

Oscillators

Principles of Oscillators

Requirements

- 1 The LO must be able to supply sufficient power to drive the mixer at the required level.
- 2 The LO must have a sufficient low Phase and amplitude noise for the application. For example FM 75 kHz deviation, for 60 dB SNR need an LO with < 75 Hz phase noise when measured in the 50Hz to 15 KHz band.
- 3 The harmonics of the LO must be sufficiently small not to cause interference to other users or other parts of the receiver. In particular harmonic mixing products must be very small and not cause any spuri.

Oscillator Types

There are two basic oscillator types:

Oscillator using positive feedback: This is the common lower frequency oscillator design technique used in EE3300, and can be used at any frequency.

Oscillator using negative Resistance: This relies on S_{11} of an amplifier in a circuit being >1 at some frequencies, resulting in oscillation. The amplifier is unstable at those frequencies where $S_{11} >1$, causing the amplifier to oscillate. This design technique is predominantly used for microwave operating frequencies. The design of oscillators using negative resistance is beyond the scope of this course.

Positive Feedback Oscillators

The oscillator consists of an amplifier and a Frequency Selective Network. The amplifier output is applied to the frequency selective network, the output of which is applied to the amplifier input. For the analysis a switch can be imagined to open the closed loop signal path. If V_2 is exactly the same as V_1 , both in amplitude and phase then steady state oscillations result. If the magnitude of $V_2 > V_1$ and the phase is the same then the oscillations will grow. If $V_2 < V_1$, then the oscillations will decay.

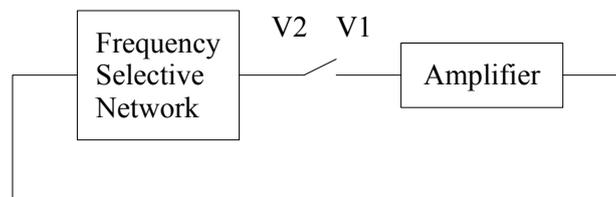


Figure. 1. Feedback Oscillator Block Diagram

Oscillator design process:

- 1: Design the Feedback network to have the correct frequency selective behaviour at the required operating frequency. A high Q network will have a rapid change of phase with frequency resulting in a lower phase noise of the resulting oscillator.
- 2: Select or design the amplifier to have the required gain at the operating frequency. The input and output impedances should also match the expected loads to be seen by the frequency selective network.
- 3: Simulate the amplifier and ensure the biasing is correct to provide the required gain and phase shift at the operating frequency.
- 4: Connect the frequency selective network and amplifier and do a linear analysis to ensure that the required gain (>1) and phase (V2 in-phase with V1) conditions are satisfied. In MWO the OSCTEST element is specially designed to perform this function and is used in place of the switch shown in the above diagram.

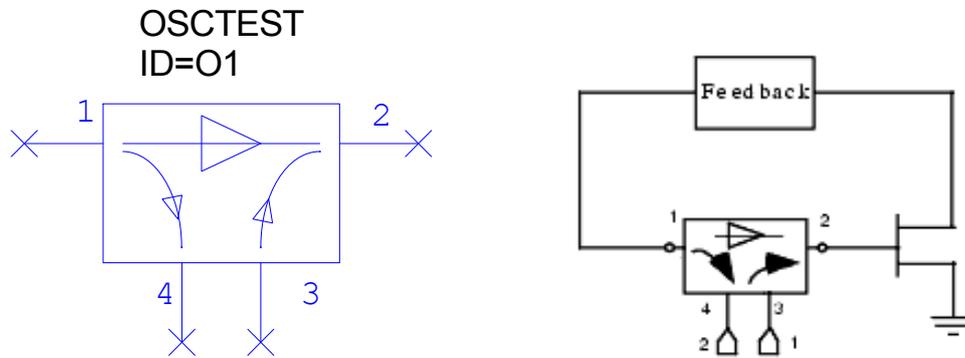


Figure 2. The use of Oscptest for linear analysis of oscillators.

- 5: Once the circuit has been adjusted to have the correct gain and phase for oscillation, modify the linear circuit by replacing the Oscptest probe with the Oscaprobe. The Oscaprobe is connected to ground at the point where the switch was, as shown below.

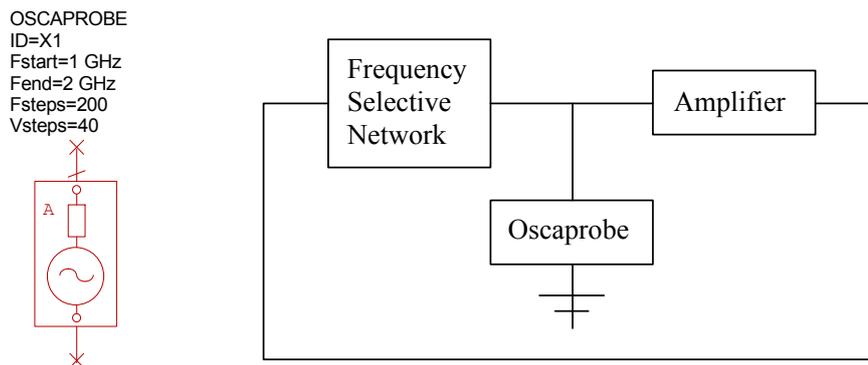


Figure 3. The use of Oscaprobe for nonlinear analysis of oscillators.

The Oscaprobe is a network that is a short circuit at the specified frequency of oscillation and an open circuit at all other frequencies, the voltage amplitude and phase is adjusted until no current flows through the probe, under which conditions the correct oscillating amplitude is determined. This amplitude is then used in a non-linear (spice) simulation of the oscillator circuit. This then allows output waveforms, harmonics and

the phase noise of the oscillator to be determined. The MWO oscillator example which is located in the MWO directory: Examples/Circuit Design Types/Oscillators/BJT Oscillator, and the Colpitts oscillator design example in these lecture notes are design examples which follow this process.

Frequency Selective Networks

For typical RF and Microwave oscillators, the following oscillator types are commonly used:

Wien Bridge Oscillator, using an RC network with a $Q=1/3$. This is a low Q resulting in a high phase noise for the oscillator. The oscillator is however easy to construct and time and as a result this oscillator is often used for audio frequencies, where the inductors required by other configurations would be too large to be used in oscillators.

Colpitts Oscillator, using a tapped capacitor LC network.

Hartley Oscillator, using a tapped Inductor LC network. Both the Colpitts and Hartley oscillators are similar, in their frequency range of operation, output voltage and phase noise. The LC resonators used in both the Colpitts and Hartley oscillators will have a typical maximum Q of 250. In practice unloaded Q values of 100 are more common.

Voltage Controlled Oscillator. One of the capacitors in the LC network for a Colpitts or Hartley oscillator is replaced with a varactor diode, allowing the capacitance of the LC network to be varied by applying a DC bias. Voltage controlled oscillators are used in many applications.

