TRF372017 Noise Analysis: Modulator Noise Estimation from Output Noise

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ABSTRACT

This report provides information about the experimental set-up and measurements carried out with the TRF372017 evaluation module (TRF370217EVM) to determine the output noise at the RF port of Texas Instruments' TRF372017 integrated IQ modulator device. The significance of using low-pass baseband and RF bandpass filters, along with the modulator noise floor estimation obtained from the output noise, is discussed.

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1 Introduction

The TRF372017 is a fully-integrated IQ modulator and PLL/VCO. Figure 1 shows a basic block diagram of the TRF372017. It integrates a highly linear, low-noise, IQ modulator and PLL/VCO over a wide bandwidth of 300 MHz to 4800 MHz. It also operates at complex-IF frequencies with the differential baseband (BB) IQ signals directly upconverted to RF. As a quadrature modulator, the TRF372017 also has the ability to suppress the carrier and unwanted sideband signals (see Ref. 1 and Ref. 2).

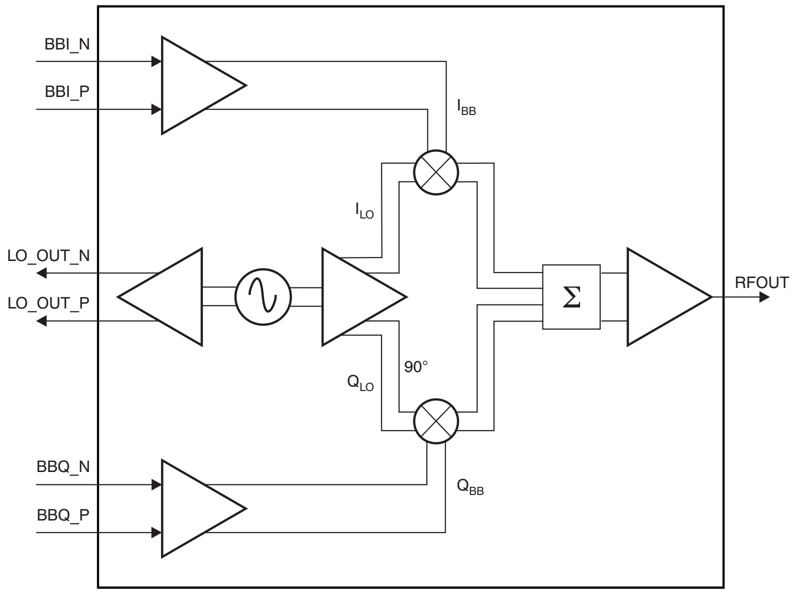


Figure 1. TRF372017 Basic Block Diagram

1.1 Basic Operation

Figure 1 illustrates the in-phase baseband signal I_{BB}, quadrature phase baseband signal Q_{BB}, inphase local oscillator (LO) signal I_{LO}, and the quadrature phase LO signal, Q_{LO}. We can consider each of these signals as separate formulas, as shown in Equation 1 through Equation 4:

$$I_{BB} = A_{BB}\cos[\omega_{BB}t + \phi_{BB}(t)] \quad (1)$$

$$Q_{BB} = A_{BB}\sin[\omega_{BB}t + \phi_{BB}(t)] \quad (2)$$

$$I_{LO} = A_{LO}\cos[\omega_{LO}t + \phi_{LO}(t)] \quad (3)$$

$$Q_{LO} = A_{LO}\sin[\omega_{LO}t + \phi_{LO}(t)] \quad (4)$$

In each of these formulas, $\Phi_{BB}(t)$ and $\Phi_{LO}(t)$ are the phase variations in BB and LO IQ signals, respectively. Considering both the I and Q signals of BB and LO with the same amplitude and phase, the summed result from the mixed product of $I_{BB} – I_{LO}$ and $Q_{BB} – Q_{LO}$ is RF_{OUT}, and is given as Equation 5:

$$RF_{OUT} = A_{LO}A_{BB}\cos\left[(\omega_{LO} - \omega_{BB})t + \phi_{LO}(t) + \phi_{BB}(t)\right] \quad (5)$$

This equation shows RF_{OUT} with a lower sideband; the upper sideband is suppressed. However, the upper sideband could be obtained mathematically, and the lower sideband could be suppressed when the polarity of one of the mixer outputs is reversed.

