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Phase Noise Analysis Performance Improvement, Testing and Stabilization of Microwave Frequency Source

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Abstract

The present article proposes a novel method to reduce phase noise in a PLL based X-Band source consisting of oscillating and non-oscillating components for the use in Pulse Doppler radar. It also provides phase noise performance stabilization under random vibration. The method consists of improved electrical design and PCB layout, noise filtering technique and passive isolation scheme to suppress vibration-induced noise. Acceleration sensitivity is an important requirement for radars and sensors mounted in unmanned aerial vehicles, aircrafts, missiles and other dynamic platforms. These systems provide superior performance when subjected to severe environmental condition. However, mechanical vibration and acceleration can introduce physical deformation that thereby degrades the frequency source generated signal phase noise. It effects the complete radar system that depends on frequency source performance. The development and testing of a stable X-Band source at 10.64 GHz using indirect method has been carried out which proved that the phase noise is stable both in steady state and under random vibration of 7g magnitude. The study of critical design aspects of test fixture, test object mounting arrangement, investigation on vibration response and performance stabilization along with description of test setup and measurement procedure has been reported. An improvement of around 35-40 dB in phase noise is achieved at close-in offset frequencies. Few challenges and suggestions for the accurate measurement of random vibration testing for frequency sources have also been mentioned.

Keywords Phase noise · Phased Locked Loop (PLL) · Pulse Doppler (PD) · Power Spectral Density (PSD) · Random Vibration (RV)

1 Introduction

High-precision microwave frequency sources have significant application in radars and sensors mounted in unmanned aerial vehicles, aircrafts, missiles and other dynamic platforms. These systems must meet their performance requirement when subjected to harsh airborne operation environment. Pulse Doppler (PD) radar technology used for strategic applications mostly uses local oscillator either in form of Stable Local Oscillator (STALO) or Coherent Oscillator (COHO) signal. In airborne platform, the acceleration experienced by these local oscillator is in the form of random vibration that introduces physical deformation in resonant and non-resonant components used, which ultimately deteriorates the microwave frequency source generated signal phase noise performance. This effects the complete airborne electronic system which is dependent on frequency source output phase noise performance. Consequently, the design and development of stable microwave frequency source having low phase noise characteristics is the desired aim of ongoing research for airborne electronics.

In tradition, microwave frequency source design frequently uses resonator circuits like cavity (stable oscillator with high Q) based, voltage tuned oscillator (VTO) and lumped element (LC or RC oscillator). There are several other commercially available oscillators above 1 GHz having low phase noise but are large, specialized and expensive by nature. Richtmyer [18] exhibited that un-metallized or dielectric geometry can function similarly to metallic cavities which is termed as dielectric resonators (DR). The recent progress in ceramic material expertise has given rise

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in DR technology which provides benefits of low value controllable temperature coefficients of the resonance frequency (f_r) over the functional temperature range and insignificant dielectric losses in microwave band of frequencies [2, 17]. Above 3 GHz, DROs provide the best trade-off between performance and cost. In spite of mentioned developments in DR technology, phase locked loop (PLL) based microwave frequency source design offers advantage of fast switching time (in us) in comparison to other methods. A low noise 10 MHz or 100 MHz quartz crystal (a piezoelectric material) serves better as a reference to PLL designed for ultra-low switc1ing time. A frequency source sensitivity to vibration is generally characterized by acceleration sensitivity which is the normalized frequency change per unit g (1 g is the acceleration of gravity, approximately 9.8 m/s^2). The frequency shift occurring due to mechanical deformations of reference crystal (resonator) in PLL design is a linear effect. Nonlinear effects in the form of nonlinear elasticity of deformed resonator material can also introduce frequency shift [1, 19]. Due to occurrence of non-linearity, spot frequency vibration excitation causes harmonically related frequency spurs in addition to corresponding single frequency spur in the phase noise of PLL generated signal spectrum. Symmetric nature, either in resonator geometry or mounting arrangement helps in reducing acceleration sensitivity. Further reduction of acceleration sensitivity can be achieved by improved electrical filtration or passive isolation implementation. In the recent years, vibration sensitivity of PLL generated signal phase noise has improved to a point where phase sensitivity of non-oscillatory components cannot be ignored. Vibration also reasons physical deformation in non-frequency determining components that leads to phase fluctuation. In common, this phenomenon frequently occurs in microwave frequency source due to low resonator quality factor (Q) and high signal phase sensitivity to physical deformation. High frequency cables and connectors, amplifier, mixer, and filters are the most sensitive components particularly in microwave frequency. The growing demand of low vibration sensitive microwave frequency source operating under harsh random vibration is greater than 7 g. It requires reexamination of sensitivity of non-oscillatory components under vibration.

The article describes a novel method to reduce phase noise in a PLL based X-Band source consisting of oscillating and non-oscillating components for the use in Pulse Doppler radar. Section II presents the relationship of oscillator closed loop phase noise in context to PLL design adopted in development of X-Band frequency source. Section III describes acceleration sensitivity and phase noise for oscillating and non-oscillating components. Section IV reports phase noise improvement techniques and mechanism of acceleration sensitivity reduction. Section V explains critical design aspect of test fixtures, occurrence of few measurement errors in random vibration (RV) testing and stabilization techniques in presence of vibration. Section VI provides the experimental validation result of phase noise measurement before and after execution of the findings and finally Section VII has been concluded.

2 PLL Based X-band Frequency Source

As shown in Fig. 1, PLL based oscillator design used in development of X-Band frequency source is a closed loop chain of amplified output fed as an input to phase modulator by feedback path. Phase modulator generates error signal required in the feedback loop of the oscillator. In the closed loop, at least one component in an oscillator design must offer power amplification. Generally, sine wave oscillators using a piezoelectric material crystal provides good frequency stability in the middle of audio frequency throughout the radio range [1, 19]. The phase noise phenomenon is collectively result of the thermal noise, shot noise, flicker noise in all the active or passive components used in microwave frequency source. The phase noise behavior in the PLL circuit get affect from the mainly following noise sources: reference oscillator noise, loop filter noise and VCO noise [19].

2.1 Reference Noise

The reference noise is low-pass filtered noise and its contribution in phase noise at the PLL output becomes dominant at lower frequency offsets. Therefore, selection of basic reference source and its sensitivity to external mechanical disturbance is critical in design of microwave frequency source and its further stabilization.

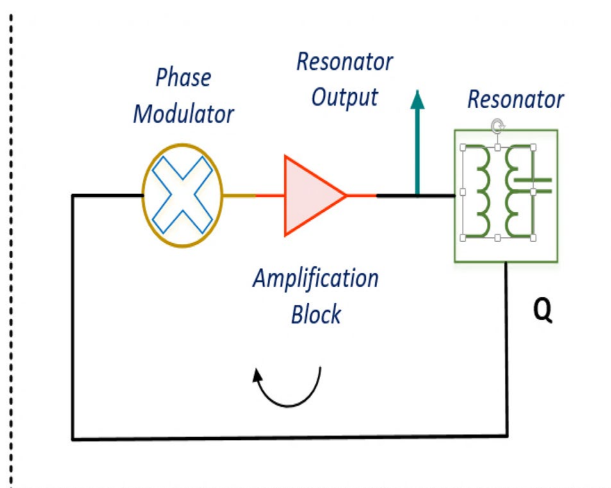


Fig. 1 Resonance output of closed loop feedback oscillator

2.2 Loop Filter Noise

A passive loop filter mainly consists of only resistive and capacitive components. Hence, the output voltage noise is the result of the thermal noise present in the real part of the complex admittance of the loop filter. If the charge pump current in PLL design is increased while keeping the transfer function of the loop filter unchanged, the thermal noise will be reduced since the value of the loop filter resistor had been decreased in order to keep the same output voltage. It helps in maintenance of low phase noise performance of microwave frequency source.

2.3 VCO Noise

The noise injected in PLL charge pump at the output of the VCO is high-pass filtered. Due to the high-pass filtering, the VCO noise will be suppressed within the loop filter bandwidth and the dominant noise contribution will appear at higher frequency offsets. The total integrated phase noise at the output of the PLL can be minimized loop filter bandwidth reduction, however this leads to increase in settling time. Hence, the trade-off between the minimum loop bandwidth and the settling time is aspect in design of microwave frequency source.

