A unique, low-voltage, source-coupled J-FET VCO

A simple feedback direct-frequency VCO principle using common SMD components for frequencies up to E-band

By Bettina Koster, Peter Waldow and Ingo Wolff

Even with the multitude of diverse oscillators available today, it happens now and again that one must design a voltage-controlled oscillator (VCO) for a specific application. Today, there are scores of established oscillator principles[1], and the job of the engineer is to select the one that suits the job best. For frequencies higher than 100 MHz having a supply voltage of 3 VDC or less, selection of an appropriate circuit becomes more and more restricted.

The frequency factor.

The JFET elements

This discussion revolves around a lesser-known oscillator circuit that uses two junction field-effect transistors (JFET) as active devices. Due to the high amplification factor caused by the application of two active devices, low-cost circuit elements with non-negligible electrical losses may be used even in the resonant circuit. The oscillator may be assembled on low-cost FR4 substrate using common surface-mounted devices (SMDs). The oscillator principle can operate down to shortwave frequencies as well, but is best suited for frequencies in the range of 100 MHz to 3 GHz (E-band).

The VCO requires a single positive supply and is primarily designed for a supply voltage in the range of 1.5 VDC to 3.0 VDC. Its primary application is to serve as the signal source in a PLL circuit. The phase noise of the free-running VCO increases with frequency, but remains acceptable for a number of applications (especially for low-cost purposes). For a supply voltage equal to or higher than 1.5 VDC, the output power is at least 1 mW at 50Ω, depending on the adjusted relevant drain current.

The principle of the oscillator

The kernel of the oscillator can be regarded either as a source-coupled differential amplifier or, alternatively, as a two-stage amplifier in which the first stage is assembled with a JFET in a common-drain configuration and the second stage is assembled with a JFET in common-gate circuit. The latter point of view is more suitable for explaining the principle of this oscillator. To illustrate how the oscillator operates, a two-stage amplifier circuit is shown in Figure 1.

The first transistor (T_1) and the source resistor (R_1) together form a common-drain stage, or a source-follower stage. This stage works simultaneously as an amplifier and an impedance transformer with a high input impedance. Consequently, the signal from the resonant circuit formed by the resonant circuit capacitor (C_R) and resonant circuit coil (L_R) is not dampened by the JFET. Additionally, the voltage amplification of a source follower stage is less than unity, the current and power amplification is high, and the output -impedance of this stage is low. Hence, the amplified signal can be taken directly from the source resistor (R_1) via the coupling capacitor (C_2). The negative bias voltage for the gate of the JFET (T_1) in this stage is automatically generated by the voltage drop via the source resistor and the vanishing DC resistance of the resonant coil.

The second transistor (T_2), together with the source resistor (R_2) and the drain resistor (R_D), forms a common-gate stage. The gate of the transistor automatically gets its negative bias voltage from the voltage drop via its source resistor. In contrast to the first amplifier stage, the input impedance of

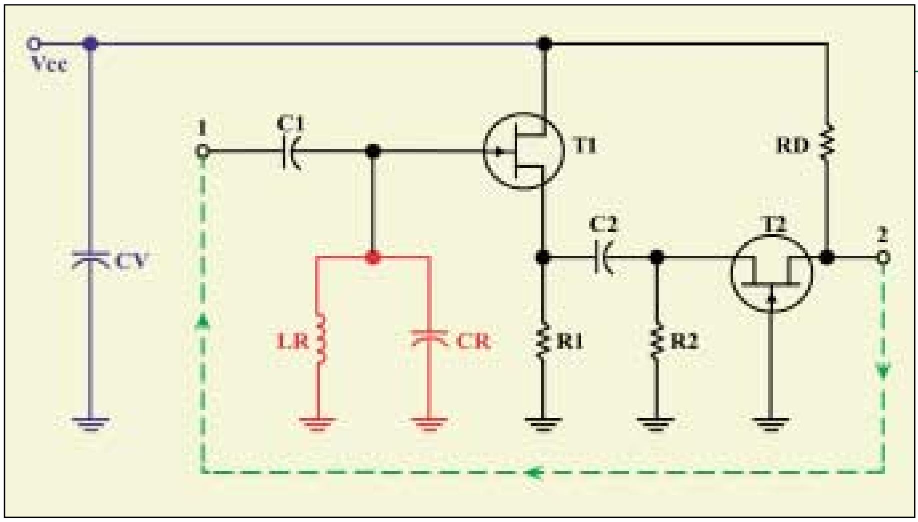

Figure 1. A frequency-selective (LR, CR) two-stage amplifier circuit.

this second stage is low, and the output impedance is high. So, there is an impedance match to the output port and the input port of the first stage as well. For this reason, the influence of the JFET´s impedances on the loaded Q of the resonant circuit is low. By connecting the two stages via the coupling capacitors (C_1 and C_2) the loop is closed and the two-stage amplifier operates as an oscillator with a frequency determined mainly by the value of the resonant circuit capacitor and that of the resonant circuit coil.

