transistor bias	R	Transistor bias
PH9	**R**	**Short**	**R**	**Short**	**NM**	**Open**	**NM**	**Open**
PH10	**R**	**Short**	**R**	**Short**	**NM**	**Open**	**NM**	**Open**
PH11	**NM**	**Open**	**NM**	**Open**	R	Transistor bias	R	Transistor bias
T1	T	Sustaining stage	T	Sustaining stage	T	Sustaining stage	T	Sustaining stage
T2	**NM**	**Open**	**NM**	**Open**	T	Buffer stage	T	Buffer stage
VC1	VC	Frequency tuning	VC	Frequency tuning	VC	Frequency tuning	VC	Frequency tuning

6. Design and evaluation

6.1 Design recommendations

- A higher C/L ratio of the tank results in a higher loaded quality factor and consequently to better phase noise, load pulling and supply pushing performance.
- Use a high unloaded quality factor resonator inductor (L3) such as a wire-wound-type inductor.
- The loop gain can be controlled by for example changing the C7/C8 ratio. Smaller ratios result in higher loop gain. Make sure that the loop gain is well above the critical loop gain to compensate for component spread and temperature variation. Take into account though that a too high loop gain results in bad harmonic performance.
- Use C3 to scale down the capacitance tuning range and use C4 to increase the tank capacitance to center the frequency of oscillation in the desired range.
- Mounting of capacitor C3 is always required for it serves as a DC blocking capacitor as well. If scaling of the capacitance tuning range is not required, choose $C3 >> C_{VC1}$.
- Generally the system has sufficient loop gain if the oscillator starts oscillating for supply voltages well below the nominal operating voltage.
- Be aware that the more power is fed back to the resonator the less power is available for the load, and vice versa.
- Use a high reactance inductor (L6) in series with the emitter resistor to limit the RF power dissipated in the emitter resistor.
- Higher output power generally results in better phase noise performance.
- To increase the output power one might increase the collector current. Be aware that this action also increases the flicker corner frequency which increases the 1/f noise contribution to phase noise. An optimum collector current for best phase noise performance might be found by using the bias tweaking pin.
- A high reactance output coupling capacitor (C11) results in better load pulling performance but might also decrease the output power.
- A low reactance output coupling capacitor (C11) generally enhances the harmonics. Notice that capacitive output coupling already behaves like a high-pass filter.
- Use an LC-type filter at the oscillator's output for better harmonic performance.
- Make sure that the tank's voltage swing does not exceed a value for which the varicap diode will enter forward conduction mode.
- Investigate the contribution of the varicap diode to the phase noise performance by replacing the device with a fixed capacitor.
- Use an amplifier with high gain, a low flicker corner frequency and low noise-figure.
- A too high transition frequency of the amplifier might result in spurious oscillations and degraded performance. Choose the transition frequency about 5 times the maximum frequency of oscillation.
- This board is designed for evaluation purposes and is designed for flexibility, not for optimal performance. Design a smaller dedicated VCO board for best performance.
- Board characteristics strongly influence the oscillator characteristics. Make sure to characterize the board for simulation by for example EM-simulation of the board.

6.2 Using the bias tweaking pin

The bias tweaking pin can be used to tweak the collector current by varying the base voltage.

- Use a high impedance resistor (R3), for example 50K.
- Decouple the supply line using a capacitor (C9), for example 47nF.
- Change the bias tweaking pin voltage in the positive and negative direction to tweak the current in both directions. Make sure that the power dissipated by R3 stays well below 60mW.
- For larger collector current sweeping, remove resistors R1 and R2 and replace R3 by a high reactance inductor, for example 100nH. Make sure that the transistor's junction voltages stay below the maximum ratings.
- Set the transistor using the R1-R2 voltage divider in the DC operating point found by optimization.
- Notice that the frequency of oscillation might shift for different DC operating points. Change the tank components after optimization accordingly.

7. BFR92A 10mA VCO implementation

7.1 BFR92A model

The used model for the BFR92A is a Mextram 504 model of the BFR92A die and is expanded with the parasitic capacitances and inductances of the package as shown in Fig 10.