Microwave frequency sources used in airborne radar application operates in X and Ku Bands for said merits. Thus, in the present development of X-Band frequency source, PLL is used to control output of slave voltage controlled oscillator (VCO) which is responsible for programmed frequency hopping capability. The phase characteristics of slave oscillator output are controllable within the loop bandwidth (β) of PLL design filter. VCO is specified by its tuning gain, k_v and output frequency range. k_v is the amount of frequency deviation (in MHz) that results from 1-volt change in the controlled voltage that is measured in megahertz per volt (MHz/V). Direct generation technique of low phase noise X-Band signal in PLL is difficult due to high sensitivity and low quality factor of VCO which generates spurious spikes within frequency bandwidth [5, 13, 16]. Therefore, in line with objective of realizing low phase noise X-Band frequency source, Indirect method is used for generation of 10.64 GHz with the help of 4x multiplier concept and stable S-Band PLL. Indirect method offers advantage of reduced in-band spurious frequency generation, which ultimately reduces thermal noise floor as compare to Direct method. In PLL design, multiplier approach also provide better spectral purity at ambient condition and over the temperature (defined in ppm) as compared to Direct method [19]. Spurious is a discrete, deterministic and periodic interference of noise in signal spectrum. It can occur from multiple sources as listed below.

(i) Reference: unwanted noise sidebands that occurs at multiples or fractional multiples of comparison frequency.
(ii) Cross talk: caused by some source other than PLL that finds its way to VCO output.
(iii) Non cross talk: caused by some inherent behavior in the PLL.

Loop bandwidth is the most critical parameter, which is fixed to meet lock time requirement with sufficient margin. In the present S band PLL, the 2nd order passive loop filter is chosen which provides low resistance and high capacitance value near the VCO having better spurious free output. The use of higher reference frequency 100 MHz provides an opportunity of having wider loop bandwidth and faster lock time. In simulation, VCO Phase noise is dominant outside the loop bandwidth as seen in the Fig. 2a. Estimation of closed loop bandwidth of PLL along with the gain of active loop filter is shown in Fig. 2c. Reference phase noise that is dominant within the loop bandwidth of the PLL is shown in Fig. 2b. The combined effect of the phase noise for simulated PLL is shown in Fig. 2d. In multiplier operation, phase noise performance degrades 20log times the ratio of translated frequency to reference crystal [14, 20, 21].

3 Phase Noise and Characterization of Acceleration Sensitivity

Phase noise is a kind of electronic noise with nature of 1/f power spectral density. Phase noise for bandwidth B in hertz at particular offset from carrier $f_0 + f_m$ produces a phase deviation. Phase noise is limited by corner frequency, f_c which separates it from higher-frequency 'flat-band' noise. It naturally has a time-reversible Gaussian distribution of its power spectral density (PSD). For oscillators, spectral phase noise envelop is defined as (1) from [2, 5, 13, 16, 17].

$$S_v(f_m) = \frac{FkTB}{P_{av}}\left(1 + \frac{f_c}{f_m}\right) \tag{1}$$

where, T is the temperature (degree kelvin), B is the frequency bandwidth, $P_{av}$is the average power in resonator, F is the noise factor and K is the Boltzman constant (=1.38xe^{-23} Joules per Kelvin), fc is the flicker corner frequency in Hz and $f_m$is the carrier frequency offset measured in Hz.

When the oscillator based frequency source is subjected to random vibration, its resonant frequency shifts due to acceleration sensitivity of frequency determining components (oscillating component) used. This frequency drift, Δf(t) is mainly governed by magnitude and direction of time dependent acceleration. The frequency source will experience maximum effect on frequency drift when the direction of applied disturbance is parallel to the axis of the acceleration sensitivity vector. In PLL design, this effect is critical in microwave frequency sources due to low resonator quality

Fig. 2 PLL generated phase noise simulation result

factor (Q) of VCO and high signal phase sensitivity to physical deformations. PLL's reference crystal sensitivity to random vibration is quantified by acceleration sensitivity vector ($\overline{\Gamma}$) which is the measure of normalized frequency change per unit g. Total acceleration sensitivity (Γ_{total}) is the sum of acceleration sensitivity squared in three axes as shown in (2).

$$\Gamma_{total} = \sqrt{\Gamma_x^2 + \Gamma_y^2 + \Gamma_z^2} \tag{2}$$

Selection of reference crystal in PLL design is dependent on factors of acceleration sensitivity, maximum PSD limit, thermal stability etc. Typical phase noise performance of basic reference crystal measured at multiple frequency offsets (f_v) is shown in Fig. 3. Apart from acceleration sensitivity of oscillating components, residual noise of a non-oscillatory device such as band pass filter, amplifier, cable and connector under vibration causes change in phase of the signal passing through them.

During random vibration, the acceleration is randomly distributed over the RV test frequency spectrum and represented by its power spectral density, $S_a(f)$ measured in g^2 per hertz ($\frac{g^2}{Hz}$). For a low modulation index, the single sideband phase noise, $L(f_v)$ is expressed in decibels relative to the carrier power per unit bandwidth (dBc/Hz) (3) and $\overline{\Gamma}$ is calculated from (4).

$$L(f_v) = 20 \times \log\left(\frac{\overline{\Gamma} A_{peak} f_0}{2 f_v}\right), \mathrm{dBc/Hz} \tag{3}$$

where peak g-sensitivity is $A_{peak} = \sqrt{2 \times S_a(f)}$

$\overline{\Gamma}$ is the acceleration sensitivity, f_o is the fundamental frequency of reference crystal and f_v is the offset from fundamental frequency.

$$\overline{\Gamma} = \frac{2.f_v}{A_{peak}.f_0} 10^{\frac{L(f_v)}{20}} 1/\mathrm{g} \tag{4}$$

On the other side, for sinusoidal vibration or spot frequency excitation $\overline{\Gamma}$ is determined from (5).

$$\overline{\Gamma} = \frac{2.f_v}{a_{peak}.f_0} 10^{\frac{L'(f_v)}{20}} 1/\mathrm{g} \tag{5}$$

where, $a_{peak}$is the peak sinusoidal acceleration and $L'(f_v)$ is the power spectrum of sinusoidal excitation.

Vibration also causes physical deformations in non-frequency determining electronic components that then causes phase fluctuations. If these phase fluctuation lies within the oscillator feedback loop, they get translated to frequency fluctuations via Leeson's effect within the resonator half-bandwidth (HBW) [3, 4, 9, 10].

Considering a typical scenario of airborne-pulsed Doppler sensor, with its parameters and operational conditions resulting in signal to clutter ratio (SCR) of -30 dB typically. For operation dwell time of 10 msec, resultant Doppler filter bandwidth is 100 Hz (20 dBHz). For reliable detection with Pd = 90% and Pfa = 10^{-6} requires minimum SIR of about 13 dB. Then, the minimum required SSB phase noise at any offset frequency of interest is at least − 63 dBc/Hz derived from (6).