1.2 Phase Noise Background Information

Phase noise is random variations in phase (or frequency) of an oscillator. It is defined at a particular offset frequency from the carrier as the ratio of power in one phase modulation sideband to the total signal power per unit bandwidth (1 Hz). as Equation 6 shows (see Ref. 3).

$$PN(f_O) = \frac{P_N}{P_C} \quad (6)$$

This equation represents *PN* as the phase noise at the offset frequency (f_O) from the carrier. P_N is the noise power at f_O in 1-Hz bandwidth and P_C is the carrier power. Phase noise is usually represented in units of decibels-to-carrier/hertz, or *dBc/Hz*. The random fluctuations that appear as phase noise in time emerge as a continuous distribution centered at the carrier in the frequency spectrum.

System noise is an important consideration because it sets the limit of the signal level to be detected in its presence. It is a random process that is caused by vibrations of charges (or thermal noise), random fluctuations of charge carriers of active devices (or flicker noise), or any other arbitrary motions of charges or charge carriers. Flicker noise is inversely proportional to frequency, and is often represented as *1/f noise*. Thermal and flicker noise also contribute to the output phase noise of the system and are assumed to be present in the overall output noise in this report.

1.3 TRF372017 Output Noise

The TRF372017 provides linear performance with high dynamic range and low output noise. The total output noise power (N_{OUT}) at RFOUT (the RF SMA connector) of the TRF372017EVM occurs because of the contributions of noise power from the LO phase noise (PN_{LO}), phase noise power injected into the TRF372017 from the IQ BB signals (PN_{BB}), and internally-generated noise power in the modulator (N_{MOD}). Total output noise power can be represented as Equation 7.

$$N_{OUT} = PN_{LO} + PN_{BB} + N_{MOD} \quad (7)$$

It must be noted that the noise plots in Figure 28 to Figure 32 of the TRF372017 data sheet show output noise (N_{OUT}) at different frequencies. This report describes the details of these noise measurements. In the same manner that these figures show, the BB signal considered is a sinusoidal tone of frequency (f_{BB}) at 150 kHz. A low-frequency tone of 150 kHz was chosen to improve the accuracy of noise measurements. BB filters at low frequencies generally have a smaller passband (the passband percentage depends on the center operating frequency). Thus, most of the out-of-band noise can be suppressed.

All the measurements in this report were performed using a PLL in integer mode with a comparison frequency (f_{PFD}) of 1.6 MHz. The LO signal was generated from a 40-MHz, onboard reference crystal oscillator.

2 Measurement Set-up and Procedure

The measurement set-up to determine the TRF372017 output noise is shown in Figure 2. A vector signal analyzer provides differential BB in-phase (BB_I) and quadrature-phase (BB_Q) signals to drive the TRF372017EVM. BB low-pass filters (LPF) were used to eliminate any harmonics and wideband noise present in these signals. The output noise at RFOUT was measured using a signal source analyzer. A tunable RF bandpass filter (BPF) was used at the TRF372017 RF output in order to filter out any RF harmonics. The details of the instruments used are provided in Section 2.1.