The principle of the oscillator is similar to the well- known Franklin oscillator[2]. However, in contrast to the Franklin oscillator, the parallel tuned circuit is not isolated from the two-stage amplifier by means of small capacitors, but rather by impedance matching. Therefore, the loop gain is higher, and the output signal is suited for low impedance loads.

The basic circuit

Some simplifications can be carried out, leading to the basic circuit of the source-coupled JFET oscillator for a fixed frequency as shown in Figure 2.

Only one coupling capacitor (C_F) is necessary to separate the different DC voltages between the gate and the drain of the two JFETs. The two source resistors are replaced with only one resistor (R_S), leading to a galvanic coupling of both the JFETs. The frequency of operation (F) can be easily estimated by the well-known expression:

$$F = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

where L is the value of the inductance of the resonant coil (LR) and C is the sum of the capacities of the resonant capacitor (C_R), a part of the T_1 JFET´s input capacitance and a fraction of the feedback capacitor. The oscillator circuit shown in Figure 2 can be built with common lumped circuit elements, leading to small physical dimensions. The values of the specific elements depend on the types of the transistors in use, the frequency range and the bias voltage. The output signal is gathered from the two galvanic- coupled source electrodes via the coupling capacitor (C_O). The impedance at this point is relatively low, so a common 50Ω load can be directly connected to the oscillator. An additional buffer amplifier is not necessary for proper operation.

The test circuit

To investigate the electrical characteristics of this oscillator circuit, a number of VCOs were built at the different operating frequency bands. One universal circuit was used, changing only values of the relevant circuit elements according to the different frequency bands. The modified and extended circuit of the design is shown in Figure 3.

Two inexpensive GaAs FETs were used as the active devices (T_1, T_2). The drain resistor (R_D) has a fixed value of 470Ω for all frequencies. Due to the fact that the JFETs used in the test circuit tend to oscillate at undesired frequencies, this resistor may be shunted by an additional capacitor (C_D), if necessary.

In this particular circuit, an operating point-dependent parasitic oscillation is observed in the 6 GHz region. This is caused by the small internal reactive elements of the JFETs, such as bonding wire inductances and case capacitances. This parasitic oscillation can mix with the desired frequency's harmonics and result in spurious modes looming in the desired frequency band. The shunt capacitor reduces the amplitude of the oscillator's harmonics and suppresses the generation of spurious modes. The value of the shunt capacitor depends on the desired frequency range and is about twice the

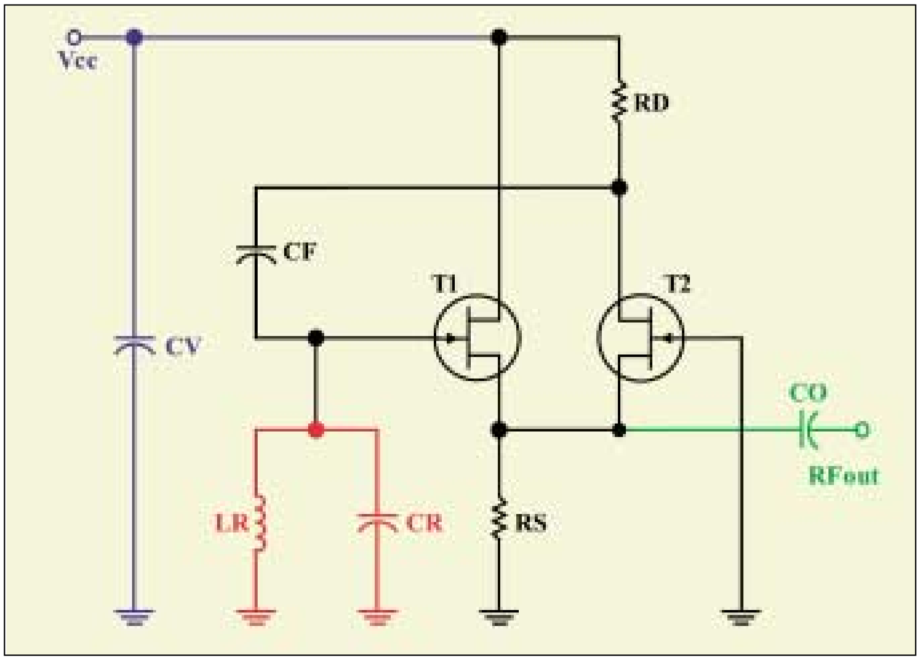

Figure 2.The basic circuit of the source-coupled JFET oscillator.

