A Design Example for an Oscillator for Best Phase Noise and Good Output Power

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Figure C-1 shows the parallel-tuned Colpitts oscillator circuit, which has to be designed with the following specifications. The unit was also built and measured. It uses a ceramic resonator and its equivalent circuit is shown.

Requirements:

- output power requirement: 13 dBm
- operating frequency: 1000 MHz
- load: 50 Ω
- phase noise –124 dBc/Hz @10KHz

Design Steps

Step 1:

Calculation of the operating point for a fixed, normalized drive of x = 20 (high output power), see Table 6-1.

Based on output power requirement, the following is calculated.

The oscillator output voltage at the fundamental frequency is

$$V_{out}(\omega_0) = \sqrt{P_{out}(\omega_0) * 2R_L} = \sqrt{20E-3*2*50} \approx 1.414V \tag{C-1}$$

The fundamental current is

$$I_{out}(\omega_0) = \frac{V_{out}(\omega_0)}{50} = \frac{1.414}{50} = 28.3mA \tag{C-2}$$

The DC operating point is calculated based on the normalized drive level x = 20. The expression for the emitter dc current can be given in terms of the Bessel function with respect to the drive level is

$$\left[I_E(\omega_0)\right] = 2I_{DC}\left[\frac{I_1(x)}{I_0(x)}\right]_{x=Normalized-Drive-Level} \tag{C-3}$$