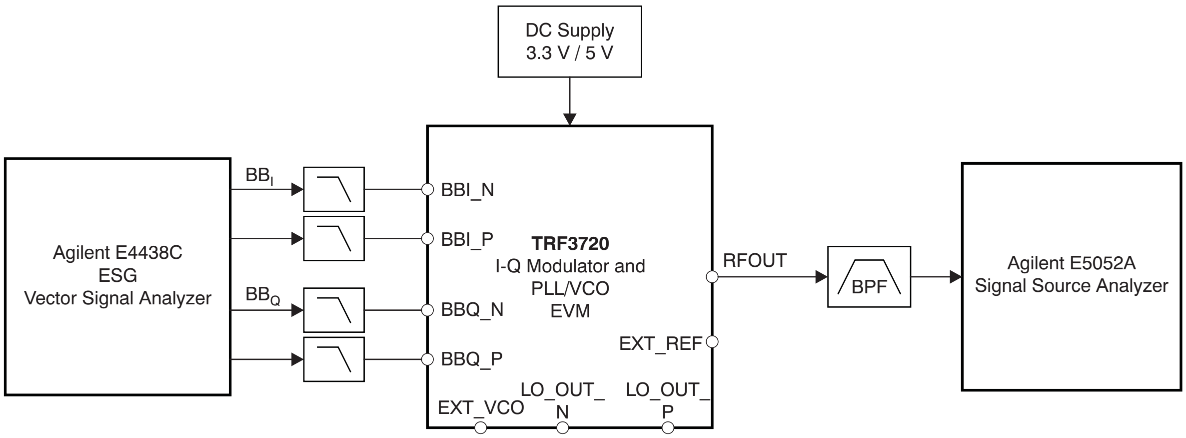


Figure 2. Measurement Set-up to Determine Output Noise

The output power level at RFOUT was varied by the varying BB input power, and the LO power was set at default. The BB input power was varied by changing the attenuation on the vector signal analyzer. An averaging factor of 5 and correlation factor of 100 were used on the signal source analyzer in order to smooth the noise response. Refer to Ref. 2 to follow the operating procedure of the TRF372017EVM. Figure 3 shows a picture of the lab measurement set-up with the BB LPF and RF BPF both in place. The significance of using these filters and a clean supply is described in Section 2.2 through Section 2.4. Figure 28 to Figure 32 of the TRF372017 data sheet were obtained using this configuration after calibrating out losses in the cables and the RF filter connecting the RFOUT SMA connector of the TRF372017EVM to the signal source analyzer input.