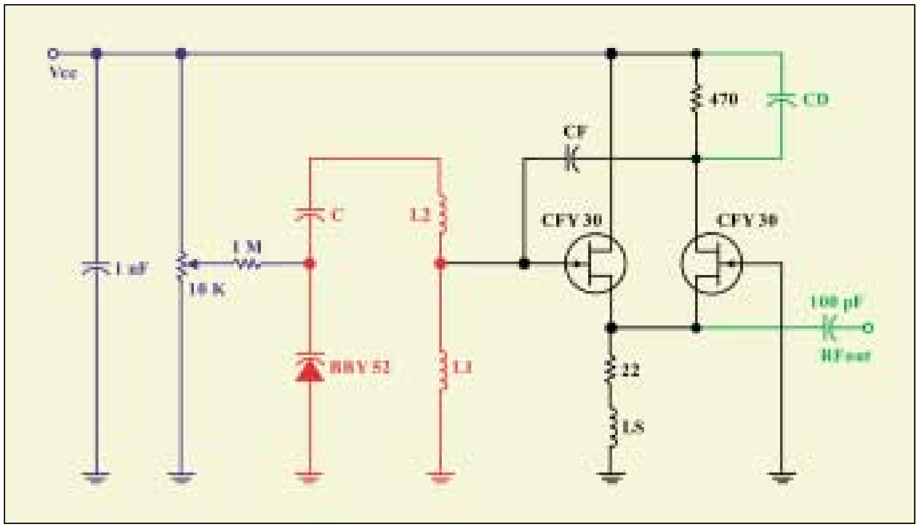

Figure 3. The investigated VCO circuit.

value of the feedback capacitor. If the shunt capacitor is required, attention should be paid to the fact that both the feedback capacitor and the shunt capacitor are connected in series to ground. And the series capacitance of these two capacitors is directly connected, in parallel, to the resonant coil. Thus, the value of this series capacitance must be added to the value of the resonant circuit capacitor when calculating the resonant frequency.

The source resistor regulates the operating point of the respective JFETs, and it determines the generated output power of the oscillator circuit. To achieve a high output signal at a low supply voltage, the source resistor is substituted by a series connection of a fixed 22Ω resistor and a source coil with a frequency-matched inductance value. This increases the DC current via the JFETs and, in turn, increases the amplification factor of both transistors. For higher supply voltage values or less output signal, the source resistor should have values in the range of 47Ω to 200Ω. The source coil can be omitted if the source resistor has a value of 47Ω or more.

For frequencies higher than 2 GHz, the input impedance of the first JFET must be taken into account. Therefore, the resonant circuit coil consists of a series connection of two coils (L_1, L_2). At these higher frequencies, the coils form a tapped coil, reducing the JFETs capacitive input load. For lower frequencies, the additional coil is not necessary and can be shunted by a jumper.

To tune the frequency of the generated signal, a capacitive- (C) coupled varactor diode was used in the tuned circuit to allow voltage tuning. The varactor diode is biased via a potentiometer (10 kΩ) and a resistor (1 MΩ). The tuning range of the VCO depends on the degree of capacitive coupling between the resonant circuit and the varactor diode.

A higher value of the coupling capacitor will allow a larger tuning variation, but will pull down the center frequency. Referring to Figure 3, the tuning voltage can be varied only between zero and the supply voltage (V_{cc}). Therefore, the tuning range depends on the amount of the supply voltage. For values of the supply voltage (V_{cc}) of 3 VDC or less, the tuning range of the capacitance of the varactor diode is low. For lower frequencies, the varactor type should be substituted by a more suitable one.

The oscillator has been developed using the same layout of the printed circuit for signal frequencies from 20 MHz to 3.2 GHz. Some typical element values for the specific frequency bands are given in Table 1 (see page XX). The oscillator of this test circuit is primarily intended to serve as a VCO in a low-voltage, small-band PLL circuit. The tuning range can be small, but must be larger than the thermal frequency drift of the oscillator. For further purpose, this oscillator should be readapted.