Crystal Oscillator. A quartz crystal is used as part of the frequency selective network, resulting in a very high Q resonator. Fundamental mode crystal oscillators are available for frequencies between 32 kHz and 100MHz. Crystal oscillators have very low phase noise. Quartz Crystal resonators will be discussed in more details later.

Stripline or microstrip transmission line resonator. At VHF and microwave frequencies such resonators are a reasonable size and have unloaded Q values of the order of 200.

Coaxial cavity oscillator. The resonators can be made from Coaxial resonators with a centre length of one quarter wavelength. These resonators can have unloaded Q values of several thousand. The resonators are large, restricting the applications.

Dielectric resonator oscillator. By filling the coaxial resonator with a material with a high dielectric constant, the linear dimension is reduced by the square root of the dielectric constant. Having a dielectric constant of 25 will thus reduce the volume of the resonator to 1/25 of the air filled resonator volume. Dielectric resonators are used frequently at microwave frequencies. The resonators can be based on the coaxial resonator and have a centre conductive resonator and conductive walls, or they can simply be a high dielectric material, relying on the dielectric-air interface to keep the electric fields inside the resonator.

A plot of the Q values of different resonators and the corresponding volume, is shown in figure 1.

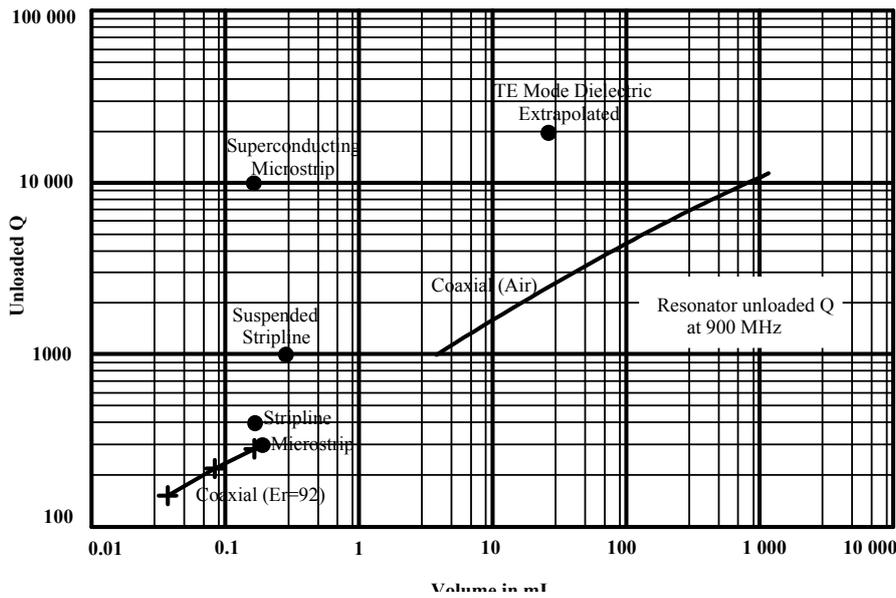


Figure 4. Q values and Volume of different resonators at 900 MHz.

The phase noise of an oscillator is primarily determined by the Q of the resonator used in the oscillator, and the way that the amplifier loads the resonator. The higher the Q of the resonator, the lower the phase noise and in general, the lower the frequency variation that can be obtained by tuning the resonator. The choice of the resonator and its Q is thus the primary factor affecting the oscillator properties.

Oscillator design procedure

Step 1: Select a transistor, FET or amplifier

The active device used in an oscillator is very important, factors for consideration are: Output power, oscillating frequency, supply voltage and cost. The low frequency phase noise of the oscillator does depend on the flicker noise of the amplifier, so that the noise figure of the amplifier is important for low noise oscillators.

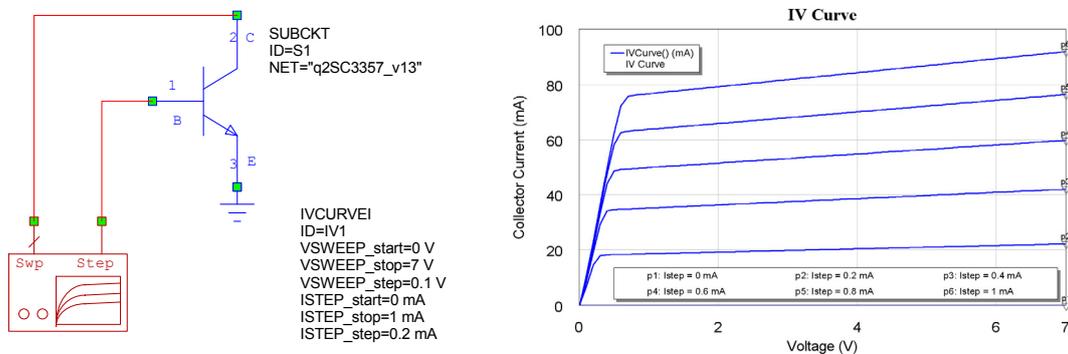


Figure 5. Circuit for determining the I-V characteristic of a transistor.

The most important design parameter is the Biasing of the transistor. In EE2300 and EE3300 it was shown that the IV curve is very useful in determining the correct biasing

conditions. It should be realised that some of the critical transistor parameters like β can vary over a 5:1 ratio between transistors. The transistor parameters used in the models of the computer simulation software, include typical values. The design must be such that the oscillator will work under all permissible variations of transistor parameters. The I-V curve can easily be obtained in MWO as shown in figure 5:

For linear biasing, a 7V supply and quiescent collector current of between 40 and 5 mA is required. 15 mA is a good compromise to minimise the power dissipation in the transistor and still have sufficient output power.