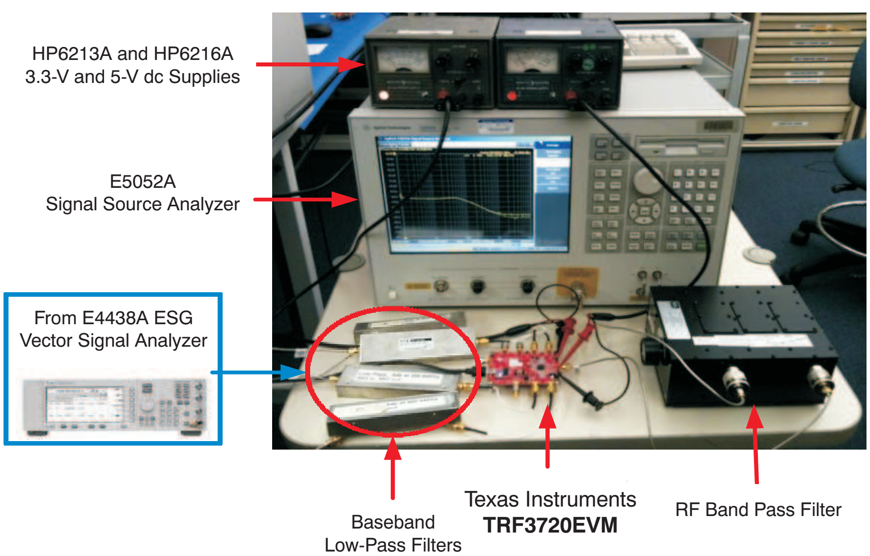


Figure 3. Lab Measurement Set-up

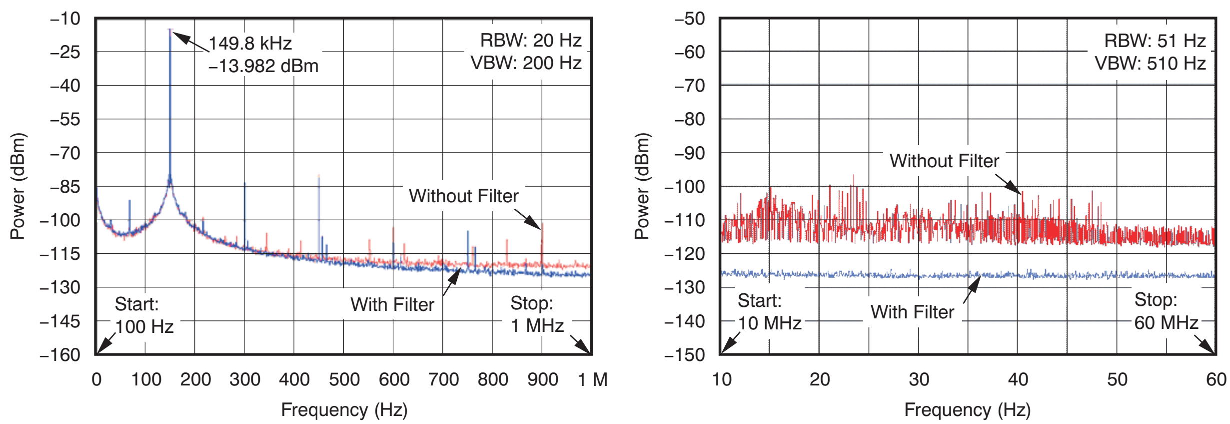
2.1 Instruments and Filters Used

This investigation used these instruments and filter configurations:

- Agilent E4438C ESG Vector Signal Analyzer
- Agilent E5052A Signal Source Analyzer
- HP6213A, HP6216A Linear DC Power Supply
- TTE Inc. LTE1182T-200k-50-750A, 200-kHz four low-pass filters
- Microwave Technologies 3BT-750/1500-5-N/N, 3BT 1000/2000-5-N/N, 3BT-1500/3000-5-N/N. Lorch Microwave 5TF-375/750-5S tunable bandpass filters to cover the RF_{OUT} range of 450 MHz to 3.5 GHz.

2.2 Baseband Low-Pass Filters

It is essential to use clean BB and LO signals for the output noise measurements of any modulator. In the TRF372017, the LO signal is internally generated; this signal has low phase noise and a noise floor. Thus, it is very important to provide a clean BB signal; otherwise, the harmonics and intermodulation products from the generator, along with out-of-band noise, will translate at RF_{OUT} and degrade the accuracy of measurement. Figure 4 demonstrates the importance of a clean BB signal.



(a) In-Band Performance (b) Out-of-Band Performance

Figure 4. 150-kHz Sinusoidal Tone Response with and without Baseband LPFs

Figure 4**(a)** shows the measured spectrum up to 1 MHz of the BB signal with and without a BB LPF. It can be seen that the LPF eliminates the harmonics of 150 kHz to some extent. Figure 4**(b)** shows the out-of-band (approximately 10 MHz to 60 MHz) spectrum of the BB signal with and without a LPF. Here, the LPF rejects the out-of-band noise to a great extent, and the filtered signal noise is at the noise floor of the instrument. Figure 5 shows the output noise measured at RFOUT. It can be seen that the LPF improved the measurement accuracy by approximately 10 dB at 13-MHz offsets.

