Frequency Stability of *L*-Band, Two-Port Dielectric Resonator Oscillators

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Abstract —**Dielectric resonator oscillators operating at 1.5 GHz and 2.0 GHz, based on a two-port resonator design incorporated into a basic feedback loop oscillator configuration, were evaluated and show state-of-the-art, close-to-carrier phase noise performance. Typically, at 1-kHz carrier offset frequency the single-sideband phase noise levels were −130 dBc/Hz and −120 dBc/Hz for the 1.5-GHz and 2.0-GHz oscillators, respectively. Vibration sensitivity was also investigated and the resonators show fractional frequency changes per g in the range of 10^{-7} to 10^{-9} for the 1.5-GHz and 2.0-GHz designs. Finally, measurements were performed to characterize both the static and dynamic temperature sensitivities of the 2.0-GHz dielectric resonator oscillator design. The static temperature coefficient was found to be approximately −1.40 ppm/°C, while the dynamic temperature coefficient was nominally −3000 ppm/°C/s, at 27.5°C.**

I. INTRODUCTION

THE PERFORMANCE requirements of next-generation radar and communication systems can only be satisfied through the development of stable, very low phase noise microwave sources. For example, improved oscillator phase noise levels will permit next-generation radars to detect reduced radar cross-section targets and discern slower moving targets. The *L*-band dielectric resonator oscillator (DRO), while considerably larger (and heavier) than several alternative choices such as surface acoustic wave or surface skimming bulk wave oscillators [1], has been shown to be an extremely low noise microwave frequency source [2]. While most previously reported DRO's have utilized a one-port resonator design, we have chosen to implement a two-port transmission mode approach, based upon a simple feedback loop oscillator configuration [3], [4]. All of the oscillator's components, e.g., dielectric resonator (DR), amplifier, and directional coupler, are designed to operate in a 50-Ω characteristic impedance environment, as illustrated in Fig. 1. This approach permits simple, precise measurements of loaded and unloaded Q's, insertion loss, and group delay, as well as the convenient evaluation of potential spurious oscillator modes and considerable ease in setting up the proper loop conditions for oscillation. Also, it is possible to individually characterize the components which comprise the oscillator loop, and thus predict their respective contributions to the oscillator's close-to-carrier phase noise level.

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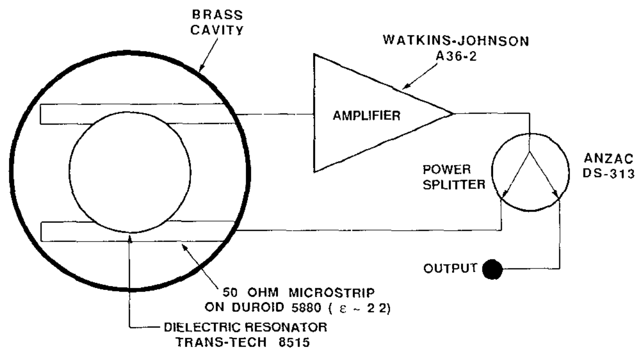

Fig. 1 Block diagram of a two-port dielectric resonator based feedback oscillator.

We report herein on 1.5-GHz and 2.0-GHz dielectric resonator oscillators constructed using commercially available components, as shown in Fig. 1. Except for the resonators, the oscillators at each frequency were assembled using identical electronic components. Silicon bipolar transistor amplifiers were used, rather than GaAs FET amplifiers, since they have been shown to have lower flicker noise levels, typically 10–30 dB better for comparable *L*-band (1–2 GHz) amplifier designs [5]. Three critical aspects of an oscillator's frequency stability were characterized for the DRO designs, namely: 1) single-sideband phase noise, 2) vibration sensitivity, and 3) temperature sensitivity, including both static and dynamic effects.

II. RESONATOR CONSTRUCTION

The performance of *L*-band dielectric resonator oscillators operating at 1.5 GHz and 2.0 GHz is described. Each 1.5-GHz resonator was constructed using low-loss cordierite ceramic supports whose outer diameters were equal to the inner diameter of the metal cavity. For one resonator design mounting was accomplished using a nylon nut and bolt, while in another design a low-loss epoxy was used. These resonators had nominal loaded and unloaded Q's of 9500 and 15000, respectively, while the insertion loss was approximately 9 dB. The inner diameter of the metal cavity was equal to twice the diameter of the dielectric resonator, while the dielectric resonator's diameter and height were 1.500 and 0.600 in, respectively. The 2.0-GHz resonators were constructed using fused quartz support pedestals whose diameters were equal to the dielectric resonator's diameter, and firmly bolted with nylon screws.