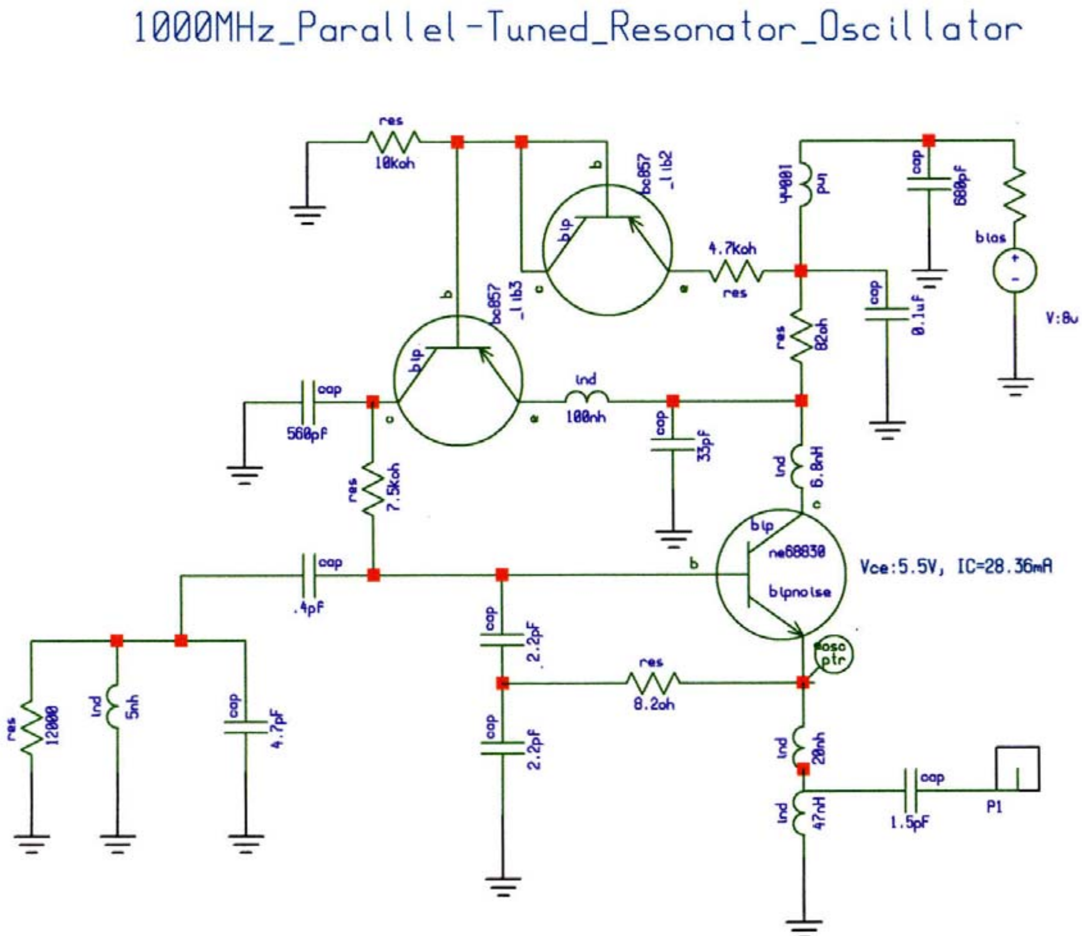

Figure C-1 Schematic of the 1000 MHz oscillator.

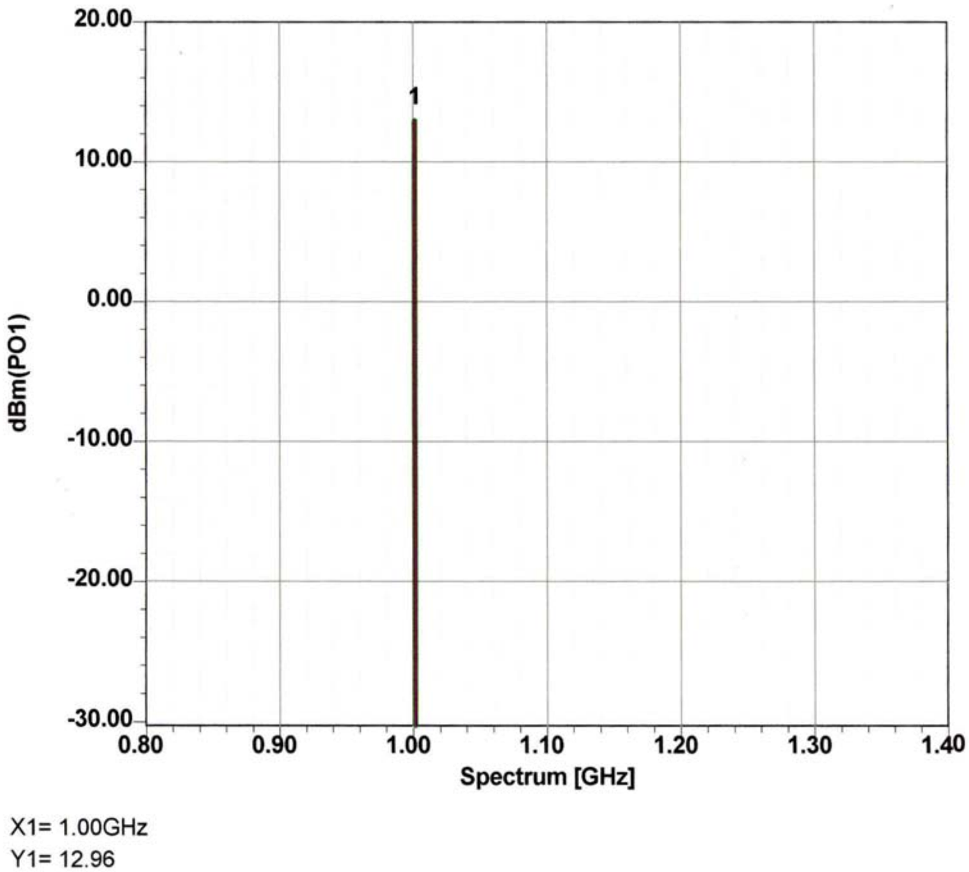

Figure C-2 Predicted output power of the oscillator.