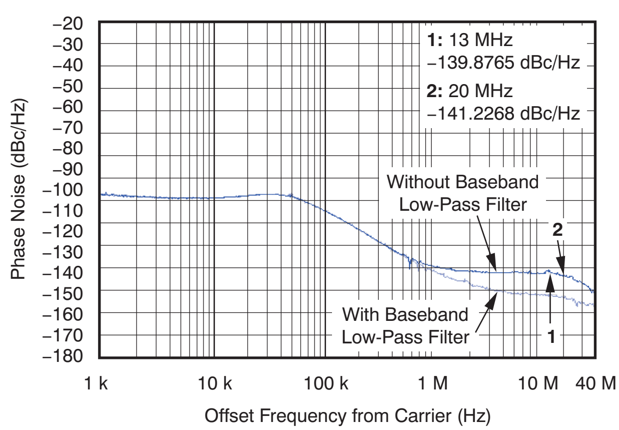


Figure 5. Measured Output Noise with and without Baseband LPF

2.3 RF Bandpass Filter (BPF)

A BPF filter at RF_{OUT} is required in order to suppress the harmonics. Otherwise, the E5052A signal source analyzer does not lock to the carrier in the presence of a strong harmonic because it sees multiple tones.

2.4 Linear Power Supply

It is essential to use a linear supply or regulated supply in order to obtain optimal noise measurements. Figure 6 shows the importance of having low supply noise while using a linear supply and the HPE3631A digital supply.

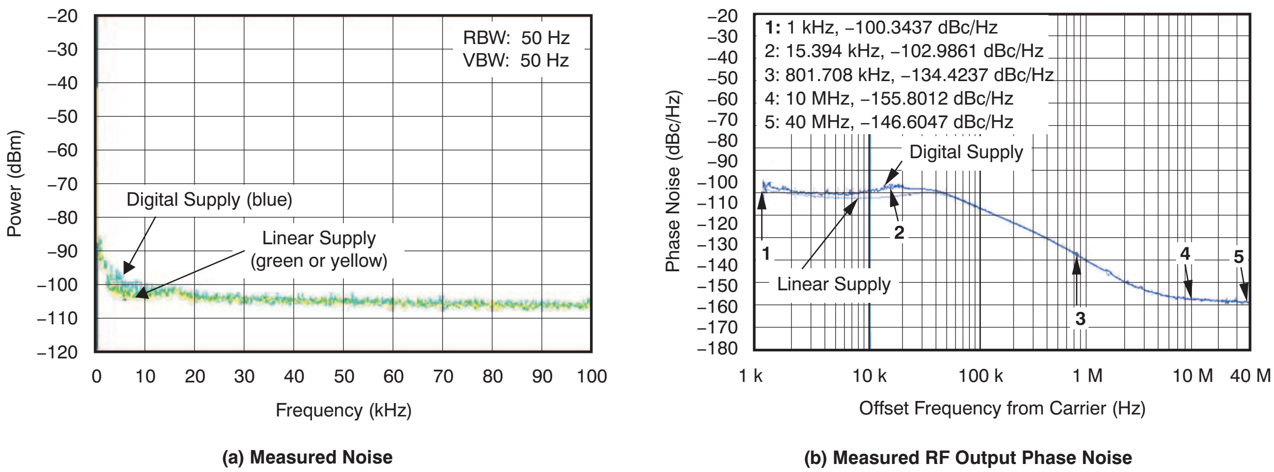


Figure 6. Digital and Linear Supply Performance Comparison

Figure 6**(a)** compares the spectrum of both a digital and a linear supply; it can be seen that the digital supply has a slightly higher noise of approximately 3 dB to 4 dB at approximately 10-kHz offsets. This noise translates at the output carrier near 10-kHz offsets and degrades the in-band output noise measurement accuracy, and is shown in Figure 6**(b)**.

3 Modulator Noise Estimation

This section provides the details of extracting the TRF372017 modulator noise from the measured output noise. In order to lock the TRF372017 at the output desired frequency, a BB input of signal of minimal power (approximately –22 dBm) is required. The modulator noise has been extracted from the output noise at a 13-MHz offset for different output carriers. For each carrier frequency, the output noise is measured by varying the output power. Varying the ESG vector signal generator attenuation approximately from 1 dB to 28 dB changes the RF output power from approximatetly 7 dBm to 20 dBm.

When the phase variations $\Phi_{BB}(t)$ and $\Phi_{LO}(t)$ are small, the total output signal shown in Equation 5 can be re-written as Equation 8.

$$RF_{OUT} = \left[A_{LