Design of Low Noise, Highly Stable GaAs Dielectric Resonator Oscillators

Low noise, highly stable GaAs FET oscillators using a dielectric resonator in the feedback loop are presented. The device line method of predicting the optimum terminating impedance reduces the design iteration to a minimum. Because of its low cost and small size, this class of oscillator is ideal for satellite, radar or microwave communications.

Microwave oscillators form an important part of all microwave systems such as those used in radar, communication links, navigation and electronic warfare. With the rapid advancement of technology, there has been an increasing need for better performing oscillators. The emphasis has been on low noise, small size, low cost, high efficiency, high temperature stability and reliability. The transistor dielectric resonator oscillator (DRO) presents an interesting solution as a quality oscillator for fixed-frequency or narrowband tunable oscillators.

"It is possible to build a low phase noise oscillator using a low cost MESFET for the active device instead of the traditional expensive bipolar transistors at X-band."

Many types of oscillator circuits have been developed through previous work. Some of the factors that enter into the choice of a circuit for a particular application include the operating frequency, output amplitude, frequency stability, amplitude stability, the purity of the output waveform and the likelihood that unwanted modes of oscillation will occur. Various designs compromise on one performance specification in order to gain on the others.

Because the microwave transistors can be used for both amplifiers and oscillators, oscillation conditions can be specified.[3] Stern's stability factor K can be calculated using

$$K = \frac{\left(1 + |\Delta|^2 - |S_{11}|^2 - |S_{22}|^2\right)}{2|S_{12}||S_{21}|} \qquad (1)$$

where

$$\Delta = S_{11}S_{22} - S_{21}S_{12}$$

Since the transistor S-parameters change with frequency, K and Δ vary with frequency. For amplifiers, the transistor is unconditionally stable if $K > 1$ and $|\Delta| < 1$. A simultaneous match can be made at both ports, resulting in

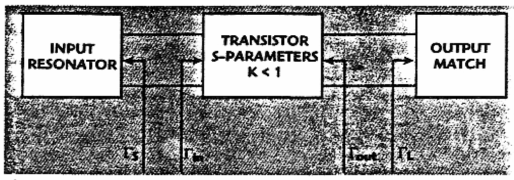
$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L} = \frac{1}{\Gamma_s} \qquad (2)$$

$$\Gamma_{out} = S_{22} + \frac{S_{12}S_{21}\Gamma_s}{1 - S_{11}\Gamma_s} = \frac{1}{\Gamma_L} \qquad (3$$

Equations 1 through 3 provide some insight into how to design oscillators from small-signal S-parameters. If an amplifier can be de-

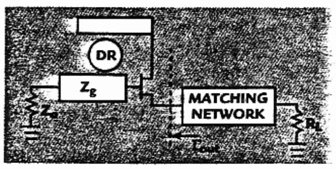
[Continued on page 106]

NICK ELMI,
Hughes Communication Products
MATTHEW RADMANESH
California State University, Northridge



▲ *Fig. 1 An oscillator block diagram.*

▼ *Fig. 2 A parallel feedback configuration.*



signed where K < 1 and either Γ_S or Γ_L is in an unstable region, an oscillator design will result. The necessary conditions for oscillation are[5]

$$K < 1 \quad (4)$$

and

$$\Gamma_{in}\,\Gamma_S \geq 1 \quad \text{and} \quad \Gamma_{out}\,\Gamma_L \geq 1 \quad (5)$$

$$\angle\Gamma_{in} + \angle\Gamma_S = 2\pi n \quad n = 0,1,2 \quad (6)$$

If K > 1 for the device selected, condition 4 can be achieved by changing the two-port configuration or adding feedback. ***Figure 1*** shows a block diagram of an oscillator.

CIRCUIT CONFIGURATIONS

There are two types of DROs in a MIC oscillator. A stabilized DRO uses the dielectric resonator (DR) in the output plane of the circuit to stabilize a free-running oscillator. This approach, although low noise, has several disadvantages including a tendency toward mode jumping, a frequency hysteresis problem, higher insertion loss due to the resonator coupling to the output circuit and increased output power variations. A stable DRO uses the DR as the feedback and frequency-determining element. The unit provides greater efficiency, simpler construction, and more resistance to mode jumping and hysteresis effects than the stabilized DRO.[10–13] Thus, the stable DRO has significant advantages.