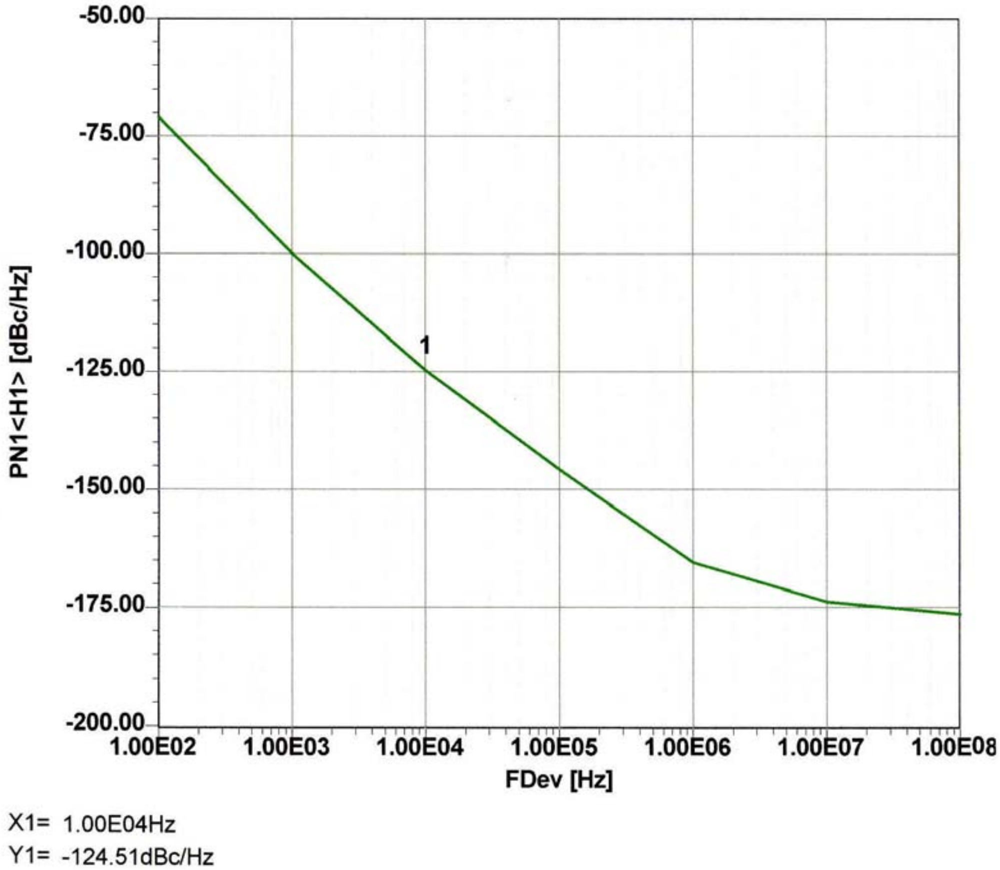

Figure C-3 Predicted phase noise of the oscillator.

For the normalized drive level x = 20, the output emitter current at the fundamental frequency can be given as

$$\left[I_E(\omega_0)\right]_{x=20} = \left[I_{E1}(\omega_0)\right]_{x=20} + \left[I_{E2}(\omega_0)\right]_{x=20} = 2I_{DC}\left[\frac{I_1(x)}{I_0(x)}\right]_{x=20} \approx 56mA \qquad \text{(C-4)}$$

$$\left[I_{E1}(\omega_0)\right]_{x=20} = I_{out}(\omega_0) = 28.3mA \text{ (output current to the load)} \qquad \text{(C-5)}$$

Figure C-4 shows the oscillator circuit configuration in which DC and RF current distribution is shown and divided into its components.

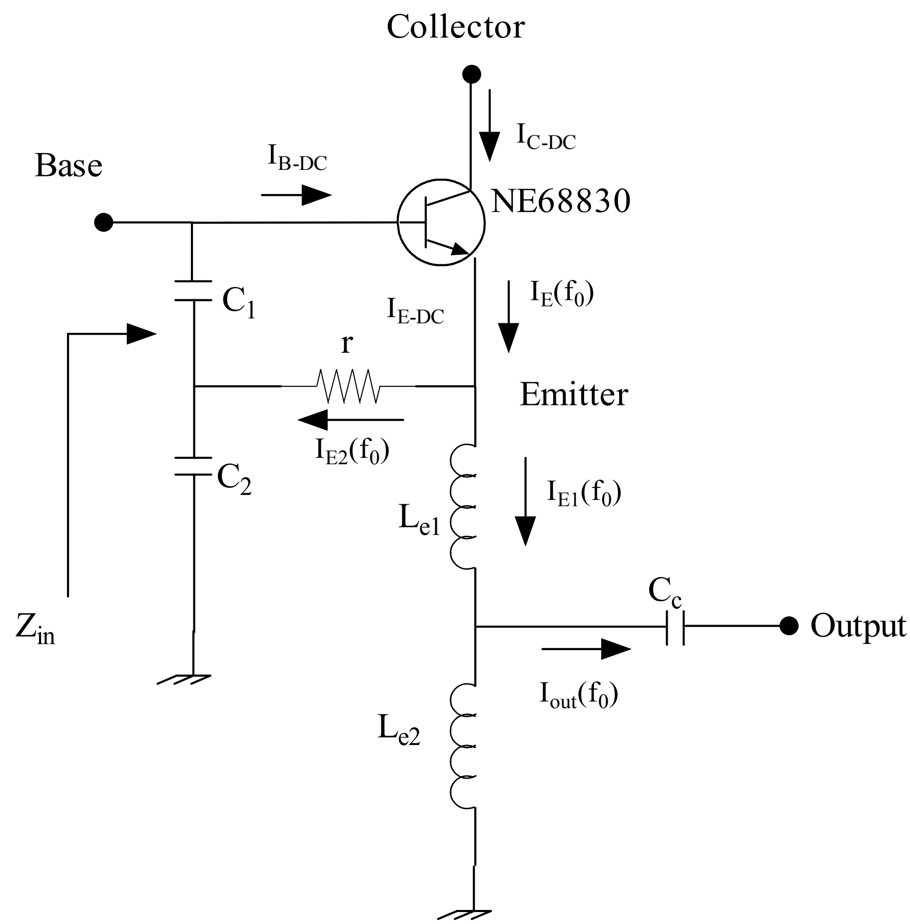

Figure C-4 Current distribution in the oscillator circuit.

$$[I_{E2}(\omega_0)]_{x=20} = [I_E(\omega_0)]_{x=20} - [I_{E1}(\omega_0)]_{x=20} = 27.3mA \tag{C-6}$$

$$I_{E-DC} = \frac{[I_E(\omega_0)]_{x=20}}{2\left[\frac{I_1(x)}{I_0(x)}\right]_{x=20}} = 28.3mA \tag{C-7}$$

For this application, the NE68830 was selected.

Step 2:

Biasing circuit

For the best phase noise close-in, a DC/AC feedback circuit is incorporated, which provides the desired operating DC condition [84]:

I_E=28.3mA

V_{CE}=5.5V, Supply Voltage V_{cc}=8V

β=120

I_B≈0.23mA

Step 3:

Calculation of the large-signal transconductance.

$$Y_{21}\Big|_{l\arg e-signal} = G_m(x) = \frac{qI_{dc}}{kTx}\left[\frac{2I_1(x)}{I_0(x)}\right]_{fundamental} \tag{C-8}$$

$$\left[Y_{21}\right]_{\omega=\omega_0} = \left[\frac{1.949 I_{E-DC}}{520mV}\right] = 0.107 \tag{C-9}$$

Step 4:

Loop Gain.