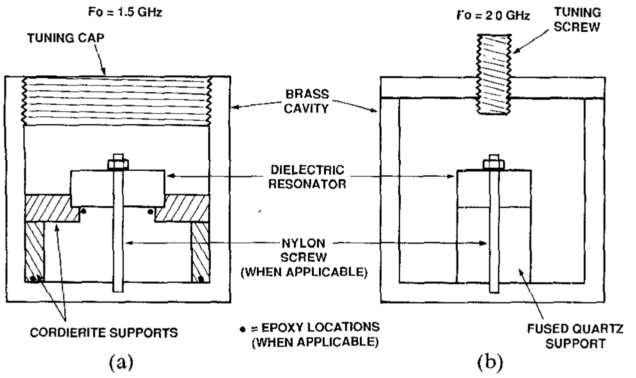

Fig. 2. Basic dielectric resonator mechanical configurations. (a) 1.5-GHz design. (b) 2.0-GHz design.

These resonators had nominal loaded and unloaded Q's of 8100 and 16000, respectively, while the insertion loss was approximately 6 dB. The inner diameter of the metal cavity was equal to 1.6 times the dielectric resonator's diameter, while the dielectric resonator's diameter and height were 1.125 and 0.450 in, respectively. All resonators were made of $ZrSnTiO_3$ ($\epsilon_r = 37$) with a 0 ppm/°C (± 0.5 ppm/°C) temperature coefficient (Trans-Tech, Inc., type D-8515), and were designed for $TE_{01\delta}$ mode operation. Fig. 2 illustrates the two styles of cavity design and supporting structures.

III. Characterization of Phase Noise

The dielectric resonators were assembled and individually tested to determine their phase noise levels. This was done using a Hewlett-Packard 11740A Microwave Phase Noise Measurement System [6]. This type of measurement is commonly referred to as an "open-loop" phase noise test. It is possible, for the feedback loop oscillator configuration, to individually test the components which comprise the oscillator feedback loop. In principle, one can account for the phase noise contribution of each device, and these data can be used to estimate the phase noise of the assembled oscillator. This technique was used to eliminate noisy amplifiers and problematic resonator construction. A careful examination of open-loop phase noise measurement data on oscillator components is necessary since their noise levels may be very close to the system noise floor. A complete characterization of the system noise floor is also essential in order to properly interpret these data.

Once assembled, the DRO's were allowed to stabilize at room temperature, and phase noise measurements were repeated at random intervals over periods of one to two weeks. Oscillator noise measurements were performed on individual oscillators using a Hewlett-Packard 5390A Frequency Stability Analyzer [7] and on oscillator pairs using the Hewlett-Packard 11740A system [8]. These measurements demonstrated that the noise was flicker of frequency and at 1-kHz offset, the single-sideband phase noise levels were typically -130 dBc/Hz and -120 dBc/Hz for the 1.5-GHz and 2.0-GHz oscillators, respectively. The observed close-to-carrier phase noise levels are comparable to those reported by Alley and Wang [2] and represent the current state of the art for an L-band DRO. We note that the 1.0-GHz, one-port oscillator design of Alley and Wang operated with $> +20$ dBm incident on the resonator, whereas the oscillators described herein ran with only $+7$ dBm of incident RF power. The fact that the close-to-carrier phase noise performance is comparable in both cases is consistent with the hypothesis that the source of close-to-carrier phase noise in DRO's (and many other oscillators) is phase fluctuations rather than voltage fluctuations. Of course, the low loop power in our oscillators did not result in a particularly low noise floor, and in fact -165 dBc/Hz was measured.