Several different circuit configurations exist, including series feedback, parallel feedback, reflection-type feedback, dual resonator and push-push. Each of these configurations are utilized to meet a specific application. However, the series and the parallel feedback configurations are most widely used in general-purpose applications. An advantage of the series feedback design is the relative ease of coupling to a single line compared to the parallel circuit's requirement for coupling to two lines. In addition, the two coupling coefficients in the parallel case are not independent, thus increasing the difficulty of alignment. However, with the parallel circuit the use of a high gain amplifier can allow significant decoupling of the resonator from the microstrip resulting in a higher loaded Q factor with associated reduced phase noise. Because of the need for low phase noise and high stability, the parallel feedback, shown in ***Figure 2***, is performed.

DEVICE CONSIDERATIONS

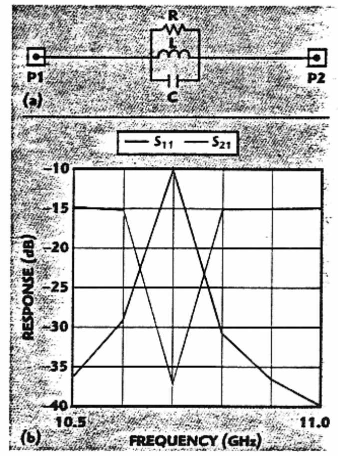
Active Device Selection

Transistor DROs can be realized using either silicon bipolar or GaAs FET devices. The maximum oscillation frequency of a silicon bipolar junction transistor (BJT) oscillator is lower than that of the GaAs FET. Reasonable output power levels have been obtained up to 40 GHz for the GaAs FET and 20 GHz for the bipolar devices (with an amplified stage). However, the silicon BJT configuration offers lower phase noise close to the carrier and faster frequency-settling characteristics compared to GaAs FET devices. Also, BJTs have approximately 10 dB better flicker noise than GaAs FETs, but the BJT oscillators at X-band and higher frequencies offer considerably lower output power and much higher cost than GaAs FETs.

The NE76000 series BJTs (in an 084 package style) are a good example for this application in terms of noise, DC supply requirement and cost. The device model was obtained from NEC's FET library, which is modeled in Curtice-cubic fit.

DR Selection

Due to good integrability in MIC circuits, DRs can be used directly as the frequency-determining element for realizing a stable microwave frequency source. A DR acts as a microwave resonator due to the boundary established at the interface between the air and the high dielectric device. This boundary confines 80 to 90 percent of the energy within the device. Approximately 20 percent of the energy radiates from the device, making it easy to couple RF power to this device and provide the resonance of the oscillator circuit. DRs are made of low loss, temperature-stable, high permittivity and high Q ceramic materials in regular geometric forms and resonate in various modes at frequencies determined by the dimensions and shielding conditions. For this design, a DR with a Q of 5000, ε'_r of 36 and a small temperature coefficient variation was selected.



▲ *Fig. 3 The (a) schematic and (b) simulated response of a DR coupled to a microstrip line.*

DRO ANALYSIS

Mathematical Modeling

DRs are used in different configurations for various applications. It is necessary to understand the DR coupling to a microstrip so that optimum Q_L and, consequently, minimum phase noise are obtained. The most commonly used DR configuration is discussed, that is, $TE_{01\delta}$-mode coupling with a microstrip line, as shown in ***Figure 3***. The resonator is placed on the upper surface of a substrate. The lateral distance between a DR and the microstrip conductor is the parameter, which determines the coupling between the resonator and the

[Continued on page 108]

transmission line. The metallic shielding, which is required to minimize the radiation loss (hence to increase Q), also affects the resonant frequency of the $TE_{01\delta}$ mode.