The 20 MHz oscillator

In this case, the tuning capacitance of the varactor diode is about 2 pF and is too small for the short wave region. To increase the capacitance, four varactor diodes were used and connected in parallel. An oscillator was built for the 20 MHz region with a resonant circuit consisting of a 940 nH coil (L_1) and an 82 pF capacitor (C) in series to the four varactor diodes. The additional coil (L_2) is not necessary, and is therefore replaced by a shunt. A 100 pF shunt capacitor (C_D) and a 56 pF feedback capacitor(C_F) were used. There is already a series capacitance of about 36 pF in parallel with the resonant circuit coil, which reduces the capacitance variation because of the small capacitance of the varactor diodes. Therefore, the tuning range is relatively small. Spurious modes could not be observed within this tuning range.

The value of the coupling capacitor is too low for a short wave signal at a 50Ω load. Hence, the output power is only 8.7 dBm at a supply voltage of 2.0 VDC. The oscillator operates well in the voltage region from 1.5 VDC to 2.5 VDC, but becomes unstable at higher voltage values. This frequency range seems to be the lower border of the test circuit. For lower frequencies, the topology of the oscillator circuit must be improved.

The 50 MHz oscillator

Two varactor diodes connected in parallel are used as the voltage- controlled capacitor for the 50 MHz oscillator. They are connected via a 56 pF series capacitor to the 470 nH resonant circuit coil. Both the 22 pF feedback capacitor and the 47 pF shunt capacitor add a constant capacitance of about 15 pF to the resonant circuit capacitor. The additional coil is bridged. The supply voltage can be varied from 1.5 VDC to 3.5 VDC without any electrical problems. At a voltage value of 2.0 VDC, the oscillator produces an output signal of 10.0 dBm. No spurious modes could be detected. This oscillator works without any problems.

The 145 MHz oscillator

A simple VCO was built for the frequency range from 144 MHz to 146 MHz. The resonant circuit coil has a value of 136 nH. Two parallel varactor diodes are connected via a 12 pF capacitor to the coil. The 10 pF shunt capacitor and the 4.7 pF feedback capacitor form an additional parallel capacitance of about 3.2 pF. For this frequency and above, the parasitic capacitances of the soldering pads and the input capacitance of the JFET will have have an influence on the signal frequency. The additional coil is bridged in this circuit as well. As before, the supply voltage can be varied from 1.5 VDC to 3.5 VDC. At a voltage value of 2.0 VDC, the oscillator produces an output signal of 10.3 dBm. No spurious modes could be detected. Although the oscillator of this test circuit is primarily intended to

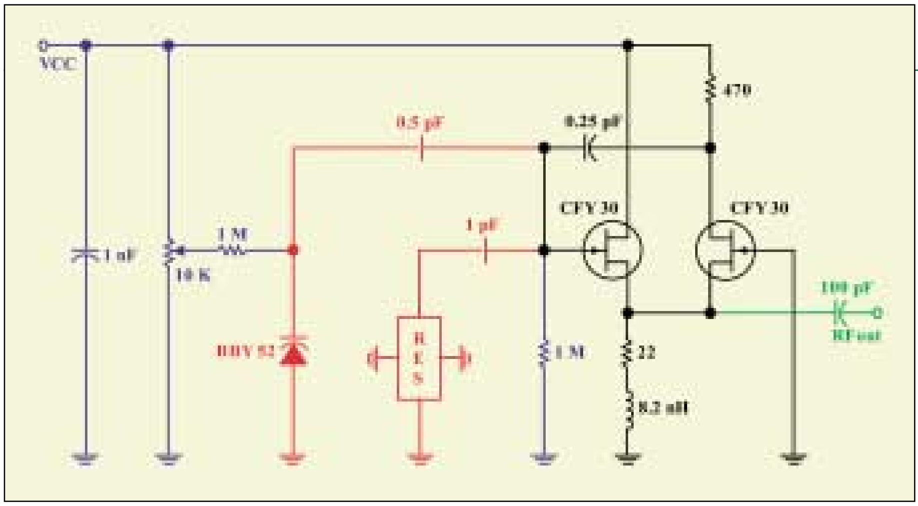

Figure 4. The microwave VCO circuit using a coaxial ceramic resonator.

serve as a VCO in a low-voltage, small-band PLL circuit, it can operate as a stand-alone emitter supplied by a 1.5 VDC button cell. Modulation via the tuning voltage is also possible.