To compare oscillator phase noise measured within the resonator's bandwidth with the component phase noise levels measured using the "open-loop" technique, one must use the relation [9], [10]

$$\mathscr{L}_c(f) = \mathscr{L}_o(f) - 20\log(f) + 20\log[F_0/(2Q_L)] \quad (1)$$

where

$\mathscr{L}_c(f)$ = closed-loop single-sideband phase noise in dBc/Hz,
$\mathscr{L}_o(f)$ = open-loop single-sideband phase noise in dBc/Hz,
f = carrier offset or noise frequency in Hz,
F_0 = carrier frequency in Hz,
Q_L = loaded Q of the DR in the oscillator loop.

Typical open-loop phase noise measurements on wideband silicon bipolar transistor amplifiers below 1 GHz give nominal flicker noise levels of $\mathscr{L}_o(f = 100 \text{ Hz}) = -155$ dBc/Hz. This is the case provided that the amplifier is not driven more than 3 dB into gain compression. When the measurements are performed at higher carrier frequencies, the system noise floor can exceed this level, precluding a direct measurement of the amplifier's noise. This problem was indeed encountered during our measurements at L-band frequencies. A detailed analysis of phase noise processes indicates that when the loop amplifier is the source of phase noise in a feedback-loop-type oscillator, the close-to-carrier phase noise of the oscillator will vary inversely with the loaded Q of the resonator [9]. For two 2.0-GHz dielectric resonators, the loaded Q was varied in order to give up to a 5-dB change in the third term on the right side of (1). When the oscillators were measured, the phase noise at 100 Hz offset from the carrier varied by 6 ± 1 dB. Finally, when the loaded Q's of the two 2.0-GHz dielectric resonators were set to the same value, comparable phase noise levels were observed. A calculation of the "open-loop" phase noise level from the oscillator phase noise gives values comparable to the amplifier phase noise level discussed earlier. This is a strong indication that the loop amplifier, rather than the dielectric resonator, is the dominant source of phase noise in the DRO's that we have evaluated to date.

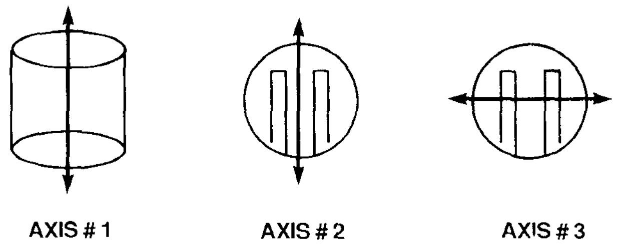

Fig. 3. Definition of the three mutually orthogonal axes used for our vibration sensitivity measurements.

IV. Characterization of Vibration Sensitivity

In many applications where it is desirable to employ low-noise frequency sources, the oscillator's environment may be subjected to relatively high vibration levels. In such situations the quiescent phase noise characteristic may no longer be relevant since vibration can significantly degrade an oscillator's phase noise spectrum. Therefore, as has been done for bulk acoustic wave (BAW) [11] and surface acoustic wave (SAW) [12] based low-noise sources, it becomes necessary to characterize the vibration sensitivity of the frequency stabilizing element, in this case the dielectric resonator.

To be consistent with the standard definitions developed to characterize the vibration sensitivity of quartz-based frequency sources, the fractional frequency change per peak g of acceleration during vibration, γ, is defined by

$$\gamma = (\Delta F_{\mathrm{MAX}}/F_0)/g \tag{2}$$

where F_0 is the "at rest" frequency of the oscillator and ΔF_{MAX} is the maximum frequency change. For a random vibration spectrum, its contribution to the single-sideband phase noise of the oscillator is given by

$$\mathscr{L}_c(f_v) = P_{ssb}/P_c\big]_{\mathrm{BW}=1\,\mathrm{Hz}} = 10\log\left[(\gamma F_0/f_v)^2(G/2)\right] \tag{3}$$

with the assumption that the levels of the vibration-induced sidebands are small compared to the carrier power P_c. The quantity G represents the vibration power spectral density in g^2/Hz at the vibration frequency f_v.

In the laboratory, vibration sensitivity is most easily evaluated with a sinusoidal vibration source. For sinusoidal vibration levels which produce small discrete sidebands relative to the carrier, the quantity γ can be found using the equation

$$P_{ssb}/P_c = 10\log\left[(\gamma F_0 g)/(2f_v)\right]^2 \tag{4}$$

where g is the peak sinusoidal acceleration in g's. Since an oscillator may experience vibration in any direction (or directions) in a real system application, it is necessary to characterize the vibration sensitivity of the oscillator along three mutually orthogonal axes. For the dielectric resonator, we selected the axes as defined in Fig. 3. Axis #1 is along the cylinder axis, while the two axes in the plane of the microstrip substrate are parallel (#2) and perpendicular (#3) to the microstrip lines.

A complete set of measurements for the magnitude of γ versus vibration frequency, using the axes just defined, was performed on a 2.0-GHz dielectric resonator. Fig. 4 shows the actual data for γ_2, the most sensitive axis observed. The nominal vibration sensitivities measured on the 2.0-GHz dielectric resonator were $\gamma_1 \sim 6\times10^{-9}/g$, $\gamma_2 \sim 4\times10^{-8}/g$, and $\gamma_3 \sim 1\times10^{-8}/g$. Experiments were performed on the resonator alone, with the oscillator electronics cabled away from the vibration equipment. Separate measurements confirmed that the cables do not contribute to the measured sensitivities using this technique. Fluctuations in the measured data above 1 kHz can be attributed to mechanical resonances within the resonator and the experimental mounting structure. Fig. 5 shows measurements of γ_1 versus vibration frequency for two different 1.5-GHz dielectric resonators, one mounted with a nylon bolt, the other with epoxy. The observed levels for γ_1, nominally $1\times10^{-7}/g$ at 1.5 GHz and $6\times10^{-9}/g$ at 2.0 GHz, are significantly higher than the $1\times10^{-9}/g$ measured for SAW resonators and the $2\times10^{-10}/g$ measured for BAW resonators. Based on the data in Fig. 5, the epoxy mount does not appear to offer any advantage over the nylon bolt in terms of vibration sensitivity. Since all resonators employed pedestal supports whose diameters were equal to or greater than the dielectric resonator's diameter, the difference in vibration sensitivity between the two dielectric resonator designs might be attributed to

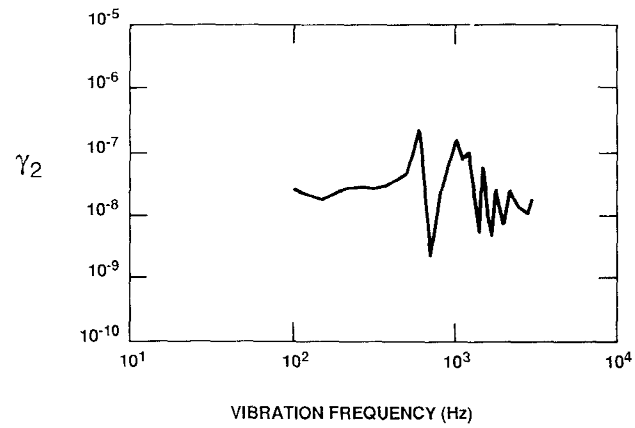

Fig. 4 Measured axis #2 vibration sensitivity for a 2.0-GHz DRO.

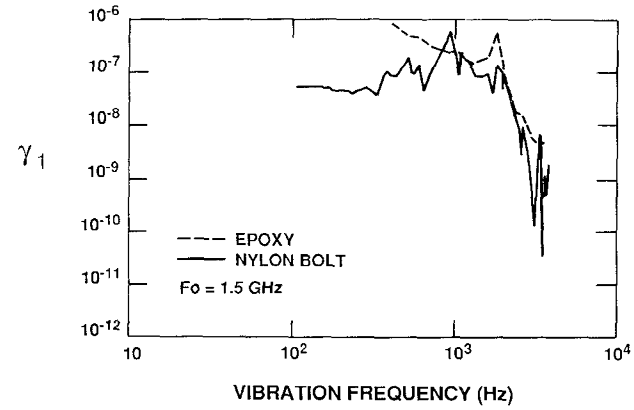

Fig. 5. Measured vibration sensitivities along axis #1 (γ_1) for two 1.5-GHz DRO's using different mounting techniques: epoxy (----) and nylon screws (——).