Step 2: Design an amplifier

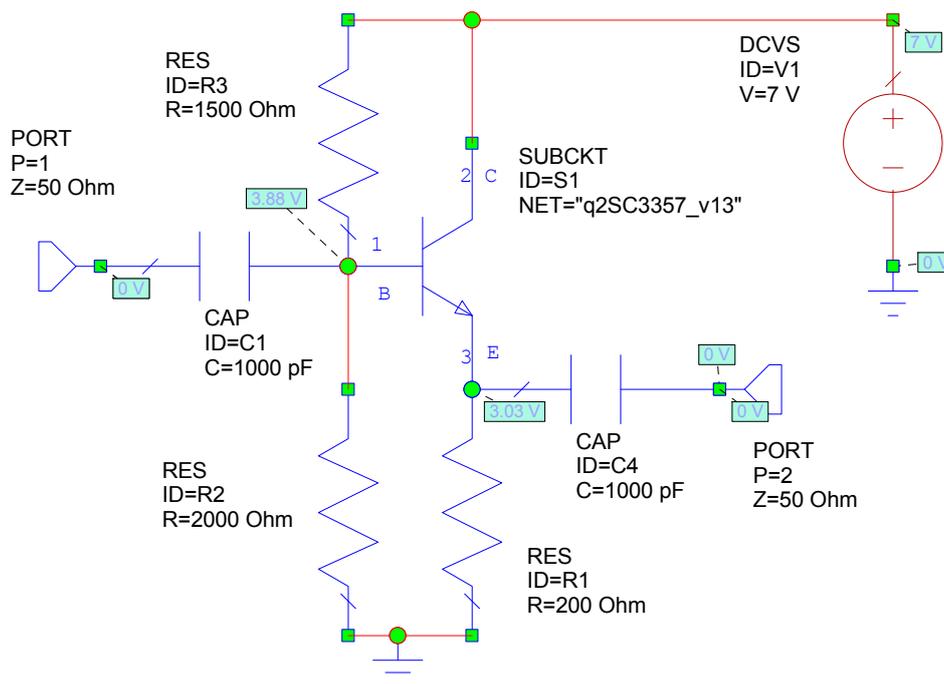


Figure 6. Amplifier for the Colpitts oscillator

A typical amplifier configuration and one that is used for this design is shown in figure 2. The first step is to select the bias voltages. For a 7 Volt supply, and having an emitter follower configuration for the amplifier, the emitter voltage should be close to half of the supply voltage, minus one volt. This results in a large swing without the transistor saturating. For a quiescent current of 15 mA, the current through the biasing chain should be of the order of 1.5 mA to 3 mA, for good quiescent current stability with temperature. For an emitter voltage of 3 Volt, a base voltage of 3.5 Volt is desired, so that a biasing resistor, between 2.4 k Ω and 1.2 k Ω is required for R3, when the values are rounded to the nearest available resistor values. Since a relatively high input impedance is required, a 2 k Ω resistor is used. A 1.5 k Ω resistor is required to then obtain the 3.5 V at the base of the transistor using a 7 V supply. The annotation setting allows the circuit voltages to be indicated on the circuit diagram in Microwave Office and allow the biasing and voltages to be checked.

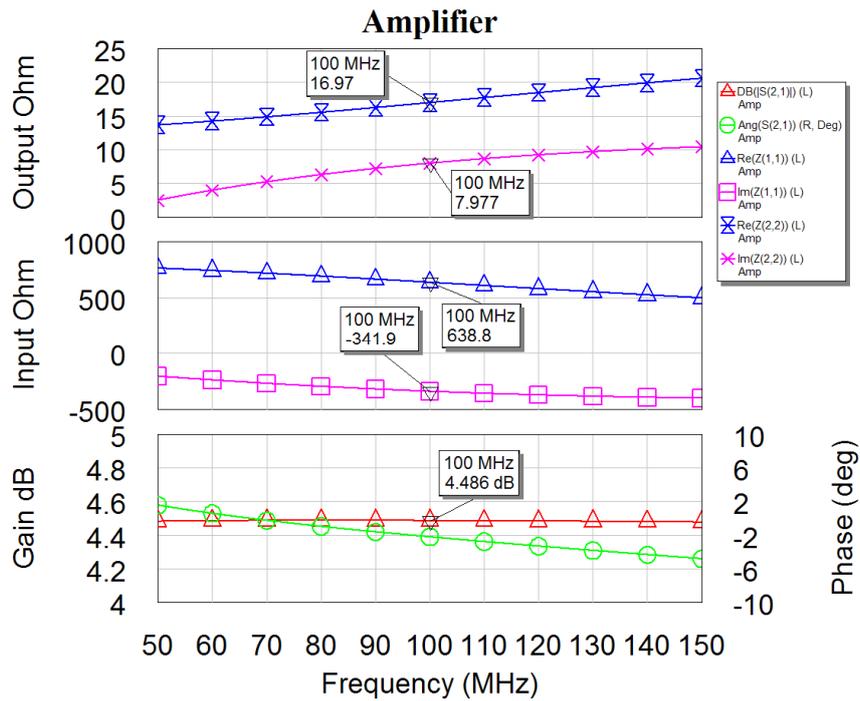


Figure 7. Amplifier Performance.

Note The gain of 4dB is the power gain taking the different input and output impedances into account. Input Impedance 638 Ω and the output impedance is 17 Ω, with a significant reactive component that will effect the resonance of the Collpitts oscillator if it is not allowed for in the design process.

Step 3: Design a resonator

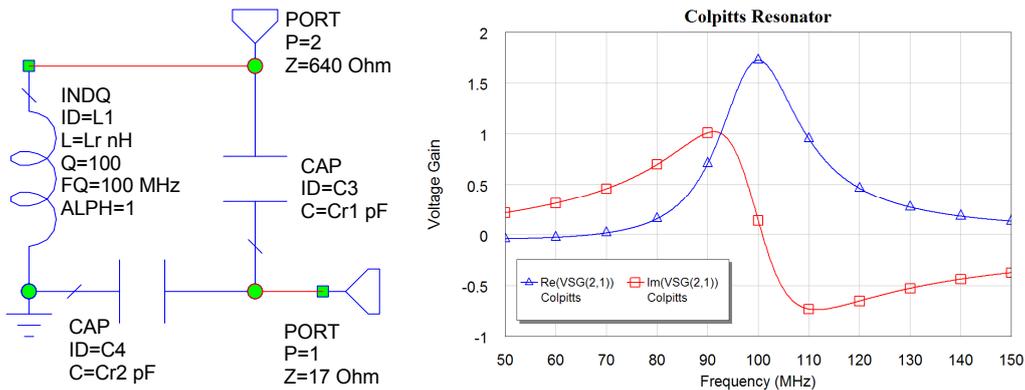


Figure 8. Colpitts resonator network

The resonator must be a frequency selective network, to ensure that the conditions for oscillation only apply at one frequency. In addition the network must be matched to the input impedance and output impedance of the amplifier and have a high Q. The components can be tuned to ensure a zero (or 180 degree if needed) phase shift at the required operating frequency. In figure 8, the imaginary part of the transfer function is not exactly zero, since the network shown is corresponds to the one actually used in the oscillator and allows for phase changes produced by the amplifier.

Step 4: Linear Oscillator Analysis

The resonator and amplifier are now combined into the once circuit. The element OSCTEST is used to determine the loop gain and phase shift. The resonator network is now tuned to give a phase shift of zero degrees between port 1 and 2, at the required operating frequency. If needed, the loop gain is changed to ensure that it is just slightly above one at the operating frequency. That then corresponds to the correct conditions for oscillations.