The 230 MHz oscillator

For the sake of completion, a 230 MHz VCO was also built. A 68 nH resonant circuit coil is shunt by two series 2.2 pF feedback capacitors and 5.6 pF shunt capacitor. A varactor diode is connected to the resonant circuit coil via a 6.8 pF capacitor. Coil L_2 is bridged in this circuit. As before, the supply voltage can be varied from 1.5 VDC to 3.5 VDC. At a voltage of 2.0 VDC, the oscillator produces an output signal of 9.8 dBm. No spurious modes could be detected. This oscillator also works well, having only a slightly larger frequency drift due to thermal influence.

The 430 MHz oscillator

A number of VCOs were built for the frequency range of 400 MHz to 460 MHz. The best results are obtained with the element values given in Table 1. The resonant circuit coil has a value of 33 nH. The varactor diode is connected via a 3.3 pF capacitor to the resonant circuit coil. The 2.2 pF shunt capacitor and the 1.0 pF feedback capacitor form an additional parallel capacitance of about 0.7 pF. Coil L_2 is still not necessary at this frequency.

The supply voltage was varied from 0.7 VDC to 4.5 VDC. The oscillator starts generating an RF signal at a supply voltage of about 0.7 VDC. At 1.0 VDC, there is already an output signal of typically 0 dBm. At a voltage value of 2.0 VDC, the oscillator requires a supply current of 26.5 mA and produces an output signal of 10.7 dBm. To further explore the limits of the circuit under test, the supply voltage is boosted up to 4.5 VDC. At this voltage, the oscillator requires a supply current of 42 mA and the output signal exceeds 16 dBm. This oscillator's frequency can be varied between 408 MHz and 457 MHz.

Some thermal problems were observed at this high value of supply voltage. Both transistors were soldered on the printed circuit board without any heat sinks. Without such heat sinks, thermal heating caused a significant frequency drift and a reduction of output power. To avoid overheating and operate in the stable area circuit, a maximum supply voltage of 3.0 VDC is recommended.

This design precipitates some interfering spurious modes with supply voltages between 1.5 VDC to 2.8 VDC. Therefore, the shunt capacitor is required to reduce the amplitude of the spurious modes and should not be omitted.

The 870 MHz oscillator

The next VCO was built for the frequency range of 860 MHz to 880 MHz. In this design, the resonant circuit coil has a value of 10 nH. The varactor diode is connected via a 2.7 pF capacitor to the coil. A shunt capacitor is not required for this frequency. For the feedback capacitor, a 0.5 pF feedback (C_F) is used. Coil L_2's position is bridged and not used.

At the voltage level of 2.0 VDC, the oscillator produces an output signal of 10.1 dBm. No spurious modes could be detected. This oscillator also is stable, but a significant frequency drift due to thermal influence is noted.

The 920 MHz oscillator

As can be seen from Table 1, the only difference between the circuit element values of both the 870 MHz and the 920 MHz oscillator is the value of the capacitor connecting the varactor diode to the resonant circuit coil. A capacitance value of 1.8 pF is used instead of 2.7 pF. The supply voltage can be varied from 1.0 VDC to 3.0 VDC. At a voltage value of 2.0 VDC, the oscillator produces an output signal of 9.9 dBm. No spurious modes could be detected.

The 2.45 GHz oscillator

Some VCOs were built around a center frequency of about 2.45 GHz. The element values for the best results are given in Table 1. The resonant circuit coil consists of a series connection of two coils. L_1 has a value of 2.7 nH and L_2 has a value of 4.7 nH. Both coils form a single tapped coil in the resonant circuit. For the microwave oscillators, the high-frequency SMD inductors were used because of the increased Q. The varactor diode is connected via a 3.3 pF capacitor to the tapped resonant circuit coil. The 0.25 pF feedback capacitor is created by two series capacitors with a value of 0.5 pF each. The supply voltage can be varied from 1.0 VDC to 4.0 VDC. At a voltage of 2.5 VDC the oscillator has a tuning range of about 50 MHz and produces an output signal of 6.7 dBm. No spurious modes could be detected. As with previous models, a frequency drift exists due to thermal influence. Additionally, the phase noise at this frequency range does not allow small- band applications.

