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

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ABSTRACT

Dielectric resonator oscillators operating at 1.5 and 2.0 GHz, based on a two-port resonator design incorporated into a basic feedback 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, respectively.

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 DROs 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, directional coupler, etc., are designed to operate in a 50Ω characteristic impedance environment, as illustrated in Fig. 1. This approach permits simple, precise measurements of loaded and unloaded Q, insertion loss, and group delay, as well as the convenient evaluation of potential spurious oscillator modes and ease in setting up the proper loop oscillation conditions. Also, the capability exists to individually evaluate the components which comprise the oscillator loop, and measure their respective contributions to the oscillator's close-to-carrier phase noise level.

We report herein on 1.5 GHz and 2.0 GHz dielectric resonator oscillators constructed using commercially available components. Silicon bipolar transistor amplifiers were used, rather than GaAs FET amplifiers, since they have been

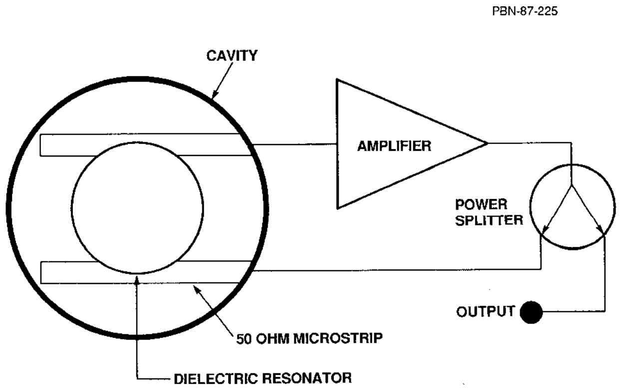

Fig. 1. Block diagram of a two-port dielectric resonator based feedback oscillator.

shown to have lower flicker noise levels, typically 10-30 dB better for comparable L-Band (1-2 GHz) amplifier designs [5]. Two critical aspects of an oscillator's frequency stability were characterized for the DRO designs, namely: 1) single side band phase noise, and 2) vibration sensitivity.

II. RESONATOR CONSTRUCTION

We report on the performance of L-Band dielectric resonator oscillators operating at 1.5 and 2.0 GHz. The 1.5 GHz resonators were constructed using low-loss cordierite ceramic supports whose outer diameters were equivalent to the metal cavity inner diameters. Mounting was accomplished in one resonator using a nylon nut and bolt and in another using a low-loss epoxy. These resonators had nominal loaded and unloaded Q's of 9500 and 15 000 respectively, while the insertion loss was nominally 9 dB. The inner diameter of the metal cavity was designed to be twice the diameter of the dielectric resonator. The 2.0 GHz resonators were constructed using fused quartz pedestals whose diameters were equal to the dielectric resonator's diameter, and bolted with nylon screws. These resonators had nominal loaded and unloaded Q's of 8100 and 16 000 respectively, while the insertion loss was nominally 6 dB. The inner diameter of the metal cavity was equal to 1.6 times the dielectric resonator diameter. All resonators were made of $ZrSnTiO_3$ (ε_r=37) and were designed for TE_{10} mode operation. Figure 2 illustrates the two styles of cavity design and supporting structures.

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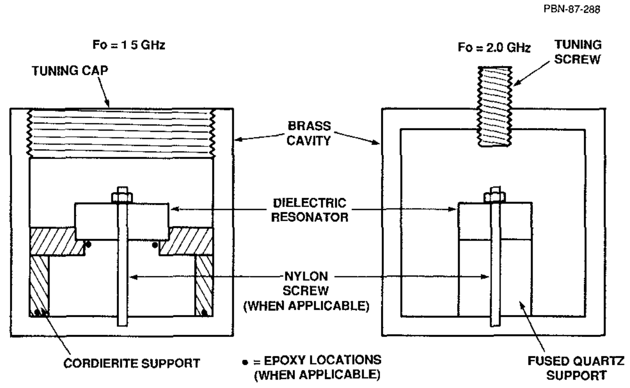

Fig. 2. Basic dielectric resonator mechanical configurations.

III. PHASE NOISE

The 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 in the configuration shown in Fig. 3. We shall refer to this type of measurement as an "open-loop" phase noise test. It is possible, for the two-port feedback oscillator configuration, to individually test each component comprising the oscillator feedback loop. In principal one can account for the phase noise contribution from each device, and the 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. Careful examination of 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 necessary in order to properly interpret this data.