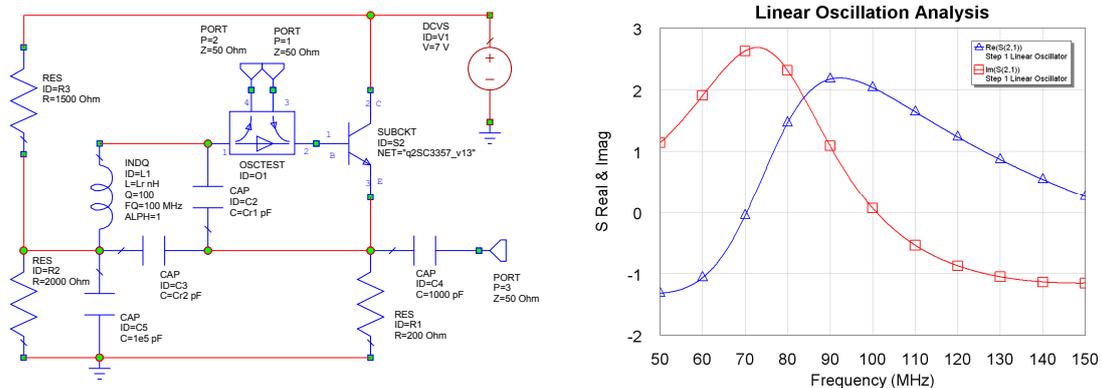


Figure 9. Linear analysis using OCSTEST

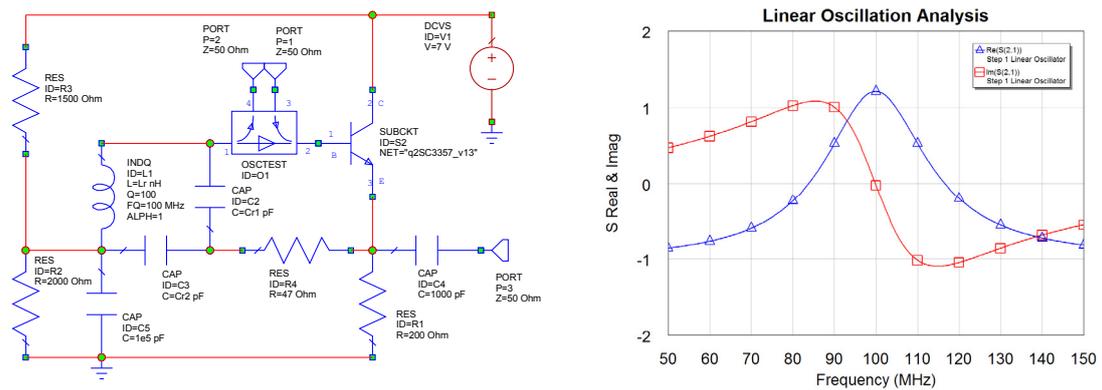


Figure 10. Linear analysis using OCSTEST Resistor added to increase Q and reduce gain.

The gain in figure 9 is too large and the 17 Ω output impedance of the amplifier, causes a severe reduction of the Q of the resonator network, resulting in a high phase noise. The gain can be reduced by inserting a 47 Ω resistor in series with the output of the amplifier. That also increases the Q if the resonator and reduces the phase noise of the oscillator, since the output impedance dominates the load to the network.

Step 5: Nonlinear Analysis

Replace OSCTEST with OSCPROBE as shown in figure 11, to do a harmonic balance analysis. This will allow the oscillation frequency, output power and output waveforms, including the amplitude of each of the harmonics to be determined. The output spectrum obtained using the harmonic balance is shown in figure 11, the tuning frequency range can be investigated by plotting the Inductance required versus oscillating frequency, and the output waveform can be determined as shown in figure 12.

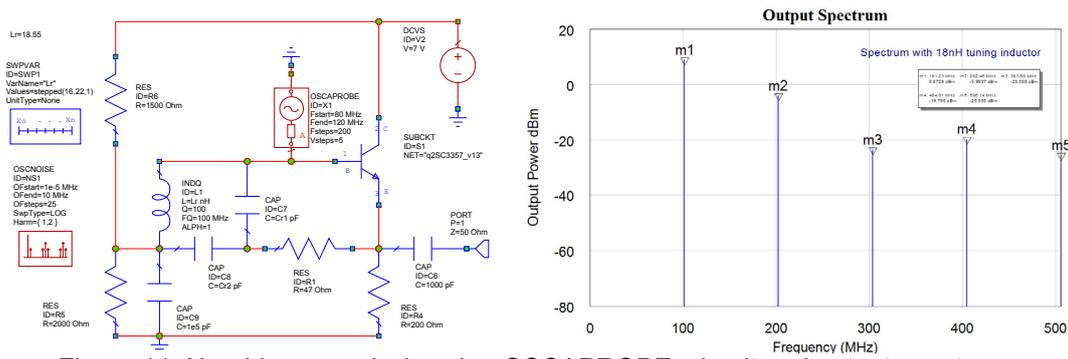


Figure 11. Non-Linear analysis using OSCAPROBE, circuit and output spectrum.

The SWPVAR simulation control (Element ⇒ Simulation Control ⇒ SWPVAR) shown in the schematic of figure 11 allows the plotting of the sweep of inductor values and their corresponding frequency. Note that the output waveform is smaller than expected, since the amplifier should have a linear output swing of at least ±2 Volt. The waveform can then be used to investigate the suitability of the biasing.

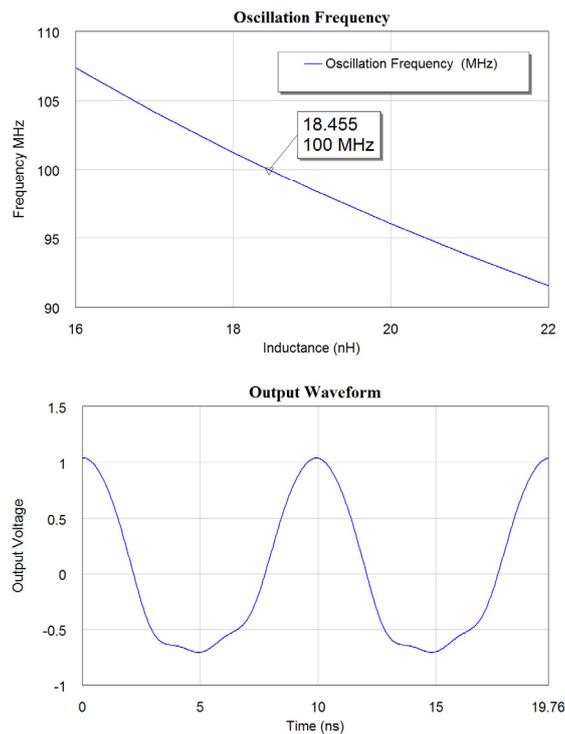


Figure 12. Non-Linear analysis using OSCAPROBE, Tuning range and output waveform.

The non-linear analysis can also be used to determine the Phase Noise of the oscillator. The OSCNOISE measurement (Element ⇒ MeasDevice ⇒ Controls ⇒ OSCNOISE) allows the phase noise of the oscillator to be measured as shown in figure 13. The phase noise will depend on the Q of the resonant network as well as other parameters, such as the noise figure of the amplifier and the amplifier power level and the loading that the amplifier places on the resonant network. In general the higher the oscillating frequency, the higher the phase noise.