Assuming 12 dB as an optimum transmission coefficient, the coupling coefficient β is calculated to be equal to 3 from which the element values are calculated (L = 0.89 ph, C = 247 pf and R = 300 Ω) and simulated on Libra software. The simulation indicated resonance at 10.75 GHz, which corresponded with the calculations. Based on the simulation, $S_{11} = -10$ dB and $S_{21} = -36$ dB for the selected DR coupled to a 50 Ω transmission line.

DR coupling was measured using a Trans-Tech D85 series DR coupled to a 50 Ω transmission line on a test board. The S_{21} and S_{11} of the coupling DR to transmission line were measured at three different distances from the transmission line. The height was kept constant at 200 mils above the resonator.

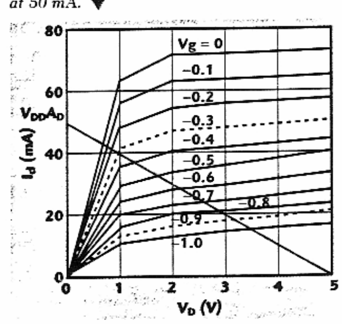
In order to find an optimum operating point so that the circuit yields the highest output power under the given DC supply condition of +5 V and 65 mA (max), the I-V curves were simulated using the model NE76000 Curtice-cubic device chip along with the 084 package parasitic model. The simulation was run using the Libra software for both common-source and common-drain configurations.[7] ***Figure 4*** shows the DC I-V curve for the common-source circuit with the load line drawn for $I_{ds} = 50$ mA.

In order to design the oscillator circuit, the active portion of the circuit was analyzed using the device line method, which starts with characterization of the active device by its device line measurement. The characterization is applicable to inherent one-port devices, such as high frequency diodes, and can be extended to potentially unstable two-port devices such as bipolar and FETs by reducing them to negative-resistance one-port configurations by proper termination.[7]

When connected as two-port devices, transistors must be terminated externally to drive a negative-resistance one-port device for oscillator applications. The reduction from two ports to one port can be performed optimally in the sense of maximizing the small-signal reflection coefficient of the device by performing a mapping of impedance planes between terminal pairs of the device.

Since the impedance to be optimized is the amplitude-independent small-signal device impedance, it is valid to analyze the device as a linear

Fig. 4 The DC I-V characteristics for the model NE76084 with the load line at 50 mA. ▼



[Continued on page 110]

p3.

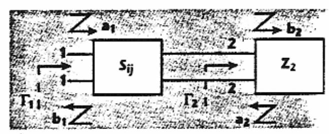
two-port network. Such a network is characterized by a small-signal scattering matrix S terminated in an impedance Z_2 with an associated reflection coefficient Γ, as shown in ***Figure 5***.

A set of small-signal S-parameters for the selected model NE76084 device at 10 GHz was obtained from the simulation at the calculated bias point. The S-parameters are used to calculate the terminating impedance that reduces the device to an optimum negative-resistance one-port device. The derived one-port device is characterized then by its device line to describe its performance as an oscillator. That is, the device was terminated in the predicted optimum output impedance and tested in a 50 Ω system. Input power is increased while monitoring the drive level and reflection coefficient. When the maximum power added is reached, the load impedance is recorded and added to the circuit. This way, the device impedance as a function of incident power at levels above small signal (large signal) results in a contour on an impedance plane of power out vs. load impedance, as shown in ***Figure 6***. The power added maximized at 30.3 mW. The load impedance then was recorded and matched to 50 Ω.

TEST RESULTS

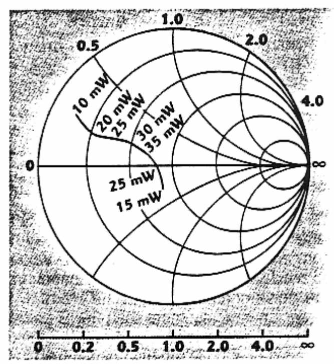
The final circuit was constructed on a 1" × 0.5", 20-mil-thick polytetraflouroethylene board. The output impedance transformer was modified to a tapered line to extend the tuning bandwidth. The oscillator circuit's metal enclosure includes the tuning screw on top. The final circuit is shown in ***Figure 7***.