The 3.2 GHz oscillator

To explore the SMD limits of this type of VCO, an oscillator was built for the 3.2 GHz region on common FR4 - substrate. Some difficulties arose because only specific discrete element values were available for SMD elements. In this case, the parasitics could not be neglected. Even the SMD pads' parasitic capacitances to ground had to be taken into account. A tapped resonant coil was used consisting of two coils. Coil L_1 has a value of 1.35 nH and coil L_2 has a value of 2.7 nH. To obtain the 1.35 nH value, two 2.7 nH coils were connected in parallel. A 2.2 pF capacitor is connected in series to the varactor diode as well as a 0.25 pF feedback capacitor. The 0.25 pF feedback capacitor is built by serially connecting two 0.5 pF capacitors.

The supply voltage can be varied from 1.0 VDC to 4.0 VDC without any electrical problems. At a voltage value of 3.0 V, the oscillator produces an output signal of 6.4 dBm. No spurious

Freq.	C	L_1	L_2	L_S	C_F	C_D	V_{cc}	P_{out}
3.2 GHz	2.2 pF	1.35 nH	2.7 nH	8.2 nH	0.25 pF	n/a	3.0 VDC	6.4 dBm
2.45 GHz	3.3 pF	2.7 nH	4.7 nH	8.2 nH	0.25 pF	n/a	2.5 VDC	6.7 dbM
920 MHz	1.8 pF	10 nH	n/a	18 nH	0.5 pF	n/a	2.0 VDC	9.9 dBm
870 MHz	2.7 pF	10 nH	n/a	18 nH	0.5 pF	n/a	2.0 VDC	10.1 dBm
430 MHz	3.3 pF	33 nH	n/a	39 nH	1.0 pF	2.2 pF	2.0 VDC	10.7 dBm
230 MHz	6.8 pF	68 nH	n/a	68 nH	2.2 pF	5.6 pF	2.0 VDC	9.8 dBm
145 MHz	12 pF	136 nH	n/a	136 nH	4.7 pF	10 pF	2.0 VDC	10.3 dBm
50 MHz	56 pF	470 nH	n/a	470 nH	22 pF	47 pF	2.0 VDC	10.0 dBm
20 MHz	82 pF	940 nH	n/a	940 nH	56 pF	100 pF	2.0 VDC	8.7 dBm

Table 1. Typical element values for the specific frequency bands.

modes could be detected. This frequency range seems to be the upper limit of the test circuit. For higher frequencies, the topology of the oscillator circuit must be improved.

Improving phase noise and stability

The only frequency-determining circuit of the oscillator is the resonant circuit at the gate electrode of the first transistor (T_1). Due to the losses of SMD elements, and of the transistor itself (both rise with increasing frequency), the circuit quality is too small to ensure a low frequency drift at frequencies above 1.5 GHz. To improve the electrical characteristics at microwave frequencies, a high Q-factor coaxial ceramic resonator was used as the frequency-determining element. A slight modification to the oscillator circuit leads to good results. The modified circuit of a 2.45 GHz oscillator is shown in Figure 4. The coaxial ceramic resonator does not exceed the dimensions 3 mm x 3 mm x 6 mm and has an intrinsic resonant frequency of 2.9 GHz. It is coupled via a capacitor with a relative high value of 1 pF, to the gate of the first transistor. This capacitor is necessary to pretune the frequency range of the oscillator, but disables the proper biasing of the first transistor. Therefore, an additional 1 MΩ resistor has to be connected from this gate to ground.

A capacitively coupled varactor diode is used to tune the frequency of the generated signal. The value of the coupling capacitor is 0.5 pF. This value is too high. Other values were not available during the test. Thus, the varactor diode is not coupled straight to the coaxial ceramic resonator[5], but is coupled, in parallel, to the input capacitance of the first transistor. This ensures the intended tuning range and does not further impair the loaded Q of the coaxial ceramic resonator. The phase noise of the improved oscillator is small enough to allow frequency shift keying (FSK) with a 50 kHz frequency deviation. The measured output power of the 2.45 GHz oscillator is 2.8 dBm at a supply voltage of 2.0 V.

Conclusion

An easily designed oscillator principle has been employed in the design of direct frequency VCOs. The use of common SMD components is investigated for a number of frequency ranges. The oscillator is primarily intended to serve as a VCO in low-voltage, small-band PLL circuits. In this application, the exact frequency will be tuned by the PLL circuit. Therefore, a raw estimate of the resonant frequency can be determined by a single formula. These experiments suggest that a consistent oscillator design principle can simplify a number of RF design problems. **RF**

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