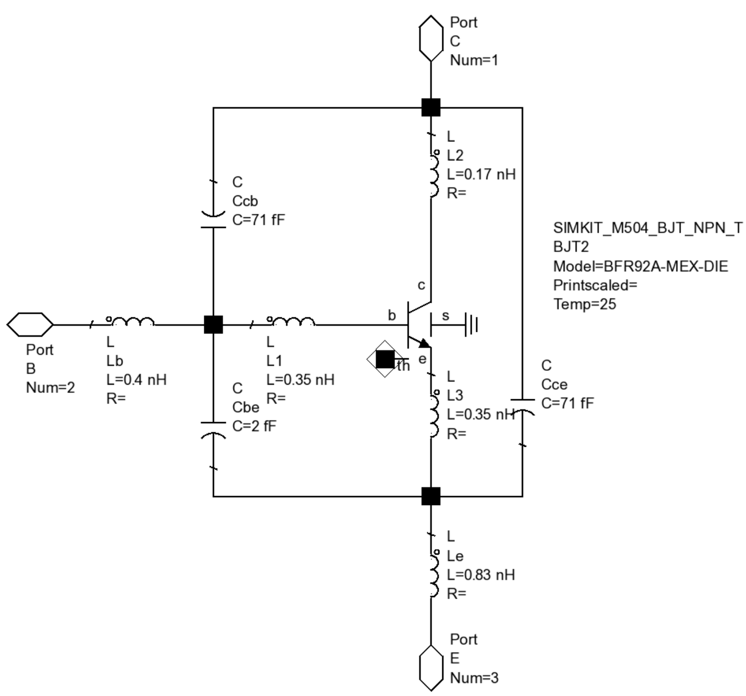


Fig 10. Mextram 504 model of BFR92A die expanded with package characteristics

7.2 PCB characterization

The VCO EVB layout was characterized by performing a 2D EM simulation with the Momentum RF simulator of Agilent Advanced Design System (ADS 2009). A layout-look-a-like symbol was created from the resulting S-parameter file allowing for co-simulation of the board. The components were connected to the simulation component of the PCB and the values are those shown in chapter 8. The zero ohm resistors are modeled as 150pH inductors with 5mOhm series resistance (estimation) for a better approximation to the reality.

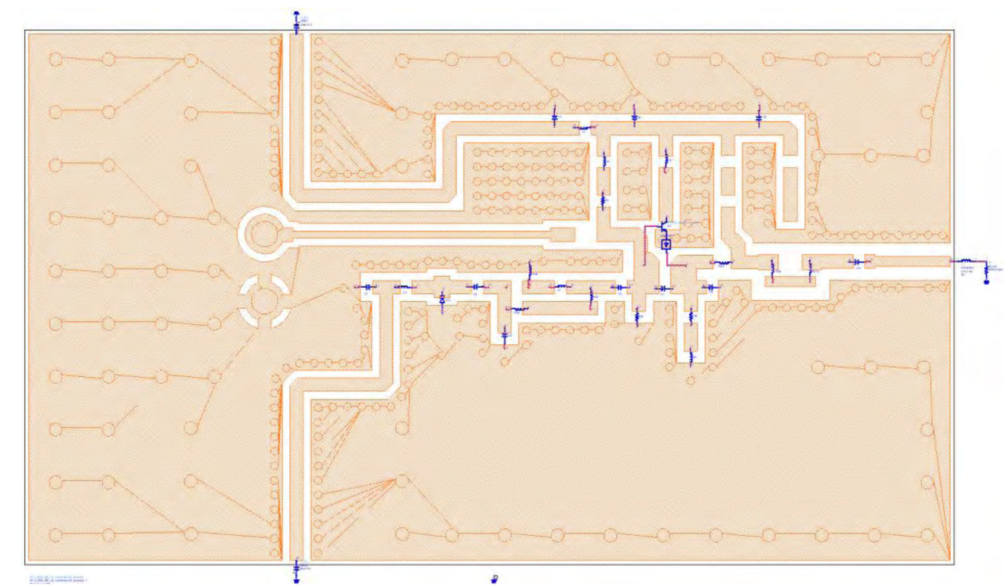


Fig 11. Layout-look-a-like co-simulation component

7.3 Simulation of oscillation frequency

By inserting the ADS OscTest component into the feedback path of the oscillator the small-signal loop can be calculated and plotted as shown in Fig 12 and Fig 13. The OscTest component is connected in series with the transistor's emitter with the arrow pointed away from the emitter. The default settings of OscTest are used and the frequency is swept from 1MHz to 5GHz. Notice that the small-signal loop gain is plotted. Steady-state oscillations occur when the active device is limiting the output amplitude and the device is then operating in non-linear mode. The characteristics of the active device will change somewhat and the frequency of oscillation will be a little lower than according to the small-signal loop gain prediction.

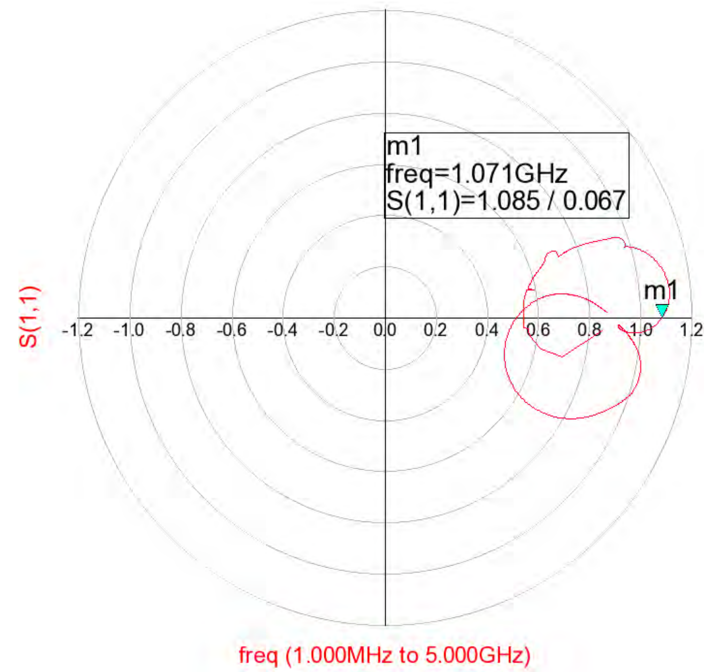


Fig 12. Polar plot of small-signal loop gain at V_{TUNE} = 5V

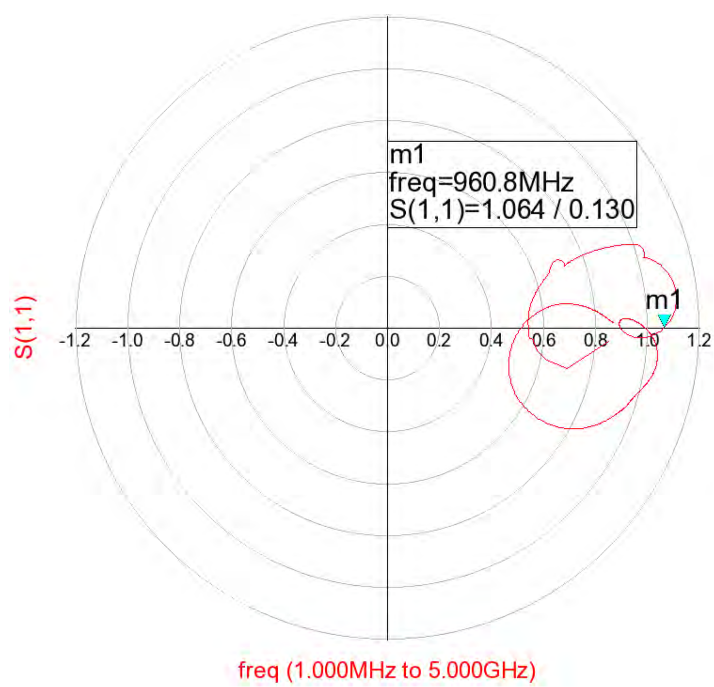


Fig 13. Polar plot of small-signal loop gain at V_{TUNE} = 0V

8. Bill of materials

Table 2. Bill of materials

Designator	Description	Package	Value	Supplier name / type	Comment
C1	Ceramic chip capacitor	0402	47nF	Murata / GRM15	Decoupling
C2	Ceramic chip capacitor	0402	47nF	Murata / GRM15	Decoupling
C3	Ceramic chip capacitor	0402	4.3pF	Murata / GRM15	Varactor scaling
C4	Ceramic chip capacitor	0402	0.6pF	Murata / GRM15	Varactor scaling
C5	Ceramic chip capacitor	0402	100pF	Murata / GRM15	DC block
C6	Ceramic chip capacitor	0402	47pF	Murata / GRM15	Decoupling
C7	Ceramic chip capacitor	0402	1pF	Murata / GRM15	Feedback
C8	Ceramic chip capacitor	0402	3pF	Murata / GRM15	Feedback
C9	*Not mounted*	-	-	-	*Not mounted*
C10	Ceramic chip capacitor	0402	47pF	Murata / GRM15	Decoupling
C11	Ceramic chip capacitor	0402	33pF	Murata / GRM15	Output coupling
L1	Zero Ohm resistor	0402	0Ω	Yageo	Short
L2	Multi-layer inductor	0402	100nH	Murata / LQG15	Bias-T
L3	Wire-wound inductor	0402	2.4nH	Murata / LQW15	Tank inductor
L4	Zero Ohm resistor	0402	0Ω	Yageo	Short
L5	Zero Ohm resistor	0402	0Ω	Yageo	Short
L6	Zero Ohm resistor	0402	0Ω	Yageo	Short
L7	Zero Ohm resistor	0402	0Ω	Yageo	Short
R1	Film resistor	0402	1K5	Yageo	Biasing network
R2	Film resistor	0402	2K7	Yageo	Biasing network
R3	*Not mounted*	-	-	-	*Not mounted*
R4	Film resistor	0402	220	Yageo	Biasing network
PH1	Zero Ohm resistor	0402	0Ω	Yageo	Short
PH2	Zero Ohm resistor	0402	0Ω	Yageo	Short
PH3	*Not mounted*	-	-	-	*Not mounted*
PH4	Zero Ohm resistor	0402	0Ω	Yageo	Short
PH5	Zero Ohm resistor	0402	0Ω	Yageo	Short
PH6	*Not mounted*	-	-	-	*Not mounted*
PH7	*Not mounted*	-	-	-	*Not mounted*
PH8	*Not mounted*	-	-	-	*Not mounted*