Once assembled, the DROs were allowed to stabilize at room temperature, and phase noise measurements were repeated at random intervals over periods of one to two weeks. Two different systems were employed to measure the oscillator phase noise. Figure 4 is a plot of oscillator phase noise data measured on two 1.5 GHz DROs using the Hewlett-Packard 11740A system. One oscillator was of fixed frequency and the other was constructed using a commercial voltage controlled phase shifter in the loop to provide a phase locking capability. The composite data clearly indicates that the close-to-carrier phase noise was flicker frequency noise (i.e., -30 dB/decade of offset frequency for single sideband phase noise). Noise measurements were also performed on individual oscillators using a Hewlett-Packard 5390A Frequency Stability Analyzer [6]. These measurements also confirmed that the noise was flicker 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 and 2.0 GHz oscillators, respectively. It was found that the voltage controlled phase shifter introduced excess flicker frequency noise into the voltage tuned oscillator, leading to the higher level shown in Fig. 4. Over periods of one to four weeks the close-to-carrier phase noise for

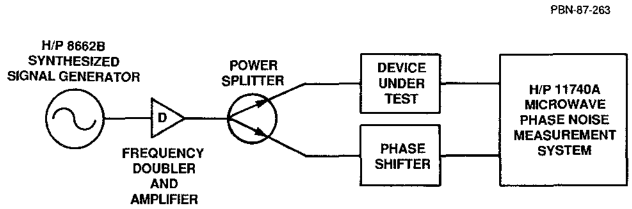

Fig. 3. Block diagram of the "open-loop" phase noise measurement set-up.

several oscillators did not vary significantly. The long-term stability over a four week period was within ±3 ppm for a non-ovenized, non-temperature compensated 2.0 GHz oscillator. 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. 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 DROs (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, as seen in Fig. 4.

To compare the oscillator phase noise measurements with the component phase noise measured using the "open-loop" technique, one must use the relation

$$\mathcal{L}_c(f)=\mathcal{L}_o(f)-20*\log(f)+20*\log(F_o/2Q_L) \qquad (1)$$

where

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

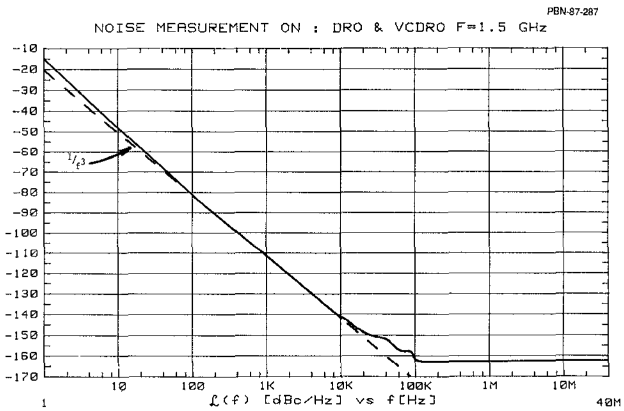

Fig. 4. Measured phase noise spectrum for one fixed and one voltage controlled DRO. Data is the sum of the individual oscillator's phase noise spectra.

Typical open-loop phase noise measurements on wide band silicon bipolar transistor amplifiers below 1 GHz give nominal noise levels of $\mathcal{L}_0(f=100 \text{ Hz})=-155$ 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, preventing direct measurement of the amplifier noise. This problem was encountered during our measurements at L-Band frequencies. An analysis of phase noise processes indicates that when the loop amplifier is the source of phase noise in a feedback type oscillator, the close-to-carrier phase noise of the oscillator will vary inversely with the loaded Q of the resonator [7]. For two 2.0 GHz dielectric resonators the loaded Q was varied to give up to a 5 dB change in the third term on the right side of equation (1). When the oscillators were measured, the phase noise at 100 Hz offset varied by 6.0 ± 1.0 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 and not the dielectric resonator is the dominant source of phase noise in the DROs that we have evaluated to date.

IV. VIBRATION SENSITIVITY

In many applications where it is desirable to employ low-noise frequency sources, the oscillator 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) [8] and surface acoustic wave (SAW) [9] based low-noise sources, it becomes necessary to characterize the vibration sensitivity of the frequency source, in this case the DRO.

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

$$\gamma = \frac{\Delta F_{MAX}/F_o}{g} \qquad (2)$$

where F_o 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 phase noise of the oscillator is given by

$$\mathcal{L}_c(f_v) = \frac{P_{ssb}}{P_c}\bigg|_{BW=1Hz} = 10*\log\left[\left(\frac{\gamma F_o}{f_v}\right)^2 \frac{G}{2}\right] \qquad (3)$$

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.