The loop gain is

$$Loop-Gain = [LG]_{sustained-condition} = \left[\frac{R_P Y_{21}(x)}{n}\right] = \left[\frac{R_P g_m}{x}\right]\left[\frac{2I_1(x)}{I_0(x)}\right]\left[\frac{1}{n}\right] > 1 \tag{C-10}$$

$$R_{PEQ}(f_0) = R_P \parallel Bias-circuit \Rightarrow 50.73\Omega \tag{C-11}$$

As earlier derived, the loop gain should be 2.1 to have good starting conditions!

$$n = \left[\frac{R_{PEQ} Y_{21}(x)}{2.1}\right] = \frac{0.107 * 50.73}{2.1} \approx 2.523 \tag{C-12}$$

Step 5:

Calculation of the feedback capacitor ratio.

$$n = 1 + \left[\frac{C_1}{C_2}\right] = 2.523 \Rightarrow \left[\frac{C_1}{C_2}\right]_{x=20} = 1.523 \ (2.523 - 1) \qquad \text{(C-13)}$$

Step 6:

Calculation of absolute values of feedback capacitor.

The expression of Z_{in} (Looking in to the base of the transistor) can be given as

$$Z_{in} \cong -\left[\left(\frac{Y_{21}}{\omega^2 (C_1^* + C_p)C_2}\right)\left(\frac{1}{(1+\omega^2 Y_{21}^2 L_p^2)}\right)\right] - j\left[\left(\frac{(C_1^* + C_P + C_2)}{\omega (C_1^* + C_P)C_2}\right) - \left(\frac{\omega Y_{21} L_P}{(1+\omega^2 Y_{21}^2 L_p^2)}\right)\left(\frac{Y_{21}}{\omega (C_1^* + C_P)C_2}\right)\right]$$

(C-14)

where

C_P = (C_{BEPKG} + contribution from layout) = 1.1pF

L_P=(L_B + L_{BX} + contribution from layout) = 2.2nH.

The expression for the negative resistance R_n is

$$R_{neq} = \frac{R_n}{(1+\omega^2 Y_{21}^2 L_P^2)} = \frac{R_n}{[1 + (2\pi * 1E9)^2 * (0.107)^2 * (2.2nH)^2]} \qquad \text{(C-15)}$$

$$R_{neq} \approx \frac{R_n}{3.65} \qquad \text{(C-16)}$$

$$R_n = -\left[\frac{Y_{21}^{+}}{\omega^2 C_1 C_2}\right]_{x=20} = \frac{0.107}{(2\pi * 1E9)^2 C_1 C_2} \tag{C-17}$$

R_n is the negative resistance without parasitics (C_P, L_P).

For sustained oscillation $\rightarrow R_{neq} \geq 2R_{PEQ} \cong 101.4$ Ohm

$$R_n = 3.65 * 101.4 \approx 371 Ohm \tag{C-18}$$

$$C_1 C_2 = \left[\frac{1}{\omega^2}\right]\left[\frac{0.107}{371}\right] \approx 7.26 \tag{C-19}$$

$$\left[\frac{C_1}{C_2}\right]_{x=20} \approx 1.52 \tag{C-20}$$

$$C_1 = 3.3 pF \tag{C-21}$$

$$C_2 = 2.2 pF \tag{C-22}$$

Step 7:

Calculation of the coupling capacitor r_e.

The expression for the coupling capacitor is

$$\frac{C}{10} > C_C > \left\{\frac{(\omega^2 C_1 C_2)(1 + \omega^2 Y_{21}^2 L_P^2)}{[Y_{21}^2 C_2 - \omega^2 C_1 C_2)(1 + \omega^2 Y_{21}^2 L_P^2)(C_1 + C_P + C_2)]}\right\} \tag{C-23}$$

$$C_c \rightarrow 0.4 pF \tag{C-24}$$

Figure C-5 shows the transistor in the package parameters for the calculation of the oscillator frequency and loop gain.