$$L(f_{offset}) = SCR\ (dB) - B_d(dBHz) - SIR_{reqd}(dB) \tag{6}$$

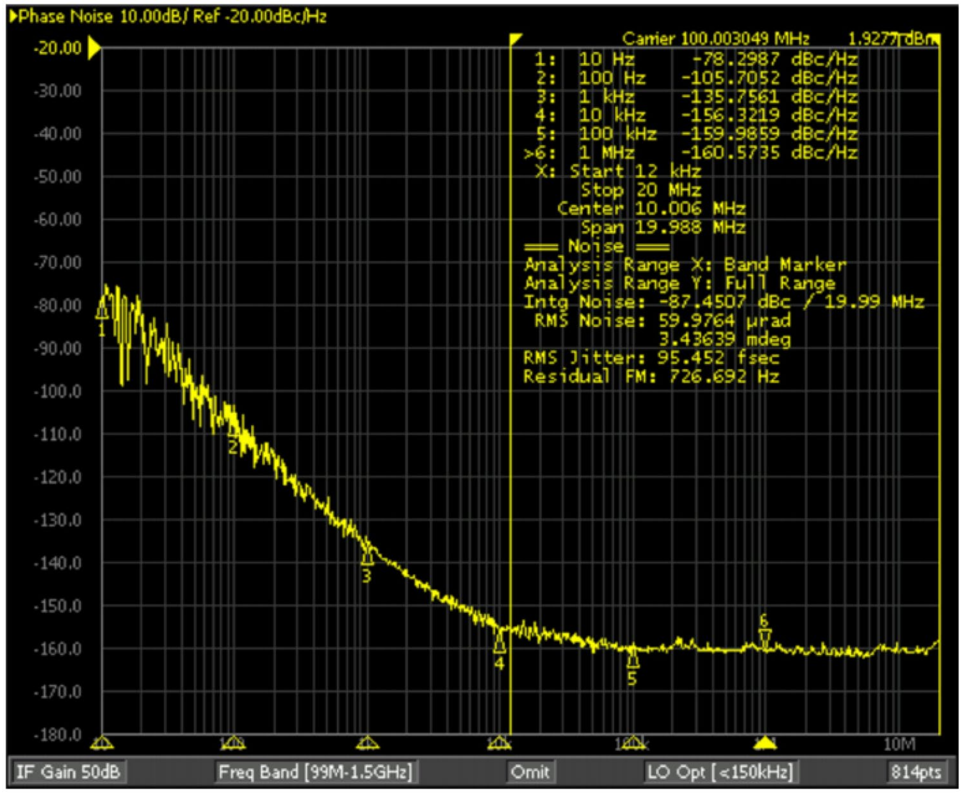


Fig. 3 Phase noise of piezoelectric reference crystal

where, B_d= Doppler filter bandwidth (dBHz)

SIR_{reqd} = Signal to interference required (dB)

As per conventional phase noise modelling [13], this value must hold at all frequency offsets. Reference crystal sensitivity to vibration is traditionally characterized by acceleration/vibration sensitivity, which is normalized frequency change per unit gravitational acceleration g. During random vibration test, amplitude level shift of 10dB phase noise $(L(f_v))$at any particular frequency offset from fundamental carrier frequency will mask return signal from target necessary for Doppler information processing. Therefore, it demands compensation method for this phase noise degradation for reliable detection and successful processing of target characteristics.

4 Phase Noise Improvement Techniques and Mechanism

While vibration-induced phase modulation on a resonator crystal is proportional to g-sensitivity, the proportionality as a function, f_v can be complicated in the range from a few hertz to 2 kHz. Resonator deformations that affect the resonator's center frequency depend on issues of mounting, acoustic resonances, elastic properties of materials, vibration isolation, orientation, etc. The most common method for reducing vibration induced phase noise is to select low acceleration sensitive materials. Low acceleration or g-sensitivity does not necessarily mean that phase noise is due to structure-born vibration that is suppressed under all conditions. Therefore, structural analysis of module (mechanical enclosure) is important. Module resonant frequency (f_r) depends on its structural dimensions and change with any alteration in that. This optimization helps in filtering out module resonance out of vibration spectrum. Structural analysis of module provides center of gravity (CG) position, which works as the best mounting place for reference crystal assembly.

4.1 Design of Vibration Isolated Reference Crystal Assembly

Passive vibration isolation scheme consists of springs and dampers. Active scheme uses accelerometer and compensating electromagnetic driver. The combination of active and passive scheme allows higher degree of achievable vibration isolation but such arrangements are not easily miniaturized and are complex in nature. Compact design requirement permits simpler mechanical vibration isolation to incorporate in X-Band frequency source. Passive vibration isolation is implemented by using silicon rubber dampers in mounting assembly meant for reduction of g sensitivity of basic reference crystal of 100 MHz in PLL. It isolates reference crystal assembly from direct physical contact with rest of the module structure in which PLL circuit resides as shown in Fig. 4. This arrangement gives free-floating or strain free nature to reference crystal printed circuit board (PCB) placed inside that experience suppressed level of vibration in comparison to module structure (metal contact). Precise selection of the best-fit vibration isolator is critical due to their weight and frequency profile dependent nature. Analysis of other environmental stress screenings i.e. thermal, shock, acceleration etc. effects on this vibration isolator is important while making selection.

The main portion of this vibration setup is the vibration equipment, table or 'shaker', table driver and vibration controller with associated accelerometer mounted on the shaker. This accelerometer gives the feedback data that the set-up computer uses to calculate the output signal. The amplitude of the amplifier which drives the shaker to the indicated software parameters are set manually. Mounting of vibration sensor (acoustic sensor) on designed reference crystal assembly arrangement for vibration intensity measurement during RV test quantifies its effectiveness. Usage of arrangement consists of threaded screw, spring washer, planar washer, and hexagonal nut that has been made for holding reference crystal assembly with the help of silicon rubber dampers as shown in Fig. 4 [4, 9, 24]. SMA connector for taking out reference signal out and reference crystal PCB are connected via thin 75-micron enamel wire. PLL circuit and other sections of frequency source module further use this reference signal output of 100 MHz. Practice of thin enamel wire pair with between reference crystal PCB and signal output connector is unique tactic for arresting any amplification effect occurring due to interconnection rigidity. Semi flexible high frequency cable is used for routing of reference crystal output within frequency source module.

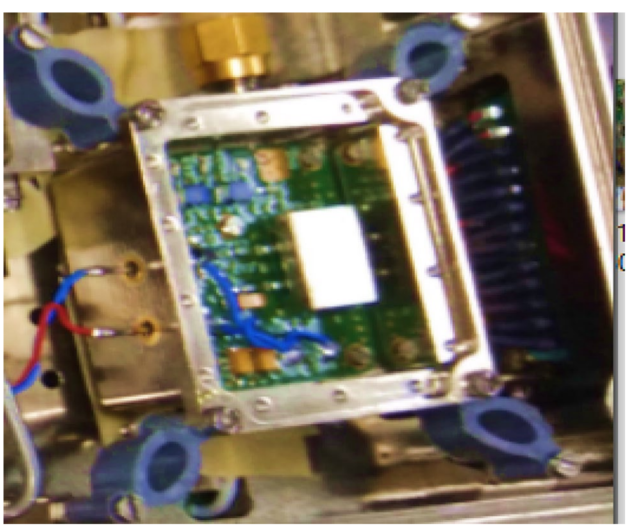


Fig. 4 Reference crystal assembly and mounting arrangement

4.2 Electrical Design Improvements

In addition to acceleration sensitivity reduction, electrical filtering tactics in design and PCB layout are important and are achieved by ensuring below mentioned points.

- Use of capacitive filtering at all input supply lines and charge pump supply in PLL. These are the most susceptible sources to noisy pickups. Multi value tantalum capacitors are used in combination of 10uF, 1uF or 0.1uF to filter out low frequency spikes that can occur during vibration due to non-resonant components.
- Use of electrolyte capacitor at the input power supply to X-Band frequency source module for avoiding any sudden fluctuations.
- Use low noise voltage regulators for achieving better phase noise from developed frequency source. While ensures that their switching frequencies does not lie within vibration spectrum.
- Charge-pump supply line and VCO tune voltage line are protected from noisy pickups (implemented by making running traces short and routing close to the PLL in layout).
- Isolated signal routing of reference crystal output to PLL circuit by use of shielded co-axial cable, to avoid any radiation pick up during random vibration test.

Proposed design techniques for X-Band frequency source are equally applicable in design of frequency source in microwave frequency region.

5 RV Test Set Up and Performance Stabilization

The X-Band frequency source module was mounted to the shaker using a custom mount designed for this purpose. The mounting hardware or test fixture allows the module under test to be mounted and vibrated along each axis.

5.1 Test Fixture Design

The vibration impact on any system depends on structure-borne vibrations and perturbations on that system. Vibration test fixture is a mounting platform that gets fixed with RV test machine shaker on which module under test is placed. In order to design of correct test fixture, mentioned design inputs about test module and RV shaker needs to considered.

(i) Test fixture design must have minimum material mass to fulfill weight constraint of shakers.
(ii) Accurate details of the shaker table i.e. hole pattern, bolt size and thread pattern.