Microwave Office allows the performance of an oscillator to be determined prior to the hardware being produced. This greatly reduced the cost of designing oscillators. The non-linear analysis can only be produced when a full Spice model of the active device is available. Many transistor manufacturers provide the required models for their transistors. Unfortunately the Spice models are not available for many MMIC's.

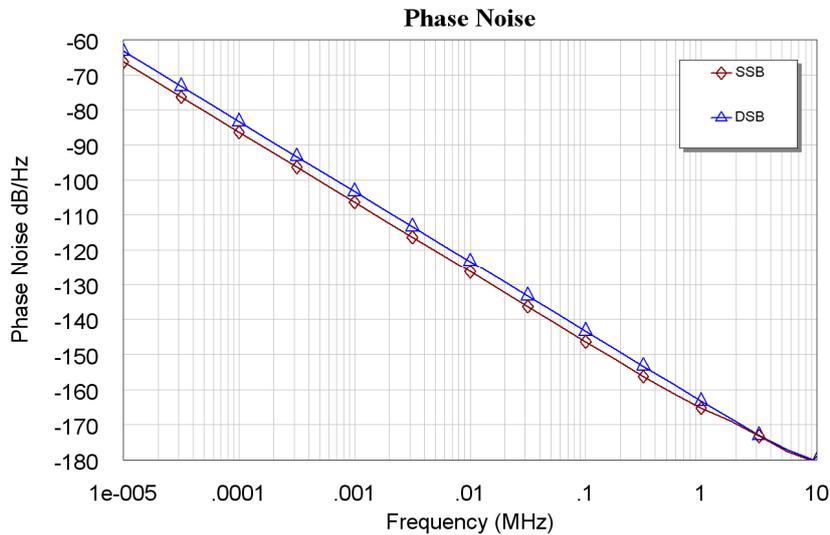


Figure 13. Phase noise of the oscillator using non-linear (harmonic balance) analysis.

Crystal Oscillators

Quartz Crystals

For details of Quartz Crystals see "Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications - A Tutorial" by the 2009 IEEE president John Vig. He has graciously given permission for those PowerPoint slides to be available as a resource for this course. As a result they are included in the "Resources"

Crystal Oscillator Design Example

The design of a crystal oscillator is similar to that of any other oscillator. For most fundamental mode crystal oscillators, the crystal is inductive at the operating frequency and the inductor in any LC oscillator is replaced with the crystal. In figure 14, the inductance of a phase shift oscillator is replaced with a quartz crystal.

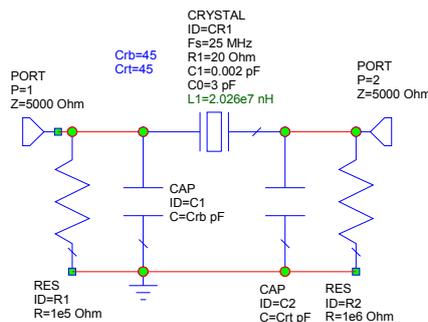


Figure 14. Phase shift network using a Quartz Crystal

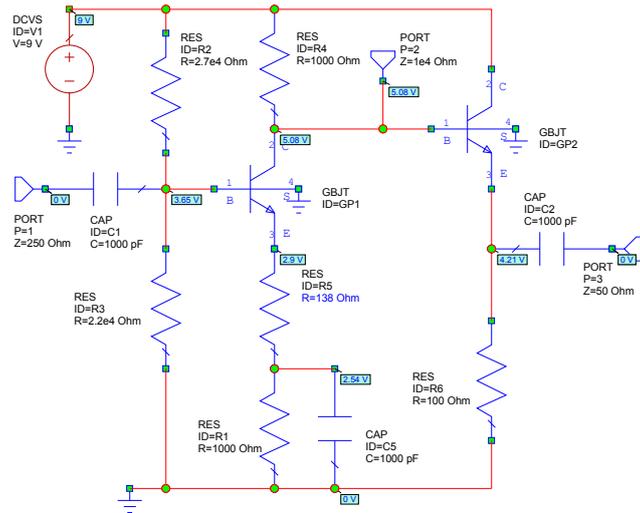


Figure 15. Resonator Network and Amplifier for Crystal Oscillator

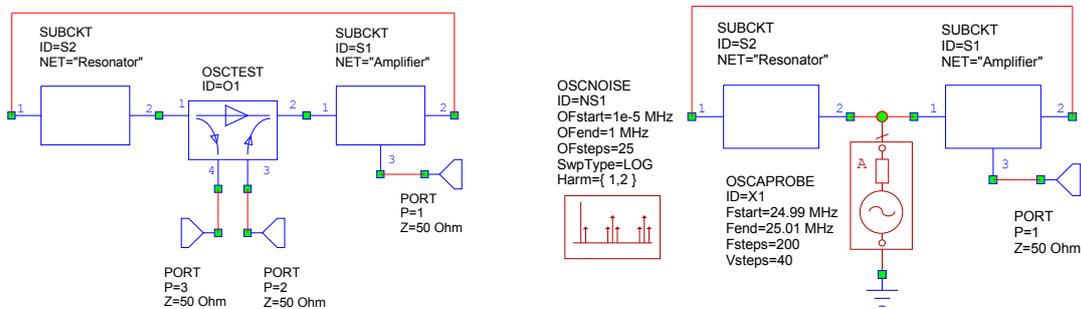


Figure 16. Linear and Non-linear Oscillator Circuits

The amplifier shown in figure 15 has a gain of 21.5 dB from the input port 1 to the output port 3. The gain from the input to port 2 is enough to cause oscillations. The gain of the amplifier can be controlled by changing R4, the resistor connected to the emitter, without affecting many other parameters. The resonant network and the amplifier are connected together to form a Crystal oscillator as shown in figure 16.

Using OSCTEST, the gain around the amplifier and resonator loop is now determined using a linear oscillator analysis as shown in figures 17 and 18.

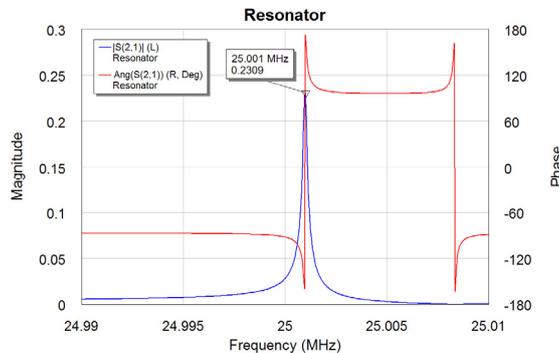


Figure 17. Frequency response of the resonator of figure 14.