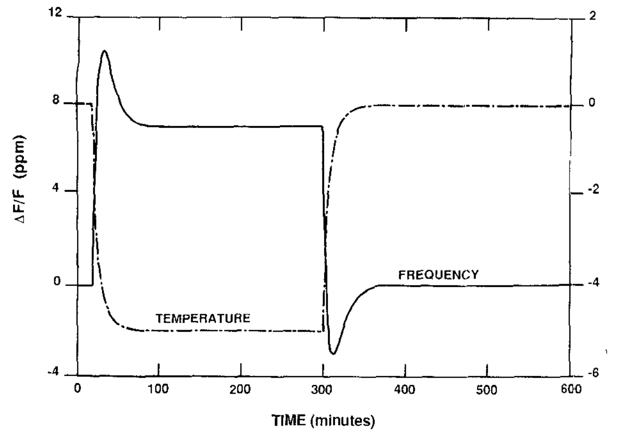

Fig. 6. Fractional frequency change versus time for a 2.0-GHz DRO in response to a 5°C temperature cycle in the range of 25 to 30°C.

their significant size difference. However, it is important to note the dielectric resonator's comparatively high vibration sensitivity and to observe that this sensitivity could further degrade if the entire oscillator were subjected to vibration.

During construction, no attempt was made to minimize the dielectric resonator's vibration sensitivity, and it is entirely possible that improvements can be made without adversely affecting other oscillator performance parameters. However, we have established a baseline for the vibration sensitivity of L-band dielectric resonators by employing a standard characterization technique. A knowledge of the quantity γ allows one to use (3), along with a known vibration power spectral density, to estimate the degradation of an oscillator's phase noise due to vibration.

V. Characterization of Temperature Sensitivity

The accurate characterization of a DRO's temperature sensitivity is very important for applications requiring the design of temperature-stable oscillators. Fig. 6 shows the fractional frequency change for a 2.0-GHz DRO in response to a 5°C temperature cycle, in the temperature range of 25 to 30°C. As might be expected, the large mass of an L-band dielectric resonator results in a very long thermal time constant, typically one hour for several devices which were tested.

The fractional frequency change of the DRO in response to a temperature step can be separated into two parts as expressed by

$$\Delta F(T,t)/F_0 = \alpha(T-T_0) + \kappa(dT/dt) \tag{5}$$

where F_0 and T_0 are the frequency and temperature at $t=0$, respectively. The first term on the right side of (5) is referred to as the "static" portion of the temperature dependence. This component depends only on the absolute temperature change and is independent of time. For small temperature changes, this contribution can be approximated by a linear term, and as the magnitude of the temperature change increases, second- and third-order effects may become more significant. The coefficient α is referred to as the static temperature coefficient. The second term on the right side of (5) represents the "dynamic" part of the temperature dependence and it depends on the rate of change of temperature with time. The coefficient κ is called the dynamic temperature coefficient. The large fractional frequency transients shown in Fig. 6 represent the dynamic responses, whereas the static responses are given by the steady-state fractional frequency changes after the oscillator has reached equilibrium. When constructing temperature-stable DRO's, it is the static part of the temperature dependence which is generally of interest. Evaluating the static temperature coefficient simply consists of measuring the steady-state fractional frequency change and dividing by the temperature change. Fig. 6 gives an average value of -1.4 ppm/°C for the static temperature coefficient at 27.5°C. Evaluating the dynamic temperature coefficient is more difficult since the dynamic portion of the response can include contributions from static effects. The figure gives a nominal value of -3000 ppm/°C/s for the dynamic temperature coefficient κ, at 27.5°C.

This model assumes that the maximum dynamic fractional frequency change occurs at the time corresponding to the maximum time rate of change of temperature. The DRO responses in Fig. 6 do not follow the model precisely, but this may be a consequence of the fact that the temperature sensor was mounted on the exterior of the metal cavity, thus responding too quickly to temperature changes. The large magnitude of the dynamic temperature coefficient is of great interest since it is some 100–1000 times larger than those measured for quartz-based acoustic resonators. This indicates a comparatively high sensitivity of the dielectric resonator oscillator's frequency to temperature fluctuations, an effect which can contribute to an oscillator's phase noise level. There are two potential explanations for the rather large dynamic thermal effect which was observed. First is the realization that the brass cavity responds rapidly to temperature changes through expansion or contraction and thus reaches thermal equilibrium sooner than the dielectric resonator. Second, the electronic circuitry will also respond to temperature changes very rapidly; thus the temperature-dependent phase shift through the electronic circuitry reaches thermal equilibrium sooner than the dielectric resonator. It is thus important that the time interval between successive temperature steps exceed the thermal time constant of the DRO for correct static temperature effects to be observed. If not, the measured data may be dominated by dynamic responses, and if used to determine the static temperature coefficients could even yield results of the wrong sign.

VI. Summary

L-band oscillators, when designed with two-port dielectric resonators and using the basic feedback loop configuration, have been shown to provide state-of-the-art, close-to-carrier phase noise performance. The two-port resonator design allows the use of convenient oscillator characterization techniques, as well as the capability to separate and individually test the oscillator components. When carefully designed, the dominant source of oscillator phase noise appears to be the oscillator electronics and not the dielectric resonator.

The vibration sensitivities for several L-band dielectric resonators were characterized. For a 2.0-GHz device the vibration sensitivities were measured along three mutually orthogonal axes, resulting in a typical sensitivity magnitude of $4\times10^{-8}/g$. The measurements were made in such a fashion that these results can be used to estimate the contribution to an oscillator's phase noise spectrum due to an arbitrary vibration environment. Static and dynamic thermal effects were also observed on a 2.0-GHz DRO which was constructed with a 0 ppm/°C (±0.5 ppm/°C) temperature coefficient dielectric puck material. The dynamic temperature coefficient was found to be nominally -3000 ppm/°C/s, while the static temperature coefficient was approximately -1.4 ppm/°C, both measured at an average temperature of 27.5°C. The vibration and dynamic temperature sensitivity measurements yielded results which are considerably larger than those typically observed for quartz-based acoustic resonators.

Improved dielectric resonator cavity designs (both mechanical and thermal) will very likely lead to reduced vibration and temperature sensitivities. This may result in the use of DRO's in certain applications which are currently being addressed by quartz-based acoustic resonator oscillators of modest performance. In such cases improved far-from-carrier phase noise levels would also be realized.

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Mark J. Loboda (M'87) was born in Chicago, IL, on January 15, 1962. He received the B.S. degree in 1983 and the M.S. degree with distinction in 1985, both in physics, from DePaul University. His thesis involved the design and implementation of an automated precise magnetic field control system and a nuclear magnetic resonance study of adsorbates on supported heterogeneous metal catalysts.

In August 1985, Mr. Loboda joined the professional staff of the Raytheon Research Division, working with the Stable Sources Group. His work involves the design and characterization of ultra-low-noise frequency sources based upon surface acoustic wave resonators and dielectric resonators. During the course of his work, he has developed UHF SAW oscillators and L-band DRO's with state-of-the-art phase noise levels and has also demonstrated a technique which reduces the close-to-carrier phase noise in SAW resonators. His primary interest at this time is investigating the physics of close-to-carrier noise processes in SAW and DRO based oscillators.

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Thomas E. Parker (M'79–SM'86) was born in Natrona Heights, PA, on September 17, 1945. He received the B.S. degree in physics from Allegheny College in 1967. He received the M.S. degree in 1969 and the Ph.D. degree in 1973, both in physics, from Purdue University. His doctoral thesis was a Brillouin scattering study of acoustoelectric domains in GaAs.

In August 1973, Dr. Parker joined the staff of the Raytheon Research Division, working with the Generalized Filters and Microwave Acoustics (now Stable Sources) Group. Initially, his work was mainly related to the development of improved temperature-stable surface wave materials. He was responsible for the development of the fused silica–lithium tantalate structure, which not only has higher piezoelectric coupling, but also has only one tenth the temperature sensitivity of ST-cut quartz. More recently, Dr. Parker has been responsible for the surface wave controlled oscillator program at the Research Division. His primary interest has been frequency stability, with emphasis on $1/f$ noise, temperature stability, and aging.

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Dr. Montress is a member of Eta Kappa Nu, Sigma Xi, and Tau Beta Pi. His IEEE activities include currently serving as an officer of the Boston Chapter of UFFCS and as a member of the Technical Program Committee for the yearly Ultrasonics Symposium.