Common-Arm Counter Propagating Phase Bridge for Vibration Sensitivity Measurement

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***Abstract*—Current methods for measuring the vibration sensitivity of microwave devices are limited primarily by choice of cables connecting a stationary platform to a vibrating actuator. We experimentally compare the current ("conventional") method with a new ("modified") common-arm counter propagating (CACP) technique for evaluation of two-port devices. We demonstrate that a CACP method reduces the vibrational noise floor of an optimized measurement system at 10 GHz by up to 25 dB. Common-mode disturbances from the vibration of cables and circulators contained in the measurement loop are rejected to first order. The CACP method enables accurate measurement of devices with low vibration sensitivity. The sensitivity measurement of such devices is normally limited by a conventional measurement system's noise floor. Our system is based on similar work at optical frequencies by Nelson et al. [2]**

I. Introduction

An increasing number of fields—navigation, communication, radar, and various military applications, to name just a few—require devices at microwave frequencies with both low phase noise and low vibration sensitivity [1]. As the quality of these devices improves it is imperative that measurement techniques keep pace. Current methods for measuring the vibration sensitivity of such devices involve a meticulous and time-consuming process, where the user must consider differing cable types, cable slack/tension, mounting of the device under test (DUT) with respect to mechanical resonances, acoustic noise and external vibrations present in the test area, airflow, VSWR-induced phase fluctuations between connector interfaces, and ground loops resulting from magnetic and electric fields generated by the vibration actuator [1]. Even after a measurement system has been optimized, the noise floor must be repeatedly evaluated to assess the measurement validity, as a slight displacement of cables (such as that of replacing the DUT) can drastically shift the floor.

In this paper we experimentally demonstrate a significantly lower-maintenance system for measuring the vibration sensitivity of filters, amplifiers, or any other two-port device. This system contains two counter-propagating signals, each carrying common-mode disturbances from the vibration of cables and other measurement system components (Fig. 1). These disturbances are rejected to first order in the final, double-balanced mixer. Our method is based on a similar innovative technique previously employed at optical frequency by Nelson et al. [2]

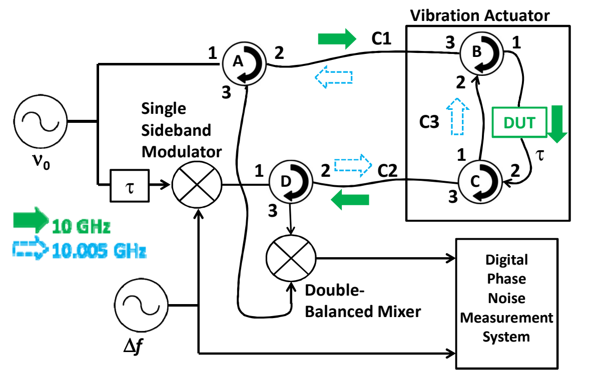

Figure 1. Common-arm counter propagating phase bridge measurement system. Solid green arrows represent the forward path, while blue dashed arrows follow the reference path. ν_0 = 10 GHz, Δf = 5 MHz. τ is the phase delay introduced by the DUT.

In a common-arm counter propagating (CACP) system a 10GHz signal is split. What we will define as the "forward" path propagates clockwise with reference to Fig. 1 and includes the DUT. The reverse "reference" path is frequency shifted to avoid the likelihood of standing waves. A single-sideband modulator upconverts the reference signal to 10.005 GHz before sending it counterclockwise through the same cables and components as the forward path, while excluding the DUT.

II. Measurement Setup

In order to demonstrate the advantages of the CACP technique, we designed a measurement system that easily switches between it and the conventional method for measuring vibration sensitivity (Fig. 1). Conventionally, a reference signal (ν_0) is split and one half of the signal travels through the 2-port DUT mounted on the actuator and then out to a mixer, while the other half of the reference signal experiences a delay and 90° phase shift before entering the mixer. The vibration sensitivity of the DUT is calculated from an analog residual phase measurement of the power spectral density (PSD) of phase fluctuations on an FFT analyzer [1]. In the modified CACP setup the "DUT" path corresponds to a similar conventional measurement system. Because we use a digital phase noise measurement system [3] instead of analog, there is no need for phase adjustment to ensure quadrature conditions at the mixer output. Cables C1 and C2 are common to both paths, and as stated in the previous section any vibration in either will cancel to first order in the phase noise measurement.