Test results show that the oscillator met and, in some cases, exceeded the design goals for this project. The

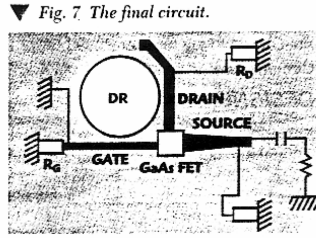


▲ *Fig. 5 A generalized two-port reduced to a one-port by terminating Γ_2.*

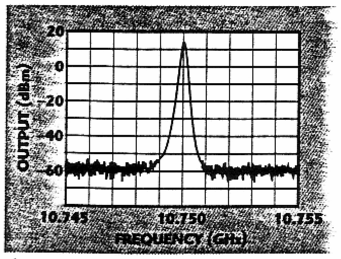
Fig. 6 The measured device line of a common-drain NE76084 at 10.75 GHz. ▼



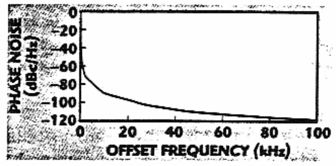
▼ *Fig. 7 The final circuit.*



[Continued on page 11–



▲ *Fig. 8 The measured output at the center frequency.*



▲ *Fig. 9 The measured phase noise.*

output is shown in **Figure 8**. The phase noise was measured at several discrete offsets from 10.75 GHz and plotted, as shown in **Figure 9**.

With a 10 V supply regulated down to 5 V and 55 mA current, the frequency pushing was measured at 1 MHz/V. The second harmonic and spurious outputs were measured below 40 dBc. The DRO was tested for stability over the specified temperature range of –30° to +60°C. Stability was measured at 0.02 percent.

CONCLUSION

A low power, low phase noise and highly stable DRO was designed and constructed for an X-band downconversion application. This compact DRO exhibited 30 mW output power at 55 mA. Frequency stability was 0.02 percent from –30° to +60°C. The observed phase noise was –90 dBc at 10 kHz offset from the carrier frequency. It is possible to build a low phase noise oscillator using a low cost MESFET for the active device instead of the traditional expensive bipolar transistors at X-band.

ACKNOWLEDGMENT

The Libra simulation software is a product of HP EEsof™ ■

References

1. H. Krauss and C. Bostian, *Solid-state Radio Engineering*, John Wiley, 1980, p. 128.
2. D. Kajfez and P. Guillon, *Dielectric Resonators*, Artech House, Norwood, MA, 1986, Ch. 7–10.
3. *Microwave Oscillator Design*, Avantek AN-A008 application note.
4. *Specifying a DRO*, Avantek AN-M004 application note.
5. R. Soars, *GaAs MESFET Circuit Design*, Artech House, Norwood, MA, 1988, Ch. 7.
6. Trans-Tech Inc., "Dielectric Resonator and Related Products," *Designer's Catalog*, 1993.
7. *EEsof User Manual*, Version 4.0, 1993.
8. W. Wagner, "Oscillator Design by Device Line Measurement," *Microwave Journal*, February 1979.
9. A.P.S. Khanna, "Q Measurement of Microstrip-coupled Dielectric Resonators," *Microwaves & RF*, January 1984.
10. S.W. Chen, L.C. Chang and J. Chin, Unified Design of Dielectric Resonator Oscillators for Telecom Systems, IEEE MTT-S, 1986.
11. R. Jones and V. Estrik, "Low Phase Noise Dielectric Resonator Oscillators, IEEE MTT-S, 1990.
12. O. Ishihara et al., "A Highly Stabilized GaAs FET Oscillator Using a DR Feedback Circuit in 9 to 14 GHz," IEEE MTT-28, No. 8, August 1980.
13. *Introduction to DROs*, Avantek AN-A00? application note.
14. Alex Hall, "Impedance Matching by Tapered or Stepped Transmission Lines," *Microwave Journal*, March 1966.