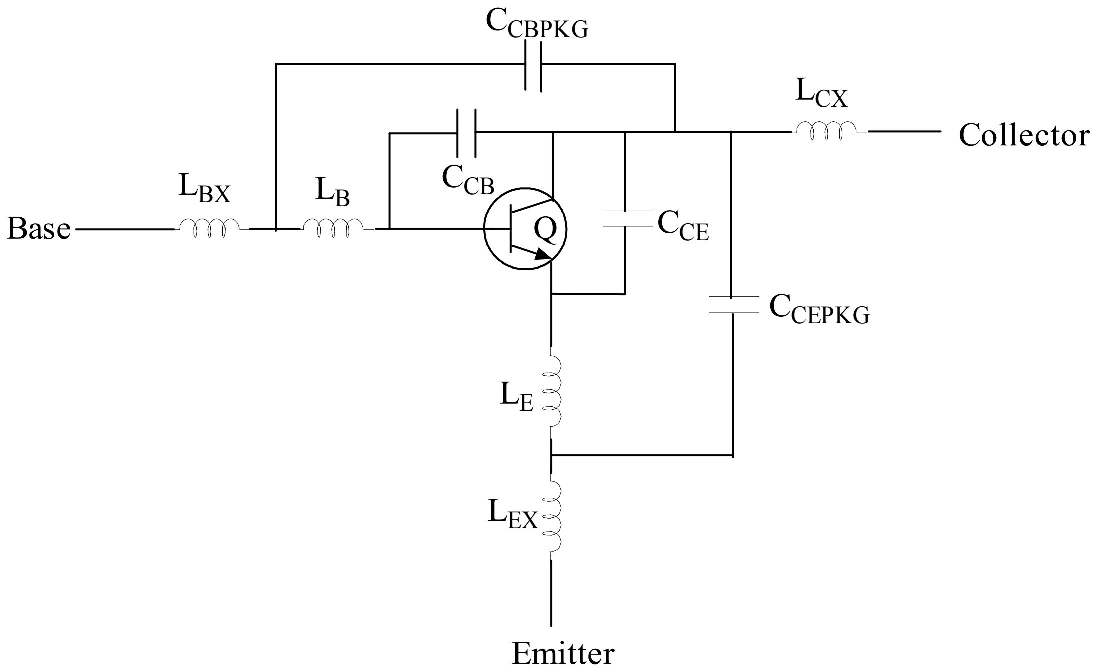

Figure C-5 NE68830 with package parasitics. Q is the intrinsic bipolar transistor.

Tables C-1 and C-2 show NE68830 nonlinear parameters and package parameters which were taken from the NEC data sheets.

Table C-1 Nonlinear parameters

Parameters	Q	Parameters	Q
IS	3.8E-16	MJC	0.48
BF	135.7	XCJC	0.56
NF	1	CJS	0
VAF	28	VJS	0.75
IKF	0.6	MJS	0
NE	1.49	TF	11E-12
BR	12.3	XTF	0.36
NR	1.1	VTF	0.65
VAR	3.5	ITF	0.61
IKR	0.06	PTF	50
ISC	3.5E-16	TR	32E-12
NC	1.62	EG	1.11
RE	0.4	XTB	0
RB	6.14	XTI	3
RBM	3.5	KF	0
IRB	0.001	AF	1
RC	4.2	VJE	0.71
CJE	0.79E-12	MJE	0.38
CJC	0.549E-12	VJC	0.65

Table C-2 Package parameters of NE68830

Parameters	**NE68830**
C_{CB}	0.24E-12
C_{CE}	0.27E-12
L_B	0.5E-9
L_E	0.86E-9
C_{CBPKG}	0.08E-12
C_{CEPKG}	0.04E-12
C_{BEPKG}	0.04E-12
L_{BX}	0.2E-9
L_{CX}	0.1E-9
L_{EX}	0.2E-9

Design Calculations

1. Frequency of Oscillation

Frequency of the oscillation is

$$\omega_0 = \sqrt{\frac{1}{L\left[\frac{\left[\frac{(C_1^* + C_P)C_2 C_c}{(C_1^* + C_P + C_2)}\right]}{\left[\frac{(C_1^* + C_P)C_2}{(C_1^* + C_P + C_2)} + C_c\right]} + C\right]}} \approx 1000MHz \tag{C-25}$$

with

L = 5nH (Inductance of the parallel resonator circuit)