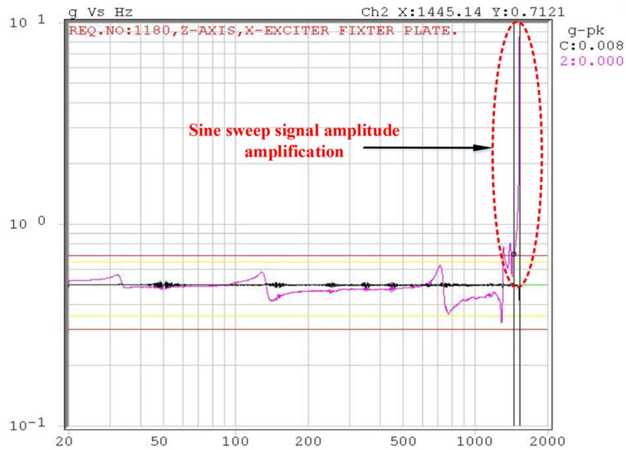


Fig. 5 Sine sweep vibration test

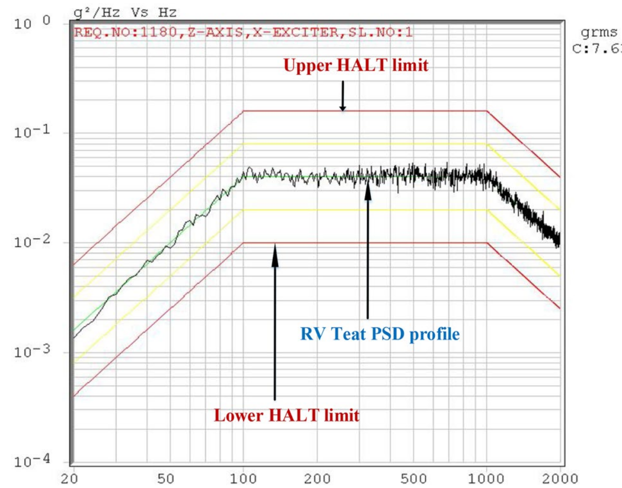


Fig. 6 Monitoring sensor response on module matching input profile

(iii) Fixture natural frequency must not lie with random vibration spectrum to avoid any amplification.

5.2 Mounting of the Test Object

The mounting hardware is allowed for the module under test to be mounted and vibrated along each axis. Mounting and placement of test object is required for the smooth execution of RV test in three-direction axis i.e. X, Y and Z. It needs to be perfect for translating input test conditions applied exactly on the module. Any mechanical assembly issue leads to wrong measurement and assessment.

5.3 Vibration Response Investigation

Succeeding step after mounting of the test object is to filter out module self-resonance or any external interference occurring apart from running RV test profile spectrum. Generally, for module under test self-resonance is found by running a sine sweep test as shown in Fig. 5, showing self-resonance occurrence at 1.5 kHz. In this analysis, acoustic monitoring sensors are used for monitoring vibration intensity level when placed on fixture. If monitor sensor response is matching with input RV test profile, then setup is okay for execution of test. For testing developed X-Band frequency source module under RV test mentioned steps are ensured [12, 15].

(i) Rigidly mounting of test object on the vibration fixture is to avoid any mechanical resonance inside the frequency range of interest.
(ii) Avoidance of any external coupling of acoustic noise in test chamber.
(iii) Ensure accurate vibration profile is running as per test requirements.
(iv) Usage of shielded power cables for module consisting with jack post connector. Properly securing the cables to minimize flexing and strain during test.
(v) Properly connect high frequency coaxial cables to provide input and monitor module output.
(vi) Usage of good quality acoustic sensors to monitor if any mismatch between applied input profile and profile are being developed on vibration fixture.
(vii) Before the RV test was performed pre-vibration module performance readings were noted, then RV test was started and monitoring of vibration level response was carried out using monitoring sensors. It was ensured sensor output matches with applied test profile as shown in Fig. 6. During ongoing test, readings were noted. In case if the monitor sensor response does not match with input profile applied as shown in Fig. 7, then test HALT situation occurs. In such situation, the root-cause analysis needs to be carried out before proceeding for test again. At last, readings were noted down after successful completion of RV test [22].

5.4 Performance Stabilization

RV test exposes assembly and workmanship issues i.e. loose wire interconnections and flaws in assembly processes. The most common types of defect which are easily avoidable are as follows

(i) Handling damage.
(ii) Inappropriate part usage or selection of incorrect mounting position (in absence of structural analysis).
(iii) Failure due to electrical overstress.

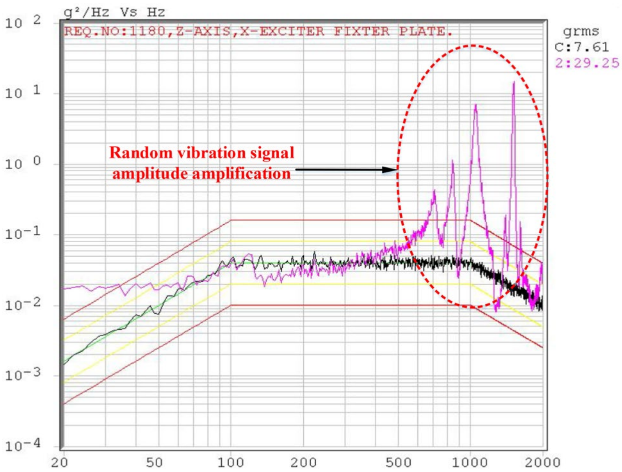


Fig. 7 Monitor sensor indicating HALT condition

(iv) Component damage due to assembly temperature.

Mentioned defect sources play crucial role in failure of any microwave system when subjected under RV test. Hence, the root cause analysis is necessary to find the scope of improvement. Spectral purity is the vital feature of frequency source under consideration. Hence, issues of power loss and phase instability needs to be addressed at ambient condition before going for RV test. Subsequently, the design of the vibration isolated reference crystal assembly and electrical design improvement are essential for maintaining spectral purity. Effects of with or without compensation in frequency source module phase noise performance under RV is shown in Fig. 8. Proposed stabilization methods for X-Band frequency source tested under ambient condition and vibration environment are equally applicable in design of frequency source in microwave frequency region.

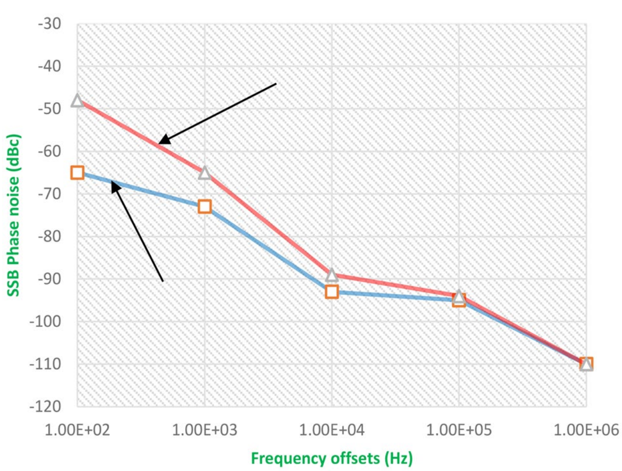


Fig. 8 Phase noise with or without compensation during RV test

Any component assembly issue or internal wiring occurrence during the test condition directly imparts signal power loss or rise in system noise floor as shown in Fig. 9. These unexpected power losses in PLL derived signals raises phase noise level immediately of that particular signal during RV testing. Hence, proper attention is required for avoidance of such issues. RF signal transitions as shown in Fig. 10 used in designed frequency source module for PCB to PCB connections plays critical role during RV test. Any type of misfit or loose connectivity directly imparts vibration pickups in phase noise performance or rise in noise floor of the travelling signals.

Phase noise performance degradation pattern due to improper RF transition during RV test at defined checkpoints is shown in Fig. 11 [7, 8, 23].

