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The Residual Phase Noise Measurement

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INTRODUCTION

This application note describes a technique to evaluate DUT noise by removing external noise sources. A residual phase noise setup is used to isolate and measure the additive phase noise contribution of a device. Designers use this information to select individual devices for their signal chain, which, in aggregate, meet the phase noise requirements for their complete system.

The benefit of a residual phase noise setup is that the effect of noise sources external to the device under test (DUT), such as power supplies or input clocks, can be canceled from the measurement. Conversely, an absolute phase noise measurement includes the impact of power supply noise and reference clock noise.

This application note includes actual phase noise measurement plots of a clocked device to highlight the attributes of the residual phase noise setup. In addition, it demonstrates how the additive phase noise of a device can be used to identify the source of noise-related issues in the signal chain.

BACKGROUND INFORMATION

The setup shown in Figure 1 measures the additive phase noise of the DUT. Note that two DUTs are used, each connected to a common power supply and a common input clock. It will be shown that the noise at each DUT output due to these common noise sources is correlated. If the amplified DUT1 output signal is denoted as E_1 and the amplified and delayed DUT2 output signal is denoted as E_2, then the output phase noise can be derived by simply modeling the phase detector as an analog multiplier with a gain of K_{PD}.

$$E_1 = E_{C1} \cos[\omega_C t + \theta_{M1} \cos(\omega_M t)]$$

$$E_2 = E_{C2} \sin[\omega_C t + \theta_{M2} \cos(\omega_M t)]$$

$$E_{OUT} = LPF\,\{K_{PD}E_1E_2\} = K_{PD}E_{C1}E_{C2} \sin\,[(\theta_{M2} - \theta_{M1})\cos(\omega_M t)]$$

The signal powers are assigned E_{CX} and the magnitude of the phase modulation (noise) is assigned θ_{MX} with carrier frequency ω_C and modulating (offset) frequency ω_M. Because superposition applies, the phase noise intrinsic to the DUTs can be neglected when considering the phase noise from external sources.

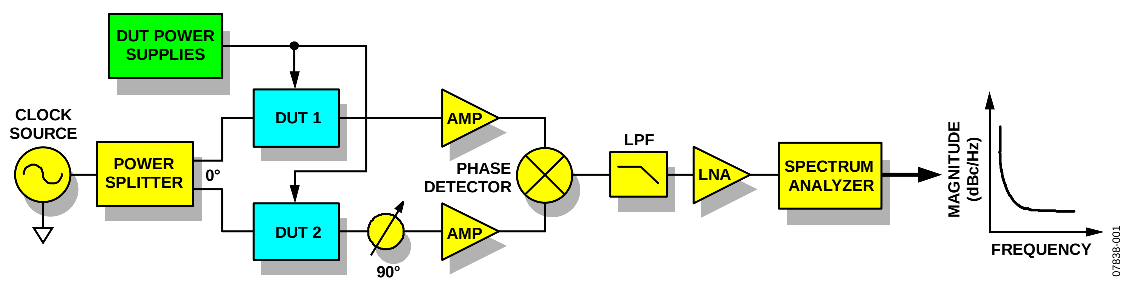

Figure 1. Residual Phase Noise Measurement Setup

Considering the input clock signal phase noise and assuming that DUT1 and DUT2 have identical excess phase transfer functions, it is apparent by inspection that the portion of θ_{M1} due to the clock source is equivalent to the portion of θ_{M2} due to the clock source. Similarly, the portion of θ_{M1} due to the power supplies is equivalent to the portion of θ_{M2} due to the power supplies. This phenomenon can be considered supply pushing and is simply described by

$$\theta_M = K_P V_M$$

$$E_1 = E_{C1} \cos[\omega_C t + K_{P1} V_M \cos(\omega_M t)]$$

$$E_2 = E_{C2} \cos[\omega_C t + K_{P2} V_M \cos(\omega_M t)]$$

The magnitude of the phase modulation is given by the product of the voltage noise on the supply and the pushing gain (radians/V). Again, it is assumed that DUT1 and DUT2 have equivalent pushing gains. As a result, these noise sources are cancelled (theoretically) at the phase detector's output, leaving only the uncorrelated noise of the two DUTs for measurement.

The intrinsic DUT noise can be ascertained with a few additional assumptions. Because the rms phase error due to device noise is generally very small, the expression can be rewritten for the output carrier using the small angle approximation as

$$\Delta\theta = (\theta_{M2} - \theta_{M1}) \cos(\omega_M t)$$

$$E_{OUT} \approx K_{PD} E_{C1} E_{C2} \Delta\theta, \Big|_{\Delta\theta << \frac{\pi}{2}}$$

The output of the phase detector can be referred to as the baseband signal since it has been demodulated. The actual phase noise can be calculated once the phase detector gain and the input signal power are determined assuming that the amplifier phase noise contribution is negligible. Because the noise intrinsic to each DUT is uncorrelated, it is assumed that they contribute equally, such that the rms sum is the measured output phase noise. For this reason, 3 dB is subtracted from the phase noise measured on the spectrum analyzer (in dBc/Hz) to ultimately determine the contribution of each DUT; this representation is just the phase noise power relative to the signal (carrier) power

$$E = E_C \sin[\omega_M t + \Delta\theta] \approx E_C \sin(\omega_M t) + E_C \Delta\theta \cos \Delta\theta(\omega_M t)$$

$$L = 10 \log\left[\frac{(\Delta\theta)^2}{2}\right]$$

When making very sensitive phase noise measurements, the noise contribution of the amplifier may be significant. An amplifier residual phase noise measurement can be performed such that DUT1 and DUT2 are removed from Figure 1, with the power splitter outputs applied directly to the amplifiers. The amplifier input signal power should resemble the actual DUT output signal in amplitude and slew rate. Using this procedure, the measured amplifier phase noise can be root-sum-square (rss) subtracted from the measured DUT phase noise to obtain the precise DUT phase noise. Again, it is important that the gain and noise figure of the amplifiers resemble one another as closely as possible.

Note that a DUT that requires clocking has a front-end amplifier that exhibits a certain amount of noise. For this reason, a clock source with a low slew rate could unintentionally increase the phase noise contribution due to threshold uncertainty at the amplifier input. When using a sinusoidal clock source, the maximum allowable amplitude, which maximizes the slew rate, should be used.

BASIC EXPERIMENT SETUP DETAILS

An experiment was performed using the setup shown in Figure 1. Two DUTs with the same part number were chosen and clocked by a single 1 GHz clock source. Both devices were set up to divide the clock source frequency by 4 to produce a 250 MHz output. In addition, the two output signals were adjusted so that they were shifted in relative phase by 90° (quadrature), which minimizes the down-converted signal level that appears at dc.

The two DUT signals were amplified using a low noise amplifier (LNA) to increase the dynamic range of the measurement system (the phase noise contribution of the amplifiers is sufficiently low to be ignored).

Both amplifier outputs were sent to a balanced mixer (phase detector). The phase detector mixes the two signals producing sum and difference mixing products at the phase detector output. The sum product was filtered out with a low-pass filter. The remaining difference product constitutes the 250 MHz output signal down-converted to dc (phase noise). The LNA in the setup provided sufficient gain to overcome the noise floor limitation of the spectrum analyzer.

COMMON CLOCK SOURCE PHASE NOISE CANCELLATION IN A RESIDUAL PHASE NOISE MEASUREMENT

Figure 2 shows the result of an absolute phase noise measurement of two different clock sources. Clearly, the two clock sources exhibit very different phase noise characteristics. Theoretically, neither clock source should impact the DUTs additive phase noise measured using a residual phase noise setup.

Figure 3 confirms this theory. Two separate residual phase noise measurements were plotted with one trace for each clock source. The two traces virtually overlap; this proves the cancellation of the common clock source noise in the residual phase noise setup. The clock source phase noise is not cancelled in an absolute phase noise setup. In fact, if the DUTs are ideal (no additive phase noise), their absolute phase noise curves match the curves as shown in Figure 2. However, the curves would measure 12 dB lower due to the factor of 4 frequency translation. For example, normalized to a 250 MHz carrier, Clock Source 2 exhibits −92 dBc/Hz at 1 kHz offset, whereas the measured DUT phase noise associated with Clock Source 2 is −135 dBc/Hz at the same offset frequency, indicating approximately a 40 dB suppression of the input clock phase noise in the residual measurement.