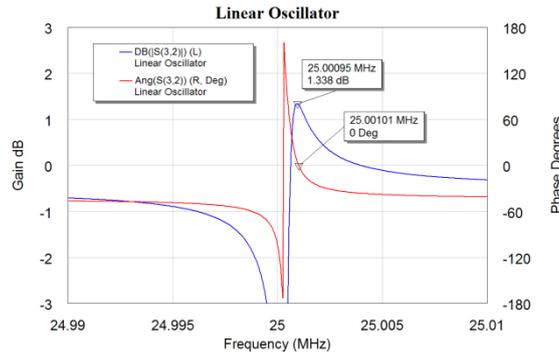


Figure 18. Frequency response for the oscillator using linear oscillator analysis (OSCTEST).

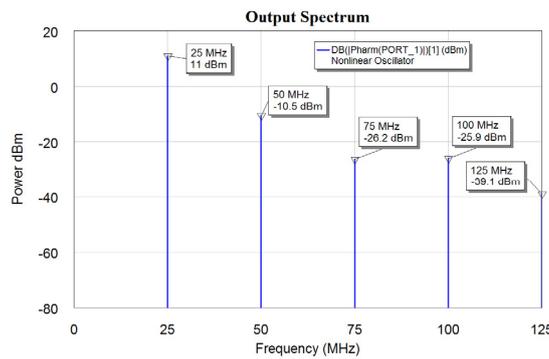


Figure 19. Output spectrum obtained using harmonic balance analysis. (OSCAPROBE)

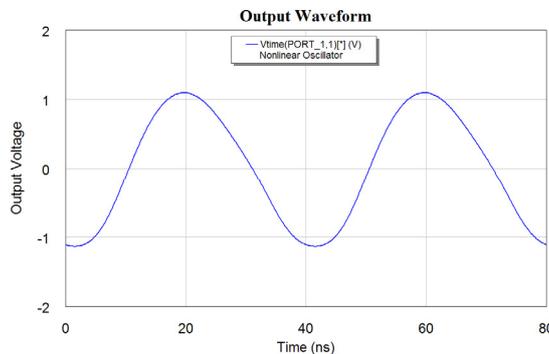


Figure 20. Output waveform obtained using nonlinear (harmonic balance) analysis.

Replacing the OSCTEST element with the OSCAPROBE element as shown in figure 16, allows a harmonic balance analysis to be done, so that the output spectrum can be determined as shown in figure 19, the output waveform can be determined as shown in figure 20 and the phase noise can be determined as shown in figure 21.

By comparing figure 13 and figure 21, it can be seen that the crystal oscillator has a much lower phase noise, due to the Q of the resonator being much higher. Using a varactor diode permits the electronic control of the frequency of the oscillator of figure 6 to 13. A 2:1 frequency range is possible. The frequency of crystal oscillators can however only be varied by several parts per million. For low noise crystal oscillators, the amplifier should impose a negligible load

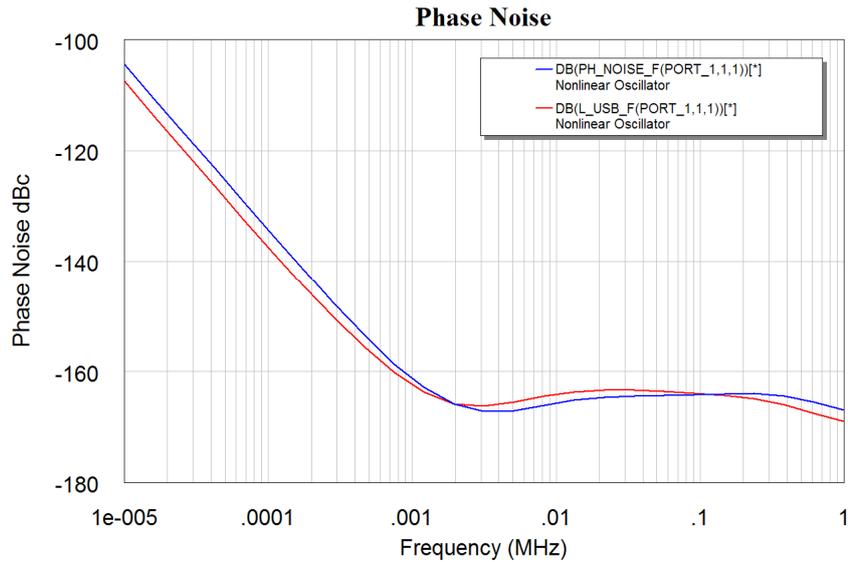


Figure 21. Phase noise of the oscillator.

RF and Microwave Oscillators

At RF and Microwave frequencies (above 1GHz), transmission lines are often used as circuit elements. The MAR6 amplifier, used here, is a typical MMIC (Microwave Monolithic IC) costing less than \$10. These devices are very simple to use and are convenient and can be used as low power amplifier blocks in many applications. The S parameters for these devices can be obtained from the Minicircuits web site as follows:

```
!MAR-6 (TA = 25°C, Id = 16mA)
!FREQ. S11 S21 S12 S22
!MHz dB Ang dB Ang dB Ang dB Ang
# MHZ S DB R 50
100 -27.96 171 20.1 171 -22.50 5 -27.96 -30
500 -26.02 -105 18.7 138 -21.30 21 -20.00 -104
1000 -17.72 -118 16.4 107 -18.80 28 -17.08 -150
1500 -13.56 -140 14.1 84 -17.10 28 -16.48 180
2000 -10.75 -163 12.0 65 -15.80 26 -15.92 157
2500 -9.37 -176 10.3 55 -15.20 28 -15.92 150
3000 -7.74 169 8.7 42 -14.80 25 -16.48 143
3500 -6.74 157 7.2 30 -14.20 22 -17.72 144
4000 -6.20 146 6.1 18 -13.80 20 -20.00 156
```

Table 1. S parameter file from Minicircuits with added line in blue.

This file can be imported into Microwave Office so that those S parameters for the device can be used in a simulation. Theo import the s parameter file, it needs to be in the “Touchstone” file format. (Touchstone was the name of an early RF simulation software, which was later taken over by EESOF, which in turn was taken over by

HP/Agilent and is now called ADS. The only change that needs to be made to the S parameter file as obtained from Minicircuits, is the addition of the line shown in blue:

```
# MHZ S DB R 50
```

That line indicates to Microwave Office that the file has frequencies in MHz, contains S parameters, which must be in the order S11(Real, Imag), S21(Real, Imag), S12(Real, Imag) and S22(Real, Imag). The real part is in DB and the reference impedance is 50 ohm. Any line beginning with ! is a comment line and is ignored in the data file import.

For other formats for data files see the Microwave Office help files on “Adding Data Files to a project”, which includes details on the Touchstone Import files format. That data file is then used as a sub-circuit in the circuit diagram.

This data file is now used to design a 1 GHz oscillator using this MAR6 amplifier and using microstrip circuits on a Rogers RO4003 substrate. The oscillator consists of three parts: The MAR6 amplifier, A microstrip resonator (TL1) with tap coupling in order to obtain the correct impedance levels for the coupling into and out of the resonator and thirdly transmission lines TL2 to TL11, which are required to connect the output back to the input and thus provide feedback. The path length around the loop must have the appropriate phase shift to ensure that oscillations will result. In addition, two coupling capacitors are used to provide the correct DC levels at the input to the MAR6 and prevent the output from being shorted at DC.

The impedance of the resonator should be as low as possible to provide a reasonable Q, with low radiation losses and a good frequency stability. This is achieved by making the width of the resonator 5mm, which corresponds to a characteristic impedance of 24.8 Ω . A program TxLine, which is part of microwave Office is used for the calculations of the required length of the resonator. A screenshot of the resulting line parameters is shown in figure 22.

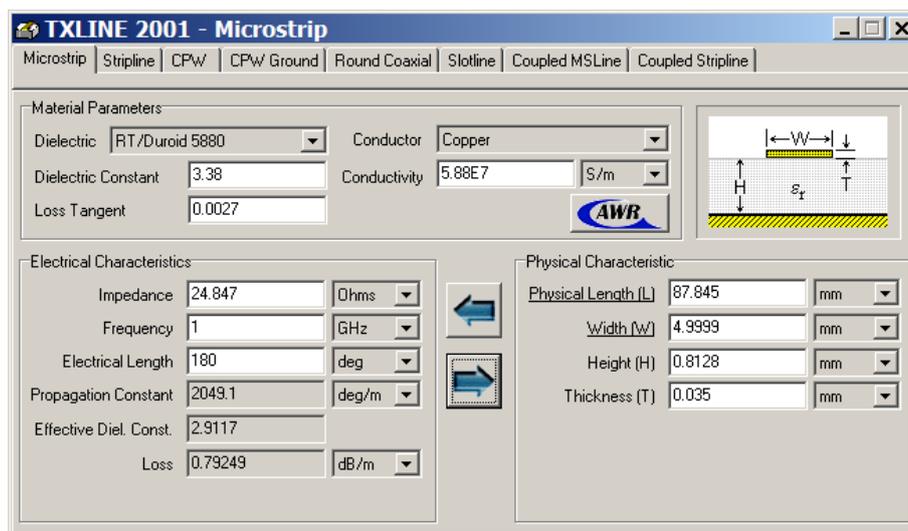


Figure 22. Resonator Width and Length Calculation

Since a full Spice model is not available for the MAR6, only a linear analysis of the oscillator can be carried out. The circuit schematic for the oscillator is shown in figure 23. Figure 24 shows the circuit diagram of the resonator. A capacitor is incorporated. That capacitor can be replaced with a variable capacitor in the hardware, to allow the

Figure 26 shows the amplitude and phase of the resonator of figure 24, as a function of frequency. The resonator has a well behaved response at 1 GHz, but is the amplifier gain is too high, there is a possibility of oscillation at 1.34 GHz. The loop gain of the amplifier and resonator must thus be carefully controlled to ensure that only oscillation at 1 GHz is possible.

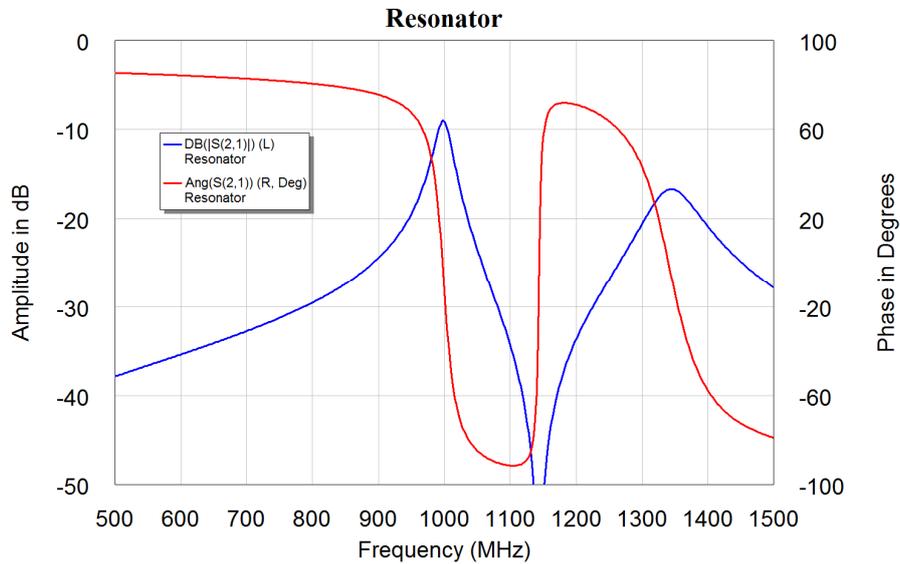


Figure 26. Resonator Transfer function, Amplitude and Phase

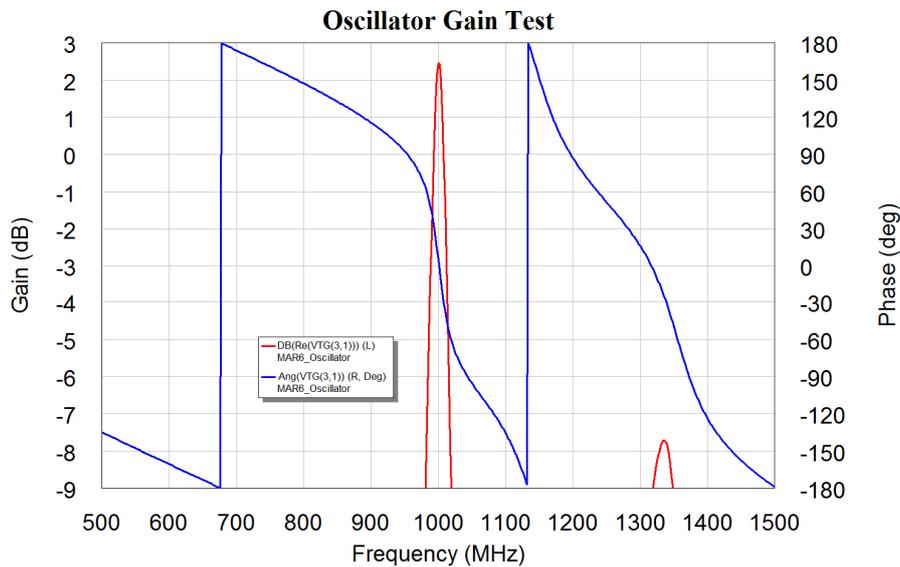


Figure 27. Complete Oscillator OSCTEST output.

The element Oscstest is used to check if the oscillator has the correct gain and phase in the feedback path. The phase shift around the loop should be exactly 0 degrees and the gain should be greater than one. An excess gain of 3 dB ensures that the loop gain is still greater than one, when different MAR 6 devices are used. The length of TL7 and TL8 are both adjusted in order to obtain the correct phase shift of 0 degrees at 1 GHz and the length of the resonator is adjusted to provide a maximum of gain at 1 GHz, to ensure that the oscillator does not oscillate at another frequency.