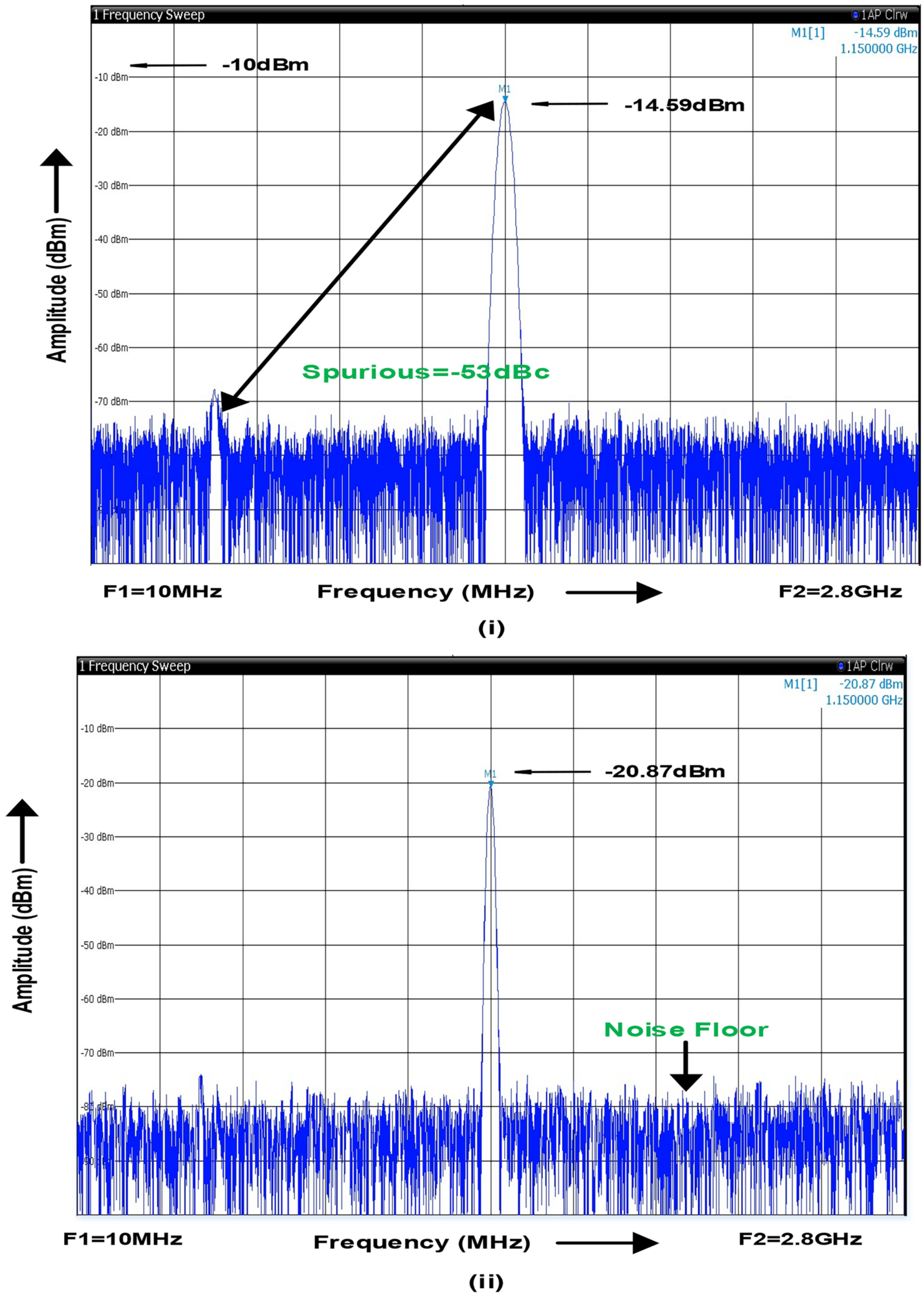
In analysis mode PCB X-Ray scan was carried out of all mounted components and observed sequentially. During fault diagnosis, process micro-crack formation in the non-resonant RF component (SMD filter) was detected as shown in Fig. 12. Excess heat transfer due to non-standardized practice is the reason of such minor crack formation. In the process of root cause, analysis after corrective action module was again tested under RV test for 5 min in all the three axis.

6 Experimental Validation Results

The shaker has the capability to vibrate in random vibration pattern or various sine patterns including dwell and sweep. In the current study, random vibration testing was chosen. Developed module under test is subjected to a constant-acceleration spectral density of 0.02 g^2 / Hz approximately and random white-noise vibration profile with frequencies between 20 and 2000 Hz. The test was performed and the data is taken in three axis for 100 MHz reference crystal and X band signal. This section covers experimental phase noise result achieved after stabilization during RV testing of frequency source X-Band signal. As mentioned earlier, X-band signal is generated from 4 x multiplication of S Band PLL signal driven on reference crystal. It was noted that performance stabilization used for 100 MHz reference ultimately leads to improvement in derived X band signal phase noise performance. During translation of 100 MHz signal into X-band signal, by virtue of selected design topology and theoretical calculation, resulted in ~38–42 dB phase noise degradation. Figure 13 shows ambient condition achieved phase noise performance of 100 MHz and X-band signal.

As mentioned RV test PSD corresponding to 7 g spread over 20 Hz to 2000 Hz was executed in all the three axis for 5-minute duration. During initial phase of product realization, the phase noise degradation pattern at frequency offsets of 100 Hz, 1 kHz and 10 kHz without any compensation techniques implemented is shown in Fig. 14 [6, 11].

Fig. 9 **i** Ambient condition signal power **ii** During RV test signal power loss



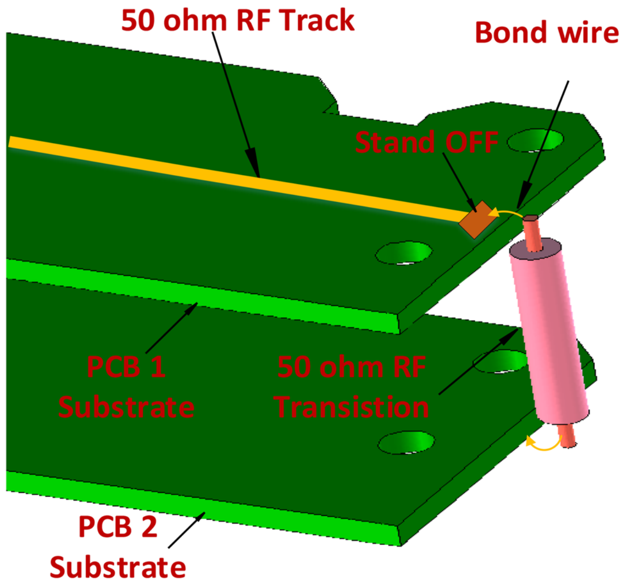


Fig. 10 RF transition for PCB to PCB signal transition

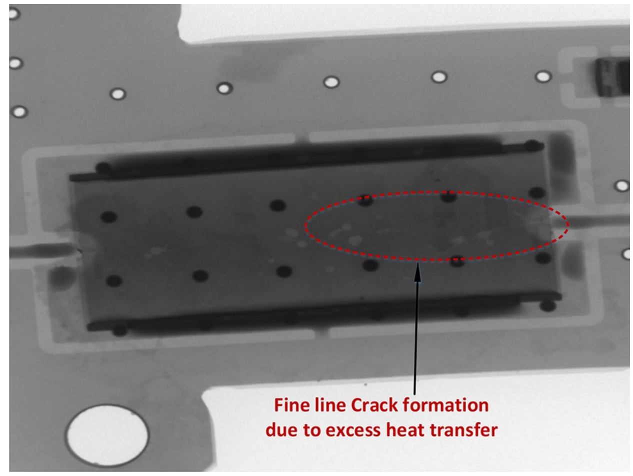


Fig. 12 Presence of fine crack development in filter substrate

In this condition, the phase noise performance degrades significantly as compared to ambient condition by ~50, ~45 and ~15 dB at an offsets of 100 Hz, 1 kHz and 10 kHz respectively. Therefore, for compensating phase noise degradation, design of vibration isolated reference assembly (including its structural analysis) and acceleration sensitivity reduction techniques (i.e. mechanical and electrical) were implemented. Significant improvement was recorded in achieving phase noise stabilization during testing in all three axis. Monitored results of phase noise performance of 100 MHz reference and X Band signal in X, Y and Z axis RV test conditions are shown in Figs. 15, 16 and 17 respectively.

Tables 1 and 2 summarizes comparison of achieved phase noise results before and during (with or without compensation) RV test for 100 MHz reference and X-Band signal in frequency source module.