$C_1^* = 2.2$pF

$C_1 = C_1^* + C_P$

C_P=1.1Pf (C_{BEPKG} + Contribution from layout)

$C_2 = 2.2$pF

$C_c = 0.4$pF

C =4.7pF

R_P=12000 (Measured)

$$Q_{unloaded} = \left[\frac{R_P}{\omega L}\right] = 380$$

2. Calculation of the Phase Noise

The noise equation which was determined in Chapter 8.4, Equations (8-109), (8-115), and (8-117), and which contains resonator noise, shot noise, and flicker noise, can now be used to graphically determine the best phase noise as a function of *n*. Figure C-6 shows a plot of this curve. It gives the best number of *n* to be 2.5, which is consistent with the calculation done for the large-signal condition. Eq. (C-12) gives the same result.

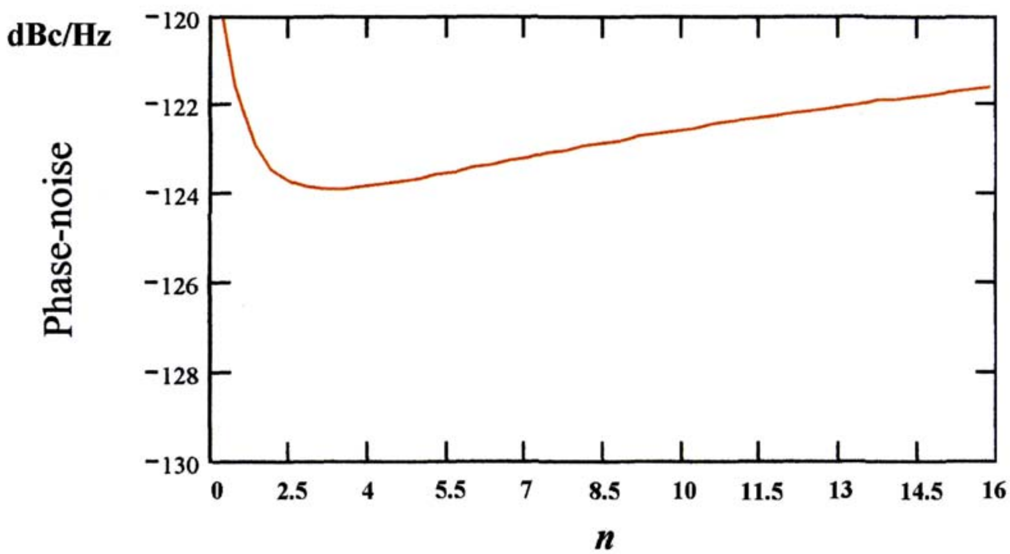

Figure C-6 The phase noise contribution of the lossy resonator at 10KHz offset.

The calculated phase noise at 10 KHz off the carrier is –124 dBc/Hz, which agrees with the measurements within 1 dB. The other values are –140 dBc/Hz at 100 kHz offset and –160 dBc/Hz at 1 MHz offset.

This circuit is shown in Chapter 9.1, Figure 9-2. The actual measured phase noise is shown in Figure 9-4, and the simulation is shown in Figure 9-5. Considering that Equation (8-109) only contains shot and flicker noise, as well as resonator noise, it has been proven that this by itself is a very accurate formula for practical use. Figure 9-5 has been generated from using Ansoft Designer, which includes all noise sources and is based on the harmonic balance principle.

The important conclusion found in Chapter 8 is that for the first time we have a complete mathematical synthesis procedure for best phase noise that covers both flicker noise and white noise for the oscillator. In the past, most publications have referenced an oscillator built with many shortcuts and then the author found that the measured results agree with the expectations. A complete synthesis approach has not appeared previously.

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