The resulting microstripline layout is shown in figure 28, with the oscillator output at the top, the supply voltage pad at the left and the largest element being the resonator. The resonator is shown slightly lighter, since that is a separate element in the layout.

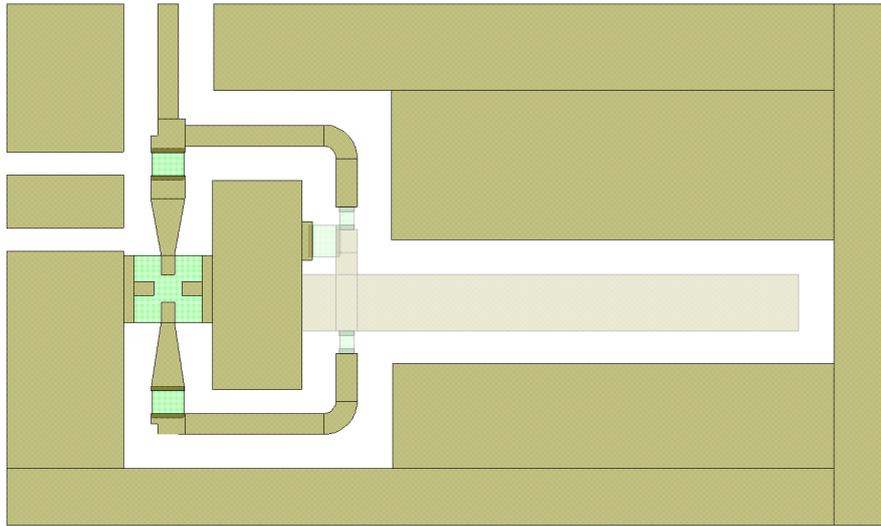


Figure 28. PCB layout for the 1GHz oscillator.

The only elements not shown on this layout are the power supply biasing and vias connecting the ground pins of the MAR to the ground-plane.

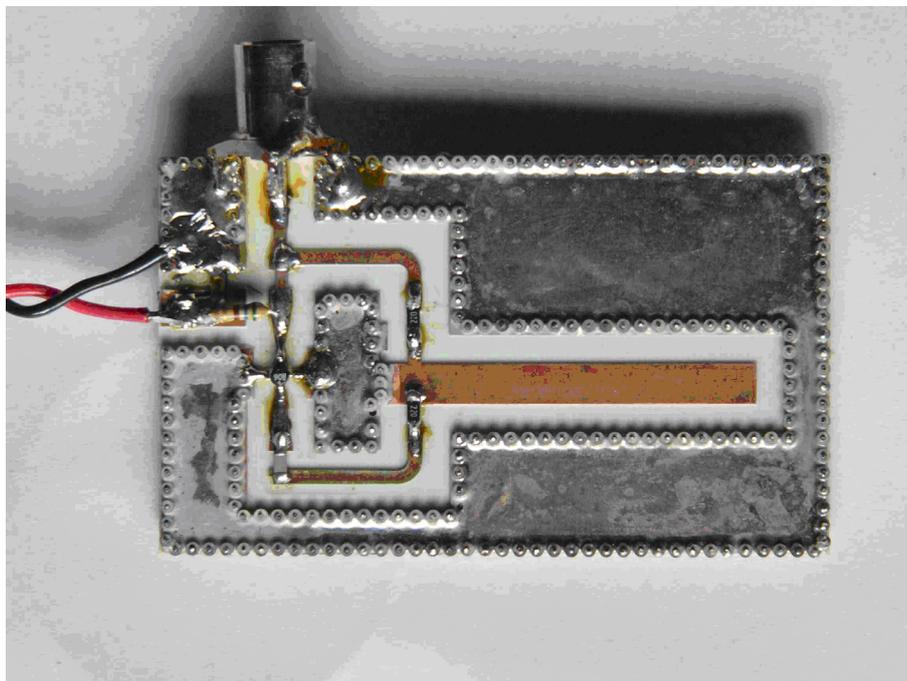


Figure 29. Photograph of the 1 GHz oscillator.

Figure 30 shows the spectrum obtained from the oscillator. The oscillator has a clean output signal and an acceptable phase noise performance. The output frequency is 990 MHz, which is within 1% of the design value. The output has a power of +5 dBm.

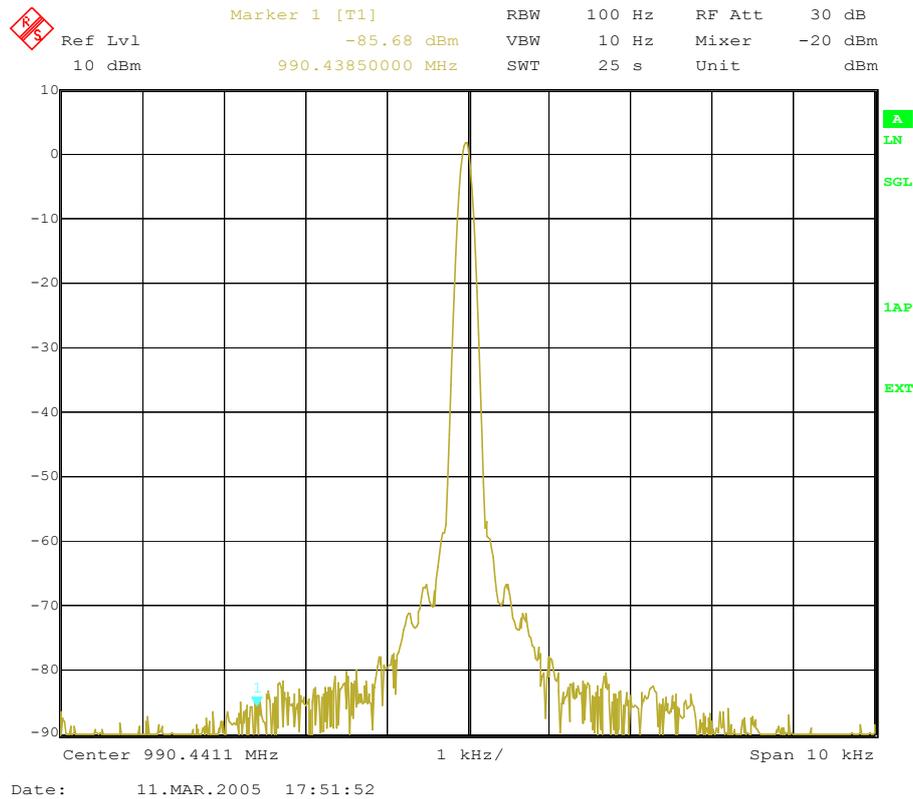


Figure 30. Measured output spectrum for the 1 GHz oscillator.

References

John Vig "Quartz Crystal Resonators and Oscillators for Frequency Control and Timing Applications - A Tutorial" John Vig, the 2009 IEEE president has graciously given permission for this PowerPoint presentation to be available under the "Resources" for this course.