Fig. 11 Phase noise degradation during RV test due to imperfect RF transition

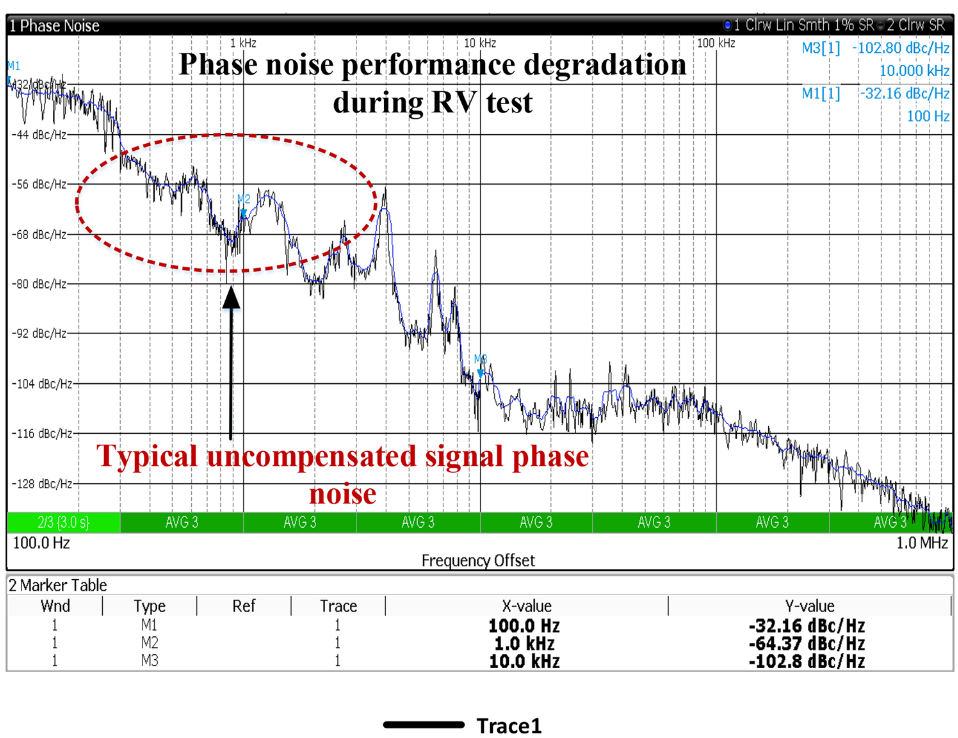
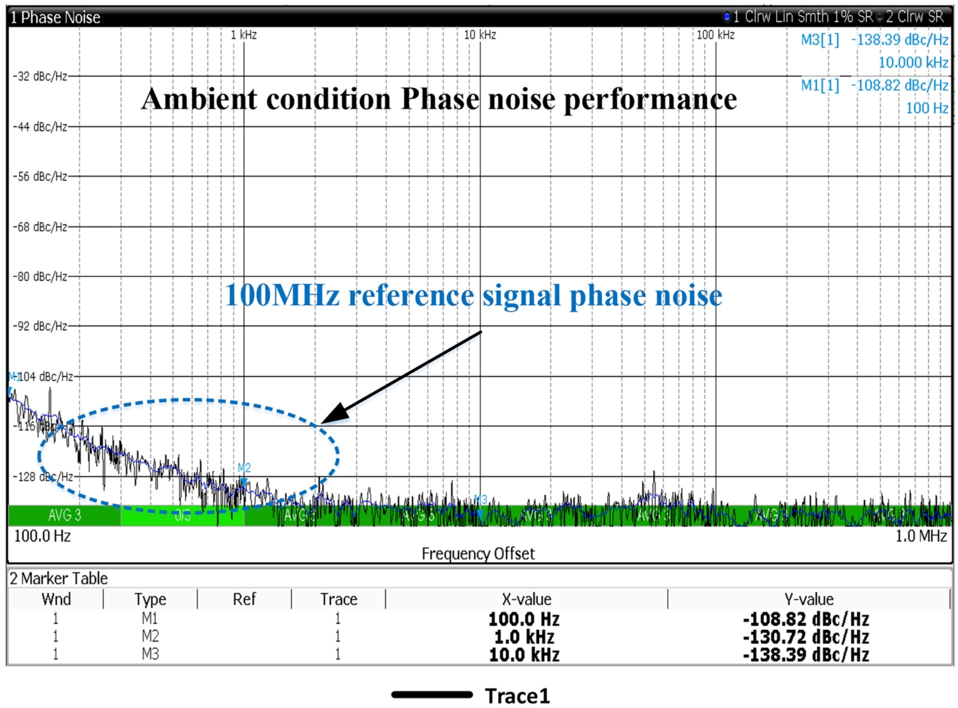
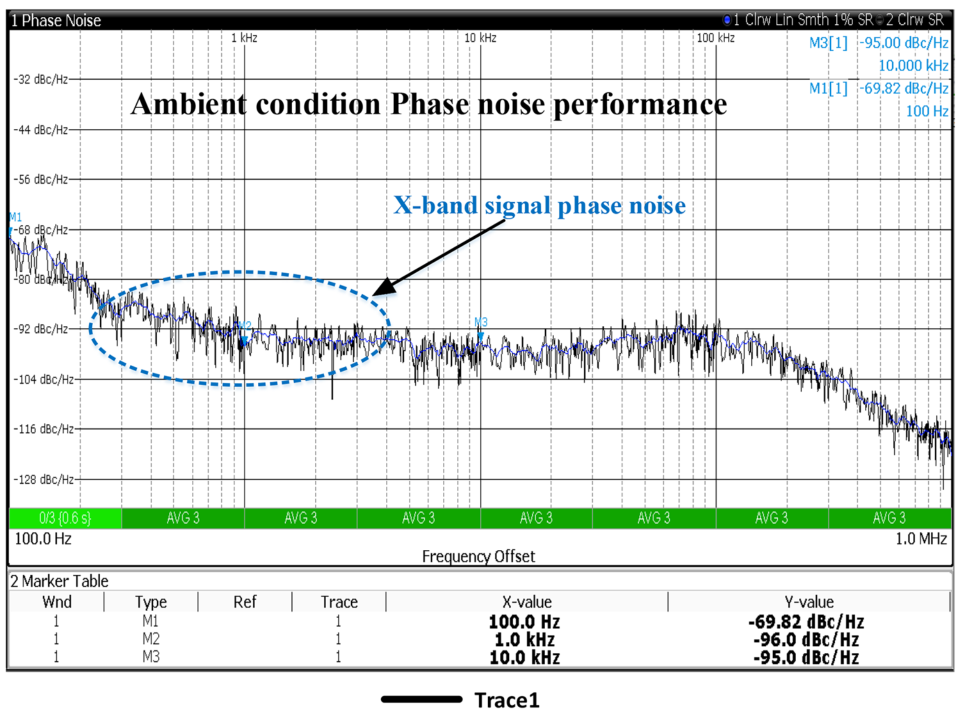