To select between the measurement setups (conventional or CACP) without disconnecting cables and thus introducing inconsistencies we insert two single pole, double throw (SPDT) 50 Ω - terminating coax latching relays after circulator A and after the single-sideband (SSB) modulator in Fig. 1. Further repeatability in the measurement system is achieved by fixing a magnetically-shielded enclosure to the actuator to contain circulators B and C (Fig. 2). Because independent vibration on the cables to and from the DUT can cause problems and uncertainty (in a conventional measurement system), cables C1 and C2 are symmetrically aligned and supported with Supreem foam and malleable poster putty at point-contact locations. C1 and C2 are fed through a foam-lined metal support structure positioned before the actuator to stabilize and dampen excess cable vibrations.

III. Acceleration sensitivity Γ_ψ

The phase change of a non-oscillatory component when subjected to vibration $\vec{a}$ is given by

$$\psi(t) = \vec{\Gamma}_\psi \cdot \vec{a}\,, \qquad (1)$$

where $\vec{\Gamma}_\Psi$ is the acceleration sensitivity vector of phase (rad/g). Taking the direction of the applied acceleration vector to be parallel to $\vec{\Gamma}_\Psi$, we write the single-sideband phase noise L(f) as

$$L(f_v) = 20\log\left[\Gamma_\psi \sqrt{\frac{S_a(f_v)}{2}}\right]. \qquad (2)$$

where $S_a(f)$ is the power spectral density of root-mean-square acceleration fluctuations. The acceleration sensitivity can be expressed in terms of phase fluctuations as

$$\Gamma_\psi(f_v) = \sqrt{\frac{2}{S_a(f_v)}}\,10^{\left(L(f_v)/20\right)} = \sqrt{\frac{1}{S_a(f_v)}}\,10^{\left(S_\psi(f_v)/20\right)}\,. \qquad (3)$$

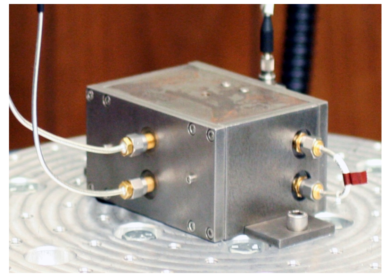

Figure 2. Cold-rolled iron enclosure for magnetically shielding circulators B and C from actuator fields. Configured for noise floor measurement.

IV. Measurement Results

A. Noise Floor

One of the most significant difficulties with a conventional vibration sensitivity measurement system is obtaining a repeatable noise floor. Selecting C1 and C2 cable type to minimize vibration sensitivity is essential, as the noise floor under vibration will vary depending on cable type, orientation, and affixation. (Fig. 3). Noise floors of our final setup are shown in Fig. 4. In this optimized configuration we achieve an improvement of up to 25 dB between the conventional and modified measurement system noise floors under vibration. Measurements of the noise floors were made by removing the DUT and connecting ports 1 and 2 of circulators B and C, respectively, with a short semi-rigid SMA cable, visible in Fig. 2. However, some measurement system resonances remain.

The phase modulation depth caused by vibration-induced delay fluctuations in the coax cables is proportional to the carrier frequency; therefore the counter propagating arms have slightly differing noise modulation depths. It follows that the phase noise cancellation is limited in proportion to the square of the single sideband frequency shift, Δf. The maximum amount of canceled phase noise due to the cable fluctuations in the CACP versus a standard measurement bridge is given by

$$\frac{\Delta f^2}{f_0^2}. \qquad (4)$$

At our chosen SSB frequency shift of 5 MHz and carrier frequency of 10 GHz, the maximum amount of cancelation is 66 dB and therefore does not appear to dominate our noise floor. Other remaining contributors to the noise floor are the circulators, any non-common arm cables, and the double-balanced mixers chosen for their low flicker phase noise and used in both the phase noise measurement system and the single-sideband modulator.

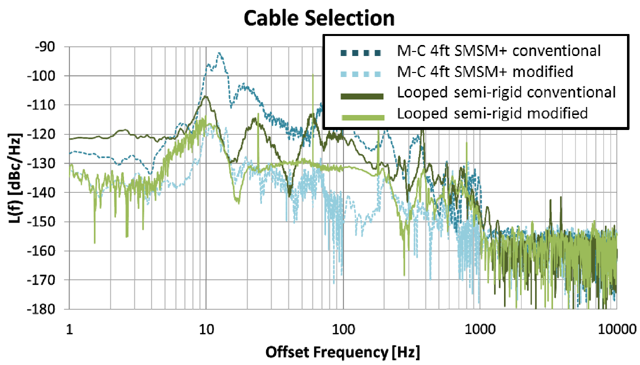

Figure 3. Measurement system noise floors under vibration, at an initial stage of the system design. **Blue dotted (M-C):** 4 ft long flexible, rugged, insulated, triple-shielded SMA male/male cable. **Green (Looped):** 2 ft long semi-rigid, 0.141 in, tin-plated copper, SMA male/male cables. Vibration profile: 0.1 mg^2/Hz random for frequency range 10 Hz-1000 Hz.

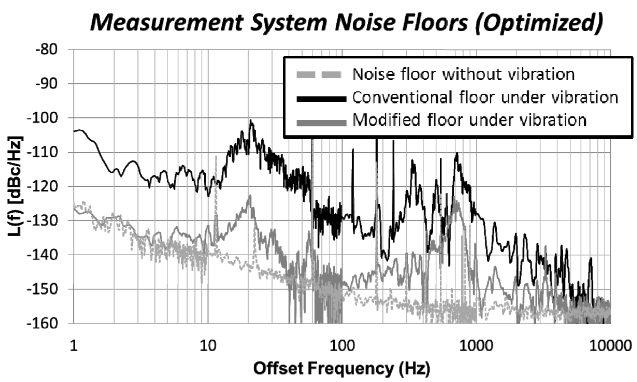

Figure 4. Optimization of cables, circulators, and other measurement system factors resulted in a noise floor improvement of up to 25 dB between conventional and modified (CACP) systems under vibration. Vibration profile: 1 mg^2/Hz random for frequency range 10 Hz -1000 Hz. Average vibration sensitivity of CACP floor for L(f) is $\Gamma_\psi = 4.46$ µrad/g.

B. Measurements of 2-port devices

1) Circulators

One must also consider the choice of circulator when assembling a CACP system. As a ferrite device the circulator is sensitive to magnetic fields from the actuator, but may also be vibration sensitive. The phase sensitivity under vibration of several circulators available in our lab is given in Fig. 5. For these measurements the circulators are terminated with 50 Ω at port #3 and placed in the DUT position of the measurement system. It should be noted that the system was not optimized for this measurement, as the goal was only to assess the relative performance of the circulators under vibration. Ultimately the UTE Microwave circulators were chosen for their repeatable performance throughout multiple measurement system modifications.[1]

2) Band-pass Filters

Band-pass filters, especially cavity filters and those with high quality factor (Q), may be especially susceptible to spectral degradation under vibration [2,4]. We studied three band-pass filters, each with different Q, and found that (for our very limited test group) vibration sensitivity Γ_ψ increases with Q [Fig. 6, Table 1].

3) Phase shifter

Limitations of a conventional vibration sensitivity measurement are apparent as the final DUT, a mechanical micrometer-trombone phase shifter, is at the noise floor and cannot be accurately measured. After switching to the CACP

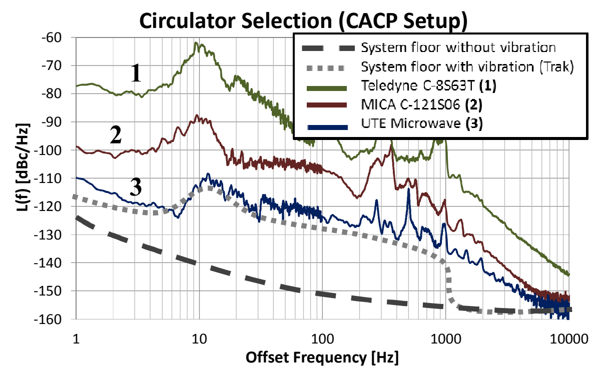

Figure 5. Early measurements of vibration and magnetic sensitivity of several circulator models for a non-optimized CACP system. Vibration profile: 1 mg^2/Hz random for frequency range 10 Hz -1000 Hz.