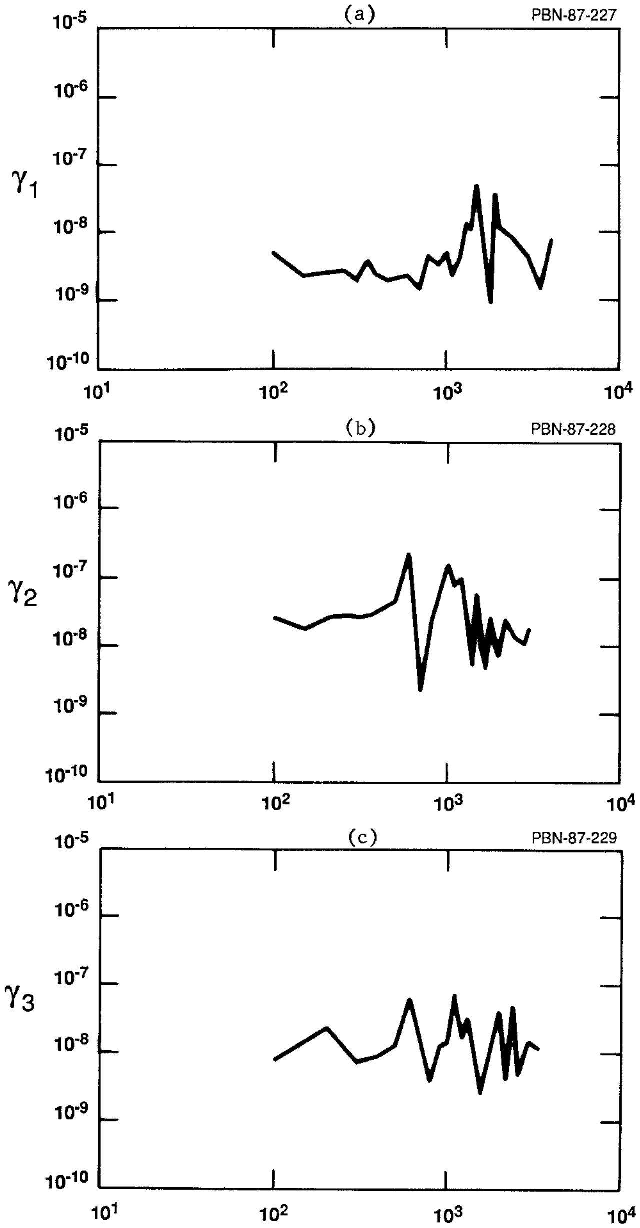

Fig. 5. Measured vibration sensitivities for a 2.0 GHz DRO. a) Axis #1 (γ_1). b) Axis #2 (γ_2). c) Axis #3 (γ_3).

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

$$\frac{P_{ssb}}{P_c} = 10*\log\left[\frac{\gamma F_o g}{2 f_v}\right]^2 \qquad (4)$$

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 chose the axes such that axis #1 was along the cylinder axis and the other two axes were in the plane of the microstrip substrate, parallel (#2) and perpendicular (#3) to the microstrip lines.

A complete measurement of the magnitude of γ versus vibration frequency for the axes just defined is shown in Fig. 5 for a 2.0 GHz dielectric resonator. Experiments were performed on the resonator alone, with the oscillator electronics cabled away from the vibration equipment. Figure 6 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 $1x10^{-7}/g$ at 1.5 GHz and $6x10^{-9}/g$ at 2.0 GHz are significantly higher than the $1x10^{-9}/g$ measured for SAW resonators and $2x10^{-10}/g$ measured for BAW resonators. Based on the data in Fig. 6, the epoxy mount does not appear to provide 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 accounted for by their significant size difference. However, it is important to note the dielectric resonator's high vibration sensitivity, and that this sensitivity could degrade further if the entire oscillator were under vibration.

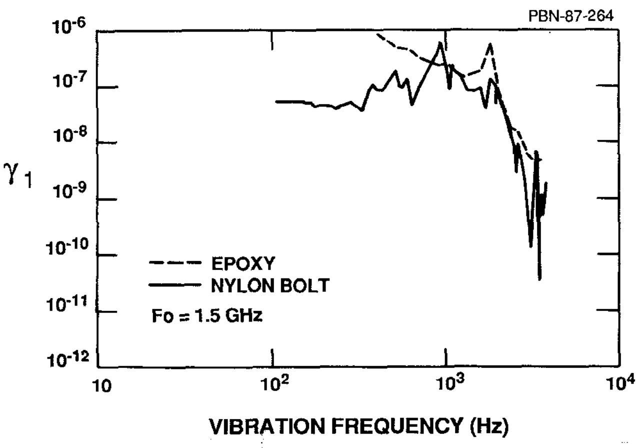

Fig. 6. Measured vibration sensitivities γ_1 for two 1.5 GHz DROs using different mounting techniques.

During construction, no attempt was made to minimize the vibration sensitivity, and it is 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 using a standard technique to characterize this parameter. Knowledge of the quantity γ allows one to use equation (3), along with a known vibration power spectral density, to estimate the degradation of an oscillator's phase noise due to vibration.

V. 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 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. 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.

Improved dielectric resonator cavity designs will very likely reduce the vibration sensitivity. This may lead to the use of DROs 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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