Fig. 13 Ambient condition phase noise **i** 100 MHz signal **ii** X Band signal

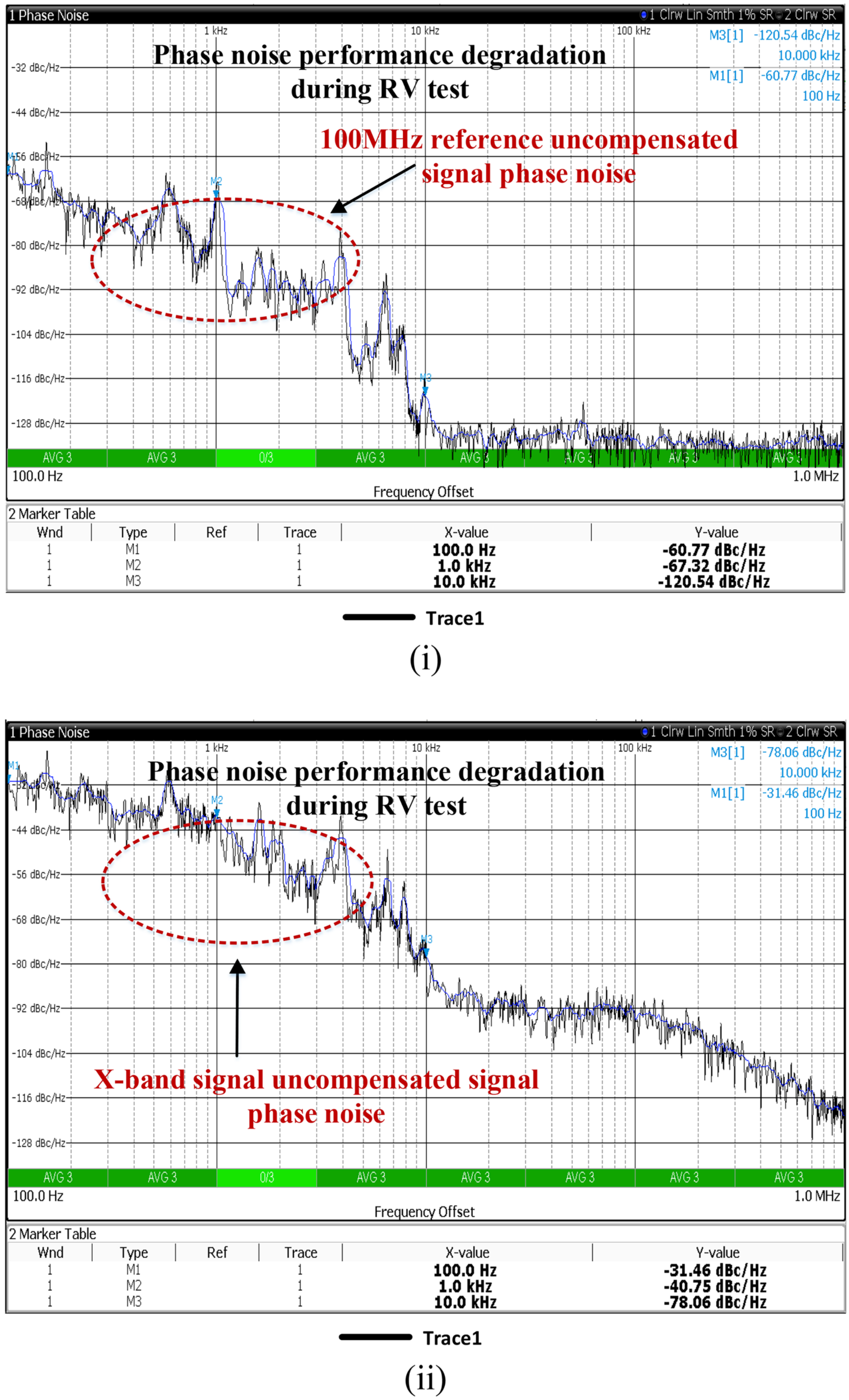


(i)



(ii)

Fig. 14 Phase noise degradation **i** 100 MHz signal **ii** X Band signal



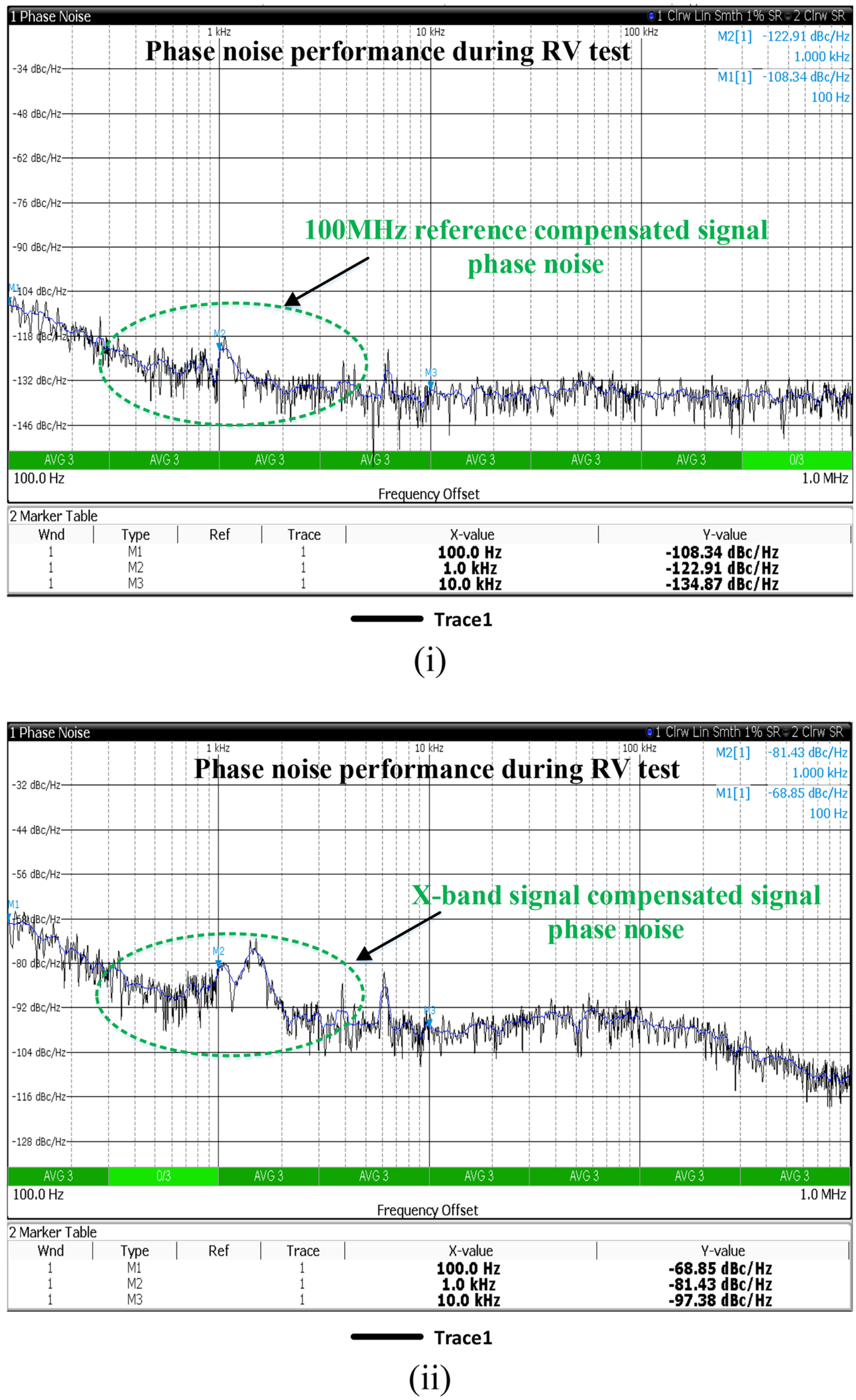
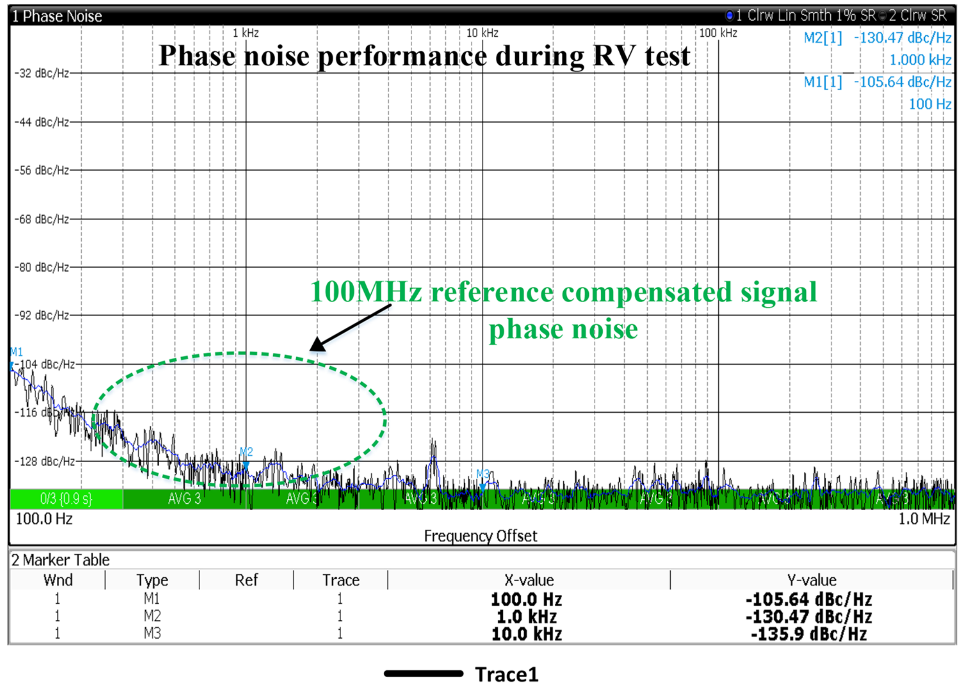
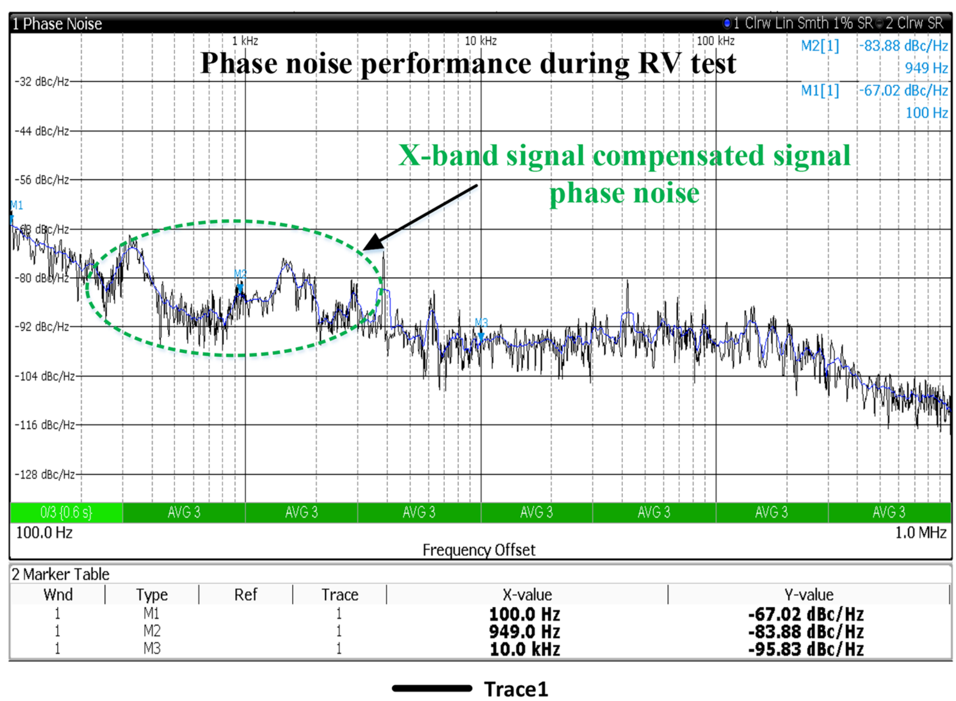


Fig. 15 X-axis RV test phase noise performance **i** 100 MHz signal **ii** X Band signal

Fig. 16 Y-axis RV test phase noise performance **i** 100 MHz signal **ii** X-Band signal



(i)



(ii)

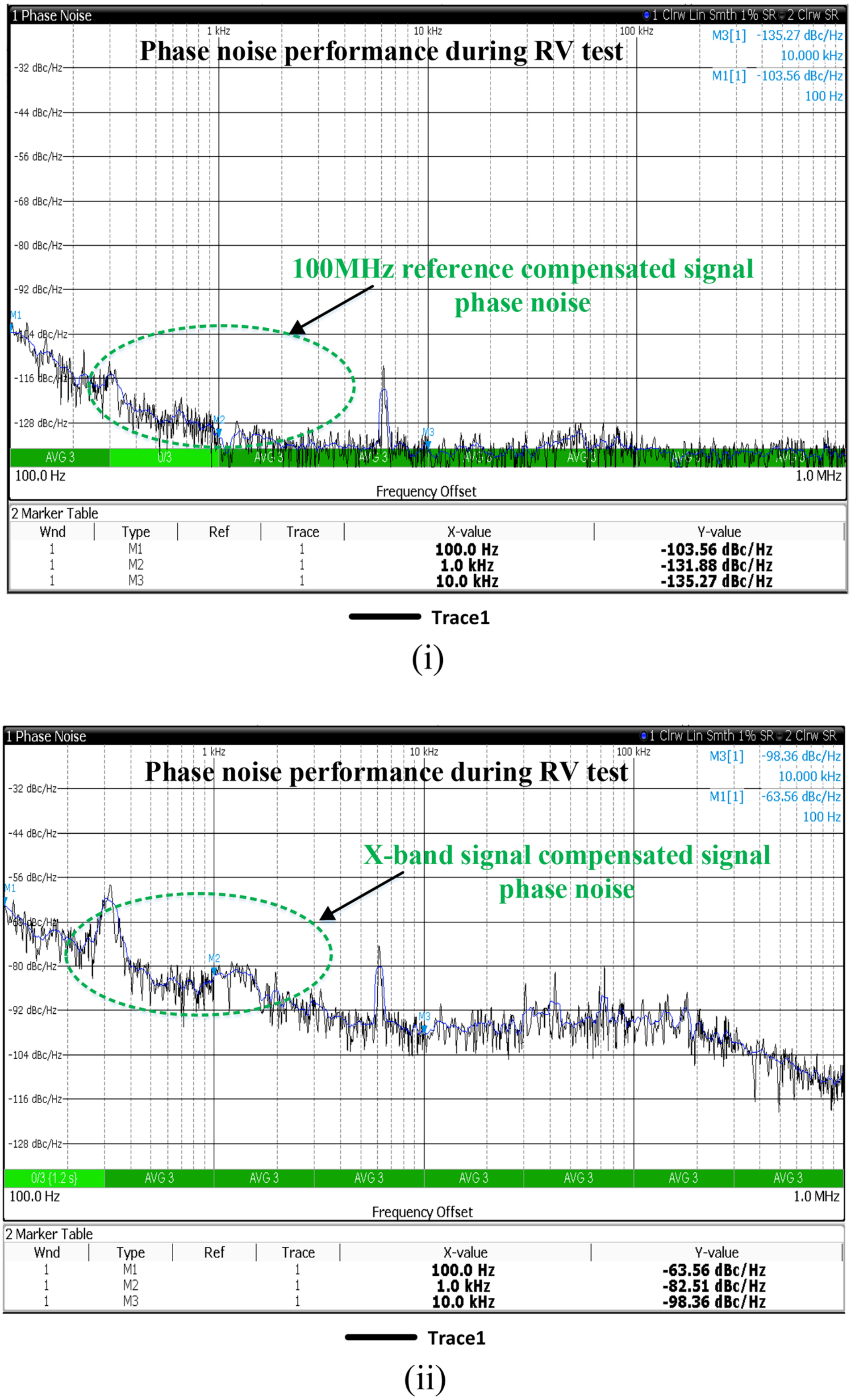


Fig. 17 Z-axis RV test phase noise performance **i** 100 MHz signal **ii** X-Band signal

Table 1 100MHz Reference RV Test results

Frequency Offset	100 Hz	1 kHz	10 kHz
PRE (dBc/Hz)	-108.82	-130.72	-138.39
INW (dBc/Hz)	-60.77	-67.32	-120.54
INC X-axis (dBc/Hz)	-108.34	-122.91	-134.87
INC Y-axis(dBc/Hz)	-105.64	-130.47	-135.9
INC Z-axis(dBc/Hz)	-103.56	-131.88	-135.27

Table 2 X-Band signal RV Test results

Frequency Offset	100 Hz	1 kHz	10 kHz
PRE (dBc/Hz)	-69.82	-96.0	-95.0
INW (dBc/Hz)	-31.46	-40.75	-78.06
INC X-axis (dBc/Hz)	-68.85	-81.43	-97.38
INC Y-axis(dBc/Hz)	-67.02	-83.88	-95.83
INC Z-axis(dBc/Hz)	-63.56	-82.51	-98.36

PRE Pre RV Test, *INW* In RV Test without compensation, *INC* In RV Test with compensation

7 Conclusion

Structure-borne vibration is the routine for airborne electronic application which causes an increase in signal phase noise of microwave frequency source that thereby degrades its performance. This paper has described and simulated closed loop phase noise for PLL based X-Band frequency source. The acceleration sensitivity and its relationship with phase noise of PLL based source design is reported. This study clarified that a low-noise source at rest is not necessary to be the best choice for vibrating platforms. A PLL based low noise at 10.6 GHz source has been developed using indirect method. The improved PCB layout, noise filtering techniques and passive isolation scheme for 100 MHz reference to suppress or cancel vibration-induced noise is implemented. Critical design aspects of test fixture, mounting arrangement of test object and vibration response investigation is reported. Stable X-Band frequency source module has been developed and tested which has shown that phase noise is completely stable in both ambient condition and under vibrating environment of 7 g. Reproducibility of each measurement has been confirmed after multiple trials.

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Declarations

Conflict of Interest The authors declare that there is no conflict of interests regarding this publication of this article. Necessary permission to publish this article has been obtained from TP/CO department of Bharat Electronics Limited.

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