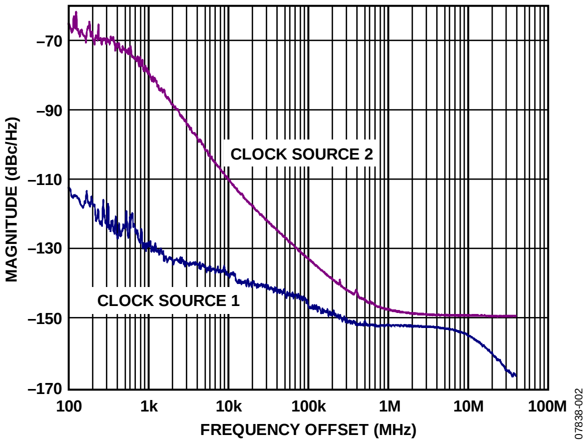

Figure 2. Absolute Phase Noise Measurement of Two Different Clock Sources

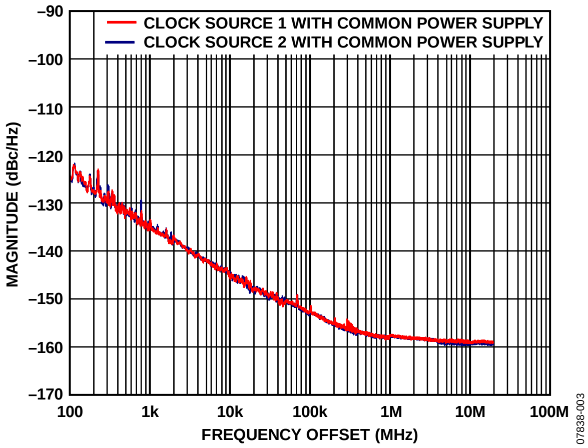

Figure 3. Residual Phase Noise Measurement with Virtually No Impact from Either Clock Source in Figure 2

DEMONSTRATION OF COMMON POWER SUPPLY NOISE CANCELLATION IN RESIDUAL PHASE NOISE MEASUREMENT

In Figure 3, the common power supply connection shown in Figure 1 is used. In Figure 4, a separate power supply is used for each DUT (that is, not a common supply). As a result, the power supply noise is uncorrelated and, as shown, impacts the residual phase noise measurement. In this case, the close-in phase noise increases substantially when using separate power supplies.

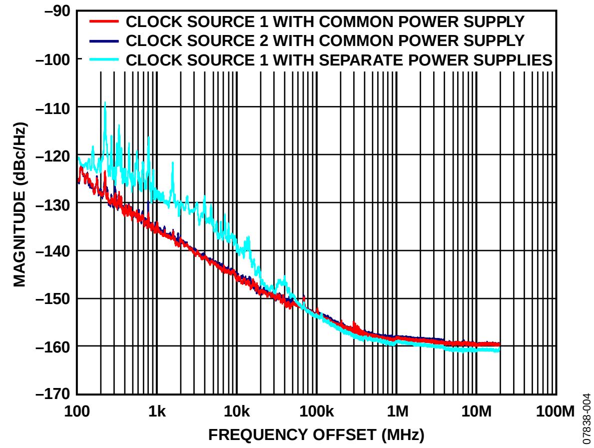

Figure 4. Residual Phase Noise Measurement Displays the Impact from Common and Separate Power Supplies

The same model (noisy) power supply is used for producing Figure 3 and Figure 4. The measured phase noise impact of this power supply becomes apparent when two separate power supplies are used instead of a single common supply. In Figure 5, the absolute phase noise is measured, this time using a new low noise power supply. There is good agreement between the absolute phase noise with low noise power supply and the residual phase noise measurement with separate low noise power supplies. Recall that in the residual phase noise measurement the input clock phase noise is cancelled whereas in the absolute phase noise measurement it is not.

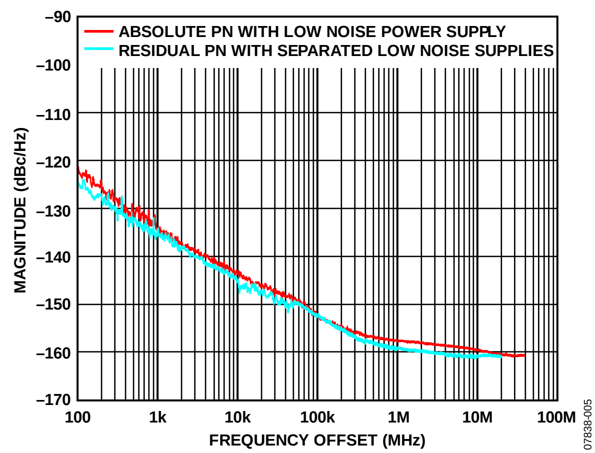

Figure 5. Close-In Phase Noise Improvement Due to a Low Noise Power Supply

The residual phase noise measurement is a valuable technique used to identify the phase noise contribution of a single component as part of a system design. Using this approach external noise sources, such as the input clock signal noise and power supply noise, can be effectively cancelled since these noise contributors are correlated at each DUT in the measurement setup. Furthermore, it is possible to account for the phase noise contribution of buffers or amplifiers used in the DUT residual noise measurement by performing additional residual phase noise measurements on these components.

Combining residual and absolute phase noise measurements is a powerful way to identify the dominant noise source in a system design. Measurement data acquired on a frequency divide-by-4 device has been presented which demonstrates the concept and utility of the residual phase noise measurement. In this example, the impact of a noisy input clock source and the impact of a noisy power supply on the DUT has been quantified; from this evaluation, the system designer can derive specifications for the input clock source and power supplies based on actual measurement data.

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