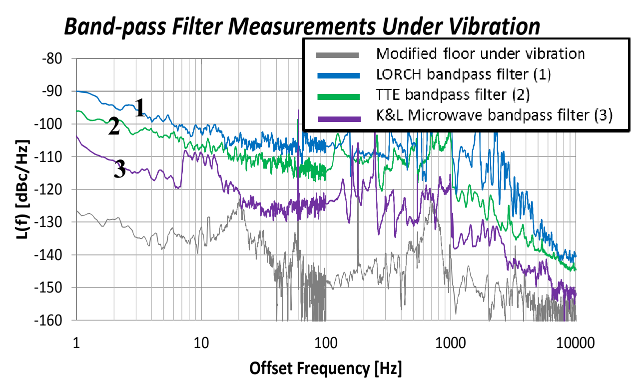

Figure 6. Measurements for three band-pass filters under vibration. Vibration profile: 1 mg^2/Hz random for frequency range 10 Hz -1000 Hz.

TABLE I.

	Band-pass Filters Under vibration		
	LORCH	***TTE***	***K&L***
3 dB BW (f_0 = 10 GHz)	11 MHz	200 MHz	550 MHz
Γ_ψ (avg. L(f)) [rad/g]	2.64×10^{-4}	1.32×10^{-4}	2.92×10^{-5}

Table 1. 3 dB bandwidths and Γ_ψ values for three band-pass filters. Γ_ψ calculated by averaging L(f) over the range of vibration (10 – 1000 Hz). Corresponds with Figure 6.

[1] This report summarizes the vibration sensitivity for various components by product name for completeness. No endorsements are implied.

system the phase shifter's actual phase noise for the given vibration profile is revealed (Fig. 7). Vibration sensitivity values are calculated by taking the average L(f) for each measurement over frequency range 10 – 1000 Hz. Γ_ψ (Conventional) = 2.83 x 10^{-5} rad/g, Γ_ψ (CACP) = 1.39 x 10^{-5} rad/g.

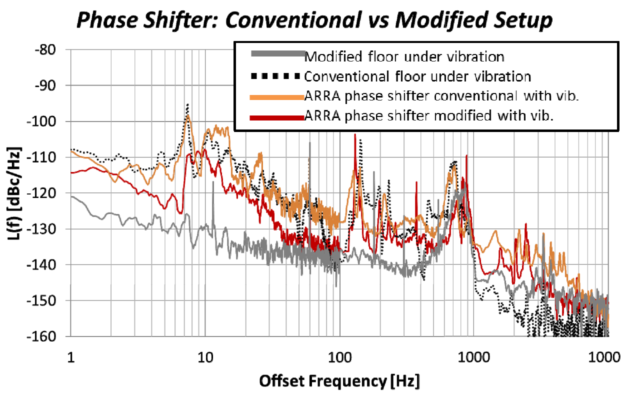

Figure 7. Vibration sensitivity of a mechanical micrometer-trombone phase shifter for conventional (orange) and CACP (red) setups under vibration. Conventional (black dotted) and CACP (grey) floors are shown for reference. Vibration profile: 1 mg^2/Hz random for frequency range 10 Hz -1000 Hz.

V. CONCLUSIONS

We demonstrate a new method for measuring the vibration sensitivity of 2-port microwave components. This method utilizes counter-propagating signals to reduce the vibration-induced PM noise from the cables in the measurement system. This technique improves upon a conventional vibration sensitivity measurement system noise floor by 25 dB or more, depending on the initial system, and has a vibration sensitivity of 4.46 µrad/g at 10 GHz, allowing for measurement of low-vibration sensitive devices.

Several 2-port devices are measured, and their Γ_ψ values are reported. Devices with low vibration sensitivity, which are initially limited by the conventional system, are measured accurately with the CACP system.

Factors that should be considered when building and optimizing a CACP system are as follows:

- Cable and circulator selection are important, as both are vibration sensitive. Circulators may also react strongly to magnetic fields from the actuator.
- Use of materials such as stiff foam and pliable poster putty are effective for damping purposes.
- Best results were achieved by removing most constraints on the system, such as intermediate rigid contact points between the stationary and vibrating platforms as well as a tertiary set of cables.

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