# ULTRA-LOW-NOISE  CAVITY-STABILIZED  MICROWAVE  REFERENCE  OSCILLATOR  USING  AN  AIR-DIELECTRIC  RESONATOR[1]

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**Abstract**

*Ultra-low-noise microwave oscillators are often required to serve as reference signals in precision phase modulation (PM) noise measurement systems and in a host of other applications. We have significantly improved the spectral purity of NIST's traditional cavity-stabilized microwave oscillator design, which uses a conventional air-dielectric cavity resonator as a frequency discriminator. We developed and tested an accurate model of the expected PM noise that indicates, among other things, that a conventional air-dielectric resonator of moderate Q will exhibit less discriminator noise than more esoteric and expensive dielectric resonators tuned to a high-order, high-Q mode and driven at the dielectric's optimum power. Additionally, we increase the discriminator's intrinsic signal-to-noise ratio by use of a high-power carrier signal to interrogate an optimally coupled cavity, while the high level of the carrier is suppressed before the phase detector. We report exceptionally low PM noise levels from a microwave oscillator operating at 10 GHz.*

## I.  INTRODUCTION

The predominant frequency-determining element in an oscillator is its resonator. The resonator acts as a frequency discriminator. At microwave frequencies, those oscillators with the highest spectral purity will often take advantage of a high-Q resonator, which, together with other components, comprise a phase-noise detector of excess phase noise in the oscillator-sustaining part of the oscillator (a positive-feedback amplifier or oscillator) [1,2]. A methodology called the "carrier-suppression technique" is used to increase detection of excess phase noise [3-5]. The detected phase noise is effectively lowered in the oscillator's output signal, but the noise level invariably increases as the carrier-offset frequency f decreases. That increased noise level is usually at a rate of $1/f^3$ or steeper, often resulting in a random-noise level that is very high close to the carrier frequency. This type of noise is referred to as flicker FM (flicker frequency modulation) noise, whose origin is flicker PM (flicker phase modulation) noise in the amplifier and other component-related noise within the resonator bandwidth (BW) [6].

A common noise-suppression scheme translates the detected excess phase noise to a voltage applied as either a feedback (using a phase-lock loop, PLL) or feedforward (using a phase modulator) error-correction signal to the oscillating output frequency via a voltage-controlled phase-shifter (VCP) or electronic frequency control (EFC). For example, a sapphire resonator operating in a whispering gallery evanescent mode achieves a high Q-factor (on the order of $10^7$) [7,8]. With appropriate temperature stabilization, an oscillator can operate with high frequency stability as well as low phase noise [9-12].

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This paper is about obtaining low noise by use of a common air or vacuum dielectric cavity [13]. We demonstrate that a conventional air-dielectric resonator of moderate Q can achieve phase detector sensitivity vs. discriminator noise comparable to solid dielectric higher Q resonators operating at high-order modes. Of all the possible types of resonators that can be used as a phase detector, conventional air-dielectric high-Q cavities are most ideally suited for handling large power levels, thereby increasing the detector sensitivity without penalty.

## II. CARRIER SUPPRESSION OSCILLATOR DESIGN

To increase the signal-to-noise ratio (SNR) of the phase detector, while reducing the flicker-noise contributed by other discriminator components, we want to drive the detector with as much power as possible and at the same time null or suppress the correspondingly large carrier signal that presents itself at any amplifier, isolator, circulator, or other component with additive flicker noise that is proportional to signal power. Carrier suppression of greater than 80 dB is obtainable. Figures 1 and 2 are schematic diagrams of the approach. Figure 2, for example, consists of a voltage-tunable Gunn oscillator, YIG oscillator or DRO (dielectric resonator oscillator), whose output is amplified and applied to a coupling port of the discriminator cavity through a circulator. The reflected signal out of the cavity comes out of port C of the circulator and is already highly suppressed, since the coupling is very nearly critical. The highly suppressed signal is then amplified by the low-noise amplifier before being applied to one port of a double-balanced mixer (DBM). As a result of the high level of carrier suppression, the amplifier output exhibits a reduced flicker-noise contribution. The DBM acts as a phase detector, whose other port has a portion of the input signal, adjusted to be in phase quadrature with the reflected signal. By having the amplifier before the mixer, the effective noise contribution from the mixer is suppressed by the amplifier gain and in practice becomes relatively insignificant. The phase detector output is the error signal that tracks the frequency fluctuations of the oscillator relative to the cavity. This output is a voltage that is proportional to phase fluctuations, regarded as an error, between the oscillating signal that drives the discriminator and the discriminator's more stable transfer or filter-response curve. This error voltage is applied to the voltage-control tuning input of the oscillator through the servo amplifier to stabilize its frequency.
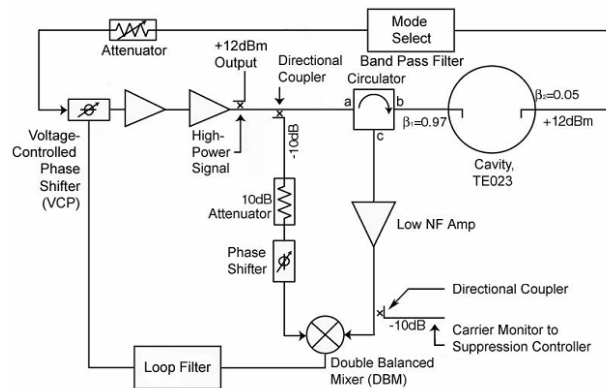


Figure 1. Oscillator scheme using a cavity mode to satisfy the oscillation conditions in an amplified feedback loop. Excess PM noise is detected by the double-balanced mixer. The VCP corrects excess oscillator loop noise. The carrier signal is suppressed at the output of the circulator (C).
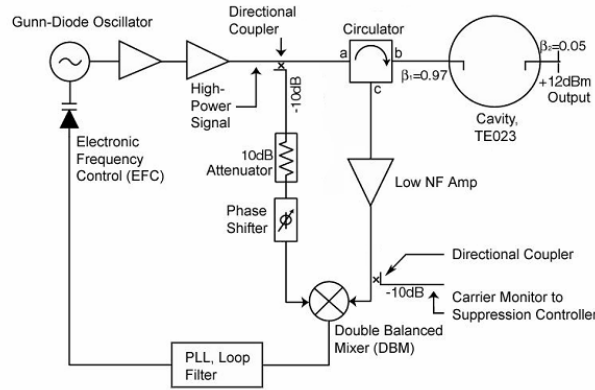
Figure 2.  Oscillator scheme in which a VCO (in this example, a Gunn oscillator) is phase-locked to a cavity resonance.  Again, carrier-suppression technique is used in the phase detector.

## III.  MECHANICAL  OSCILLATOR  DESIGN

### A. CAVITY RESONATOR

The air cavity is the open bore of a silver-plated aluminum right-circular cylinder with an inner diameter and an inner height of about 6-7 cm, varying in size depending on centering of a specific resonance mode at 10 GHz.  The cavity is designed with six outer flat surfaces for mounting heaters and other additional components.  Of the two endcaps, one has two semi-rigid coaxial cables with coupling loops that slide into the open bore and provide rf coupling to the air cavity.

### B. TUNING AND TEMPERATURE CONTROL

Owing to the aluminum cavity's moderate temperature coefficient, coarse frequency tuning of the cavity is obtained by setting the cavity temperature (operating temperature is about 50 deg. C for the mode that is used).  Temperature, hence frequency, is set by means of five electronic thermostatic controllers with one thermistor sensor placed under each of (1) three power transistors and attached resistive loads on the cavity flats, and (2) power transistors and resistive loads on each of two cavity endcaps, thus providing temperature control to each end separately.  An insulated housing around the cavity provides passive temperature isolation from the environment.

### C. OSCILLATOR

The noise of the free-running voltage-controlled oscillator (VCO) is significantly reduced by the cavity stabilization. This reduction can be relaxed by prudent selection of a very-low-noise, low-cost VCO. We have chosen to use a commercial DRO because of its inherent low close-in noise compared to commercial YIG or Gunn VCOs.

## IV. PHASE  NOISE  RESULTS

Figure 3 shows two measurements of phase noise at 10 GHz made with two different cavities fabricated with candidate modes, TE023 and TE025 with unloaded Qs of about 60,000 and 80,000, respectively.  Results using the two different modes (TE023 and TE025) are comparable.  The cavity signal power for these measurements is +27 dBm.
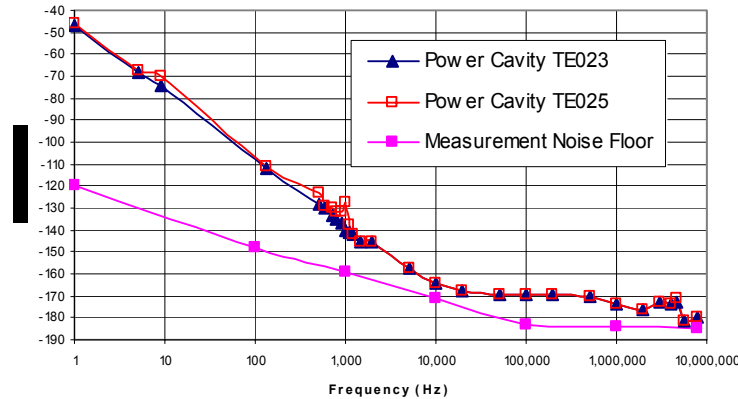
Figure 3.  Phase noise of NIST 10 GHz oscillator.  Future work will investigate the use of higher power into the cavity and improved temperature control.

For these measurements, a dual-PLL cross-correlation scheme is used in which the signal of the air cavity oscillator splits to two nearly identical phase-locked loops whose phase deviations are simultaneously analyzed by a cross-spectrum analyzer **[14-16]**.  The reference signal for each PLL is from a 10 GHz commercial sapphire-loaded cavity oscillator (SLCO) of low phase noise.   The correlated spectrum, representing the phase noise of the device under test, is extracted, while uncorrelated noise from components in each bridge averages down.

## V.  CONCLUSION  AND  FUTURE  WORK

We have built a 10 GHz oscillator that shows that a conventional air-dielectric resonator of moderate Q, optimally coupled and driven at 0.5 W, will exhibit close-to-carrier discriminator noise comparable to more esoteric and expensive dielectric resonators tuned to a high-order, high-Q mode.  This is because we can increase the discriminator's intrinsic signal-to-noise ratio by an increase in carrier-signal power that interrogates the air cavity, since the high level of the carrier is suppressed by 80 dB or more before the oscillator's phase detector.  We plan to use a microwave amplifier of higher power than that of the current 0.5 W amplifier, and expect lower noise levels at higher offset frequencies as a result.

Future work will be directed at finding ways to reduce cavity frequency fluctuations due to temperature, the predominant environmental influence.   The temperature controller has sufficient temperature stability; however, gradients remain a concern to controlling and/or removing close-to-carrier resonator frequency fluctuations and drift.   A new temperature controller for the aluminum cavity design is expected to lower the PM noise levels at an offset frequency range of 1 – 10 Hz. While we have not been phase-noise-limited by fluctuating microwave power (that can translate to cavity temperature fluctuations), we plan to investigate this effect to see at what level it becomes a concern.

We also plan to fabricate an Invar cavity that has a significantly lower temperature coefficient than aluminum. A ceramic cavity is planned for fabrication for those environments that require reduced sensitivity to vibration and acceleration.

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