PH9	Zero Ohm resistor	0402	0Ω	Yageo	Short
PH10	Zero Ohm resistor	0402	0Ω	Yageo	Short
PH11	*Not mounted*	-	-	-	*Not mounted*
T1	NPN BJT	0402		NXP Semiconductors / BFR92A	Sustaining stage
T2	*Not mounted*	-	-	-	*Not mounted*
VC1	Varicap diode	0402		NXP Semiconductors / BB145	Tuning
BIAS header	Bias tweaking	-	-	-	Bias tweaking
Vcc, Vtune, RFout	SMA RF connector			Johnson / 142-0701-841	VCO ports

9. Measurements

9.1 Required equipment

In order to measure the evaluation board the following equipment is required:

- ✓ DC Power Supply Unit for V_{CC} capable of sourcing 30mA at 5V
- ✓ DC Power Supply Unit for V_{TUNE} capable of sourcing 500nA at 5V
- ✓ If possible both DC PSUs are battery power supplies to minimize the contribution of supply noise/ripple to the phase noise performance
- ✓ Digital Multimeter for supply current measurement and supply voltage verification (optional)
- ✓ RF Spectrum Analyzer covering the frequency range up to about 9GHz
- ✓ RF SSB Phase Noise Analyzer for phase noise measurement with a sensitivity of at least -150dBc at 1MHz offset
- ✓ Proper RF cables
- ✓ A banana-plugs-to-BNC-connector can be used when the power supply has banana plug outputs

9.2 Connections and setup

9.2.1 Current measurements

1. Set the DMM in DC current measuring mode and connect the meter in series with the DC power supply for V_{CC}.
2. Set the DC power supply to 5V and verify this voltage using a DMM
3. Connect the output of the DMM and the ground terminal to a shielded RF cable with an SMA-connector to connect it to the VCO's V_{CC} port
4. Connect the V_{TUNE} PSU with a shielded RF cable with an SMA-connector to the VCO's V_{TUNE} port
5. Connect the VCO's RF_{OUT} port to a 50Ohm load
6. Turn on both DC power supplies and sweep the V_{TUNE} voltage while noting the measured currents

9.2.2 Frequency and power measurements

1. Connect both the V_{CC} and the V_{TUNE} port to the power supply (preferably a battery supply) with short shielded cables
2. Connect the RF_{OUT} port to the spectrum analyzer using the shortest possible connector
3. Verify the voltages for the V_{CC} and V_{TUNE} using a DMM, then disconnect the DMM and turn on both DC power supplies
4. Use the marker function of the spectrum analyzer to measure the frequencies and corresponding powers. Make sure to measure with the narrowest bandwidth as possible for most accurate results
5. Setting the spectrum analyzer in averaging mode makes readout more easy and accurate
6. Perform frequency and power measurements for multiple values of V_{TUNE} and make sure to verify this tuning voltage every time it is changed

7. Pushing measurements can be performed by varying the V_{CC} voltage by for example 0.5V in both directions from the nominal supply voltage while measuring the frequency deviation

9.2.3 Phase noise measurements

1. Connect both the V_{CC} and the V_{TUNE} port to the power supply (a battery supply is required for a valid phase noise measurement) with short shielded cables
2. Connect the RF_{OUT} port to the phase noise analyzer using the shortest possible connector
3. Some phase noise analyzers switch the load at the start of the measurement causing the oscillators frequency to be pulled somewhat and consequently the analyzer will not be able to capture the carrier. In this case it would help to connect for example a 10dB attenuator in between RF_{OUT} and the RF input of the spectrum analyzer to provide some isolation
4. Set the measurement range of the phase noise analyzer to run from 1KHz to 1MHz
5. For most accurate results, make sure to perform a highly correlated measurement and preferably also to average multiple curves

10. Typical results

Table 3. Typical results

V_{TUNE} [V]	I_{CC} [mA]	P_{OUT} [dBm]	F1 [MHz]	P_{F2} [dBc]	P_{F3} [dBc]	P_{F4} [dBc]	Phase noise @ 1MHz [dBc/Hz]	Pushing [MHz/V]
0.0	11.69	1.51	950.78	-10.2	-24.55	-35.47	-127.25	1.79
0.5	11.73	1.45	966.90	-10.1	-24.96	-34.72	-127.49	1.40
1.0	11.75	1.39	980.34	-10.1	-25.39	-33.02	-127.55	1.02
1.5	11.77	1.35	992.17	-9.97	-25.76	-31.35	-127.20	0.563
2.0	11.79	1.31	1003.1	-9.81	-26.19	-30.11	-127.48	0.236
2.5	11.82	1.26	1012.8	-9.65	-26.42	-29.43	-127.71	0.324
3.0	11.84	1.19	1022.6	-9.48	-26.60	-28.93	-127.68	0.770
3.5	11.85	1.12	1032.2	-9.44	-26.80	-28.72	-127.61	1.36
4.0	11.85	1.08	1041.2	-9.41	-27.04	-28.70	-127.20	2.00
4.5	11.85	1.06	1048.8	-9.61	-27.38	-28.85	-126.70	2.58
5.0	11.85	1.05	1054.4	-9.70	-27.69	-28.94	-126.33	3.01

[1] Frequency and power measurements performed with spectrum analyzer set to 50KHz bandwidth

[2] Phase noise measurements performed with phase noise analyzer set to correlation =25 and averaging = 50

The characteristics of this VCO are shown below.

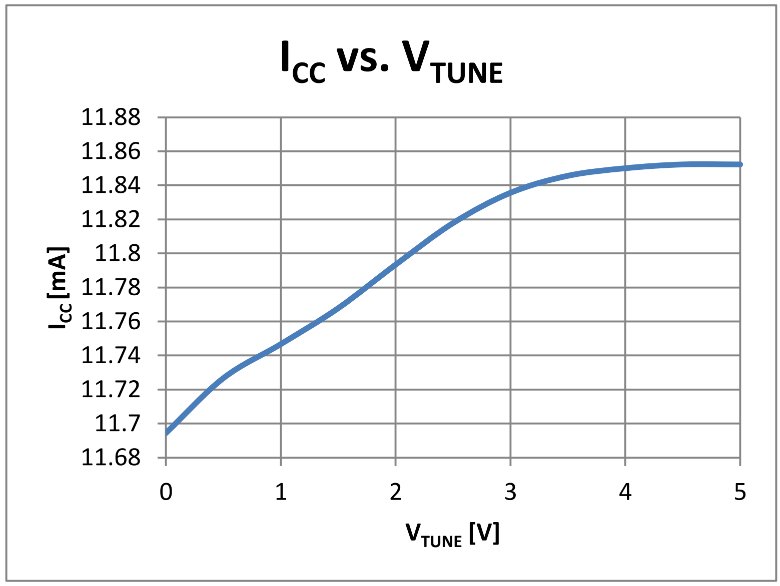


Fig 14. I_{CC} vs. V_{TUNE} for V_{CC} = 5V

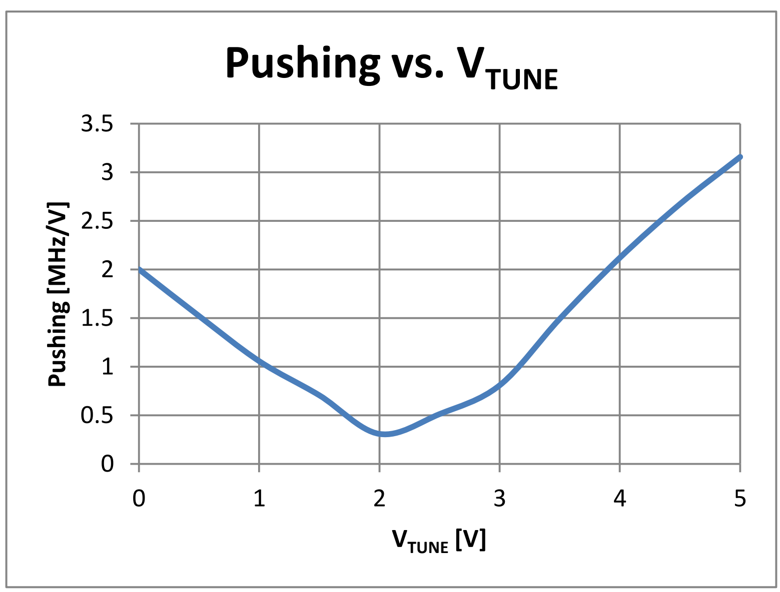


Fig 15. Pushing vs. V_{TUNE}

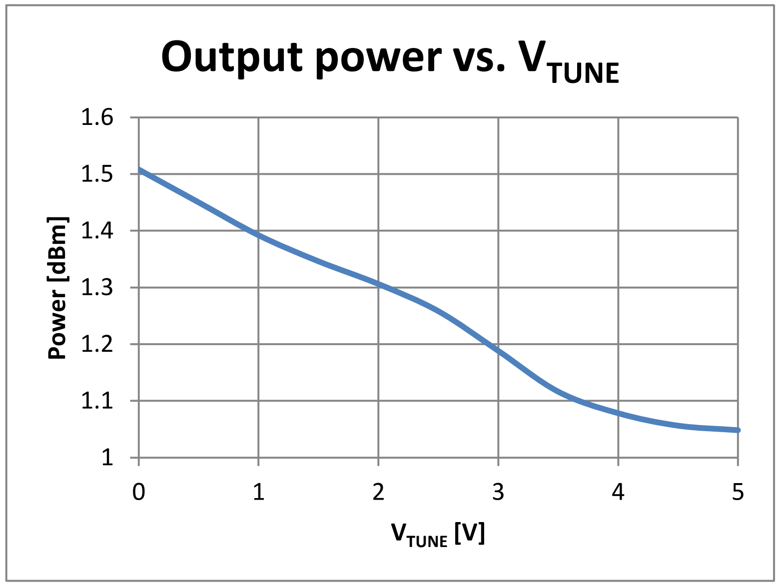


Fig 16. Output power vs. V_{TUNE}

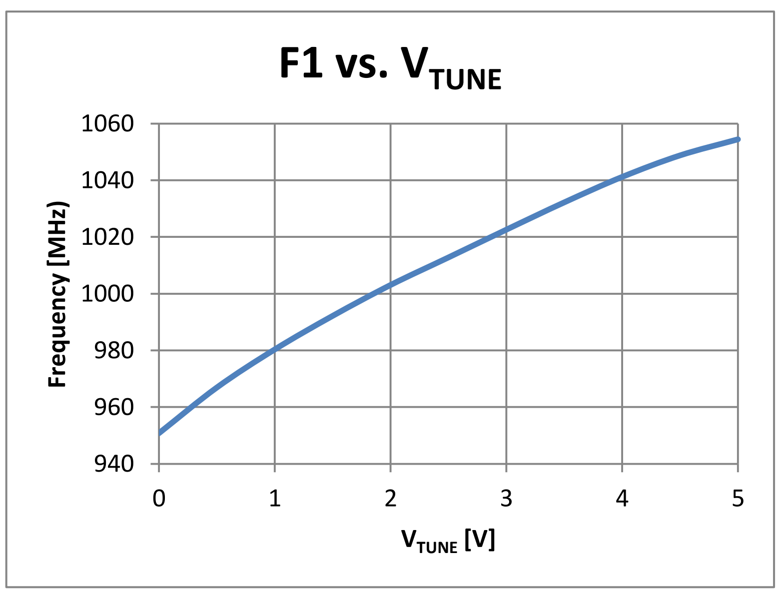


Fig 17. F1 vs. V_{TUNE}

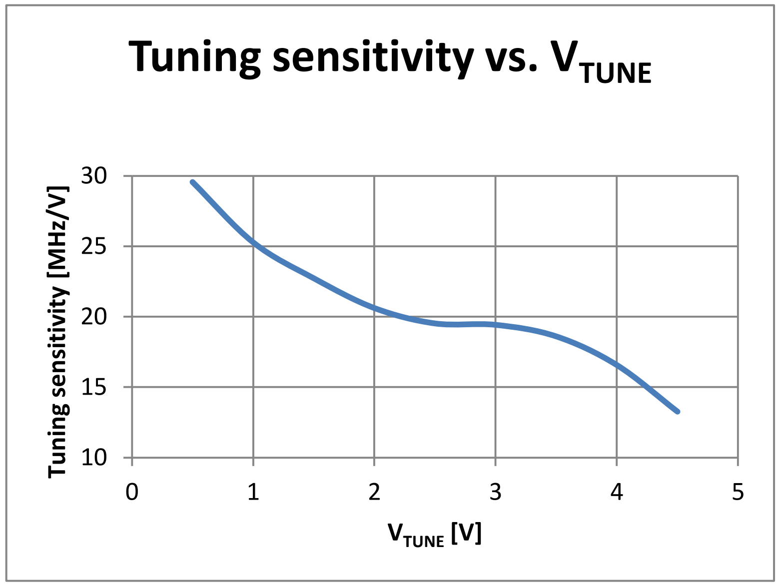


Fig 18. Tuning sensitivity vs. V_{TUNE}

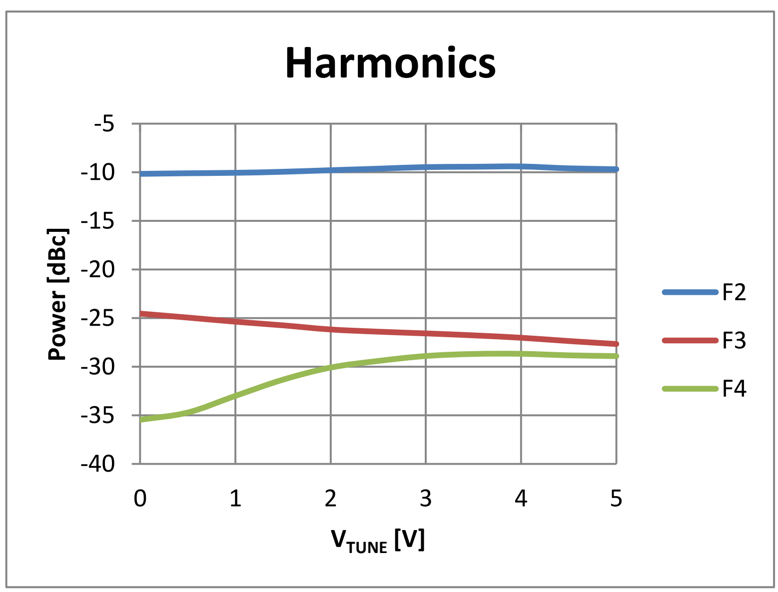
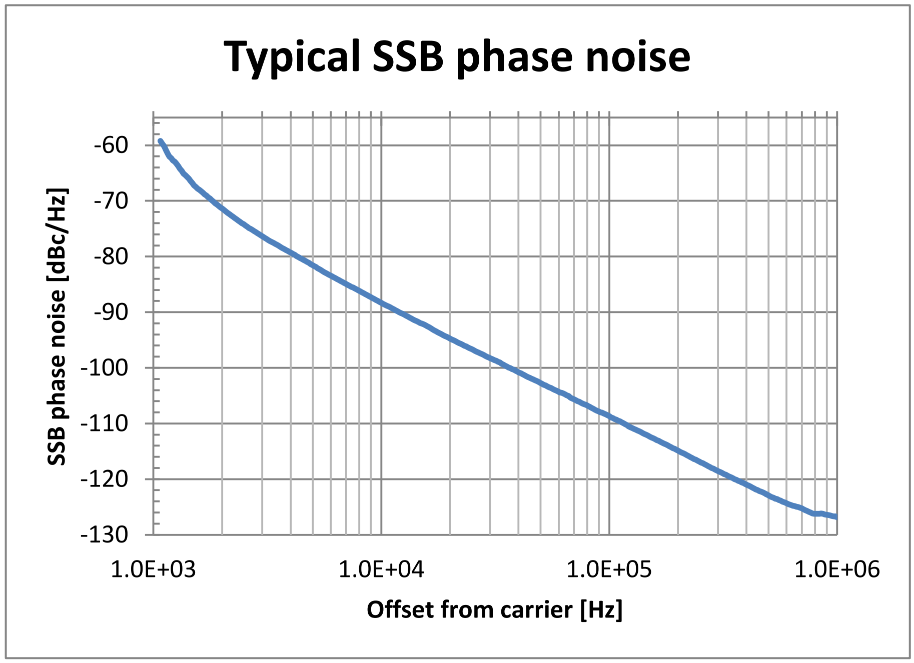


Fig 19. Power of harmonics



(1) The phase noise shown in this graph is the typical value of the phase noise averaged across the tuning range

Fig 20. Average SSB phase noise

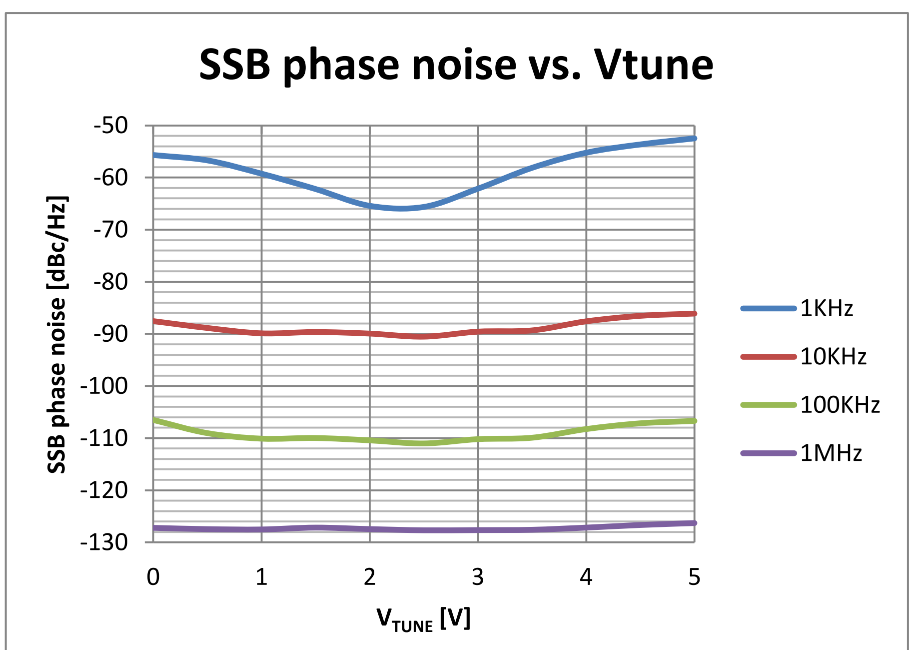


Fig 21. SSB phase noise vs. V_{TUNE}

11. Legal information

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For sales office addresses, please send an email to: salesaddresses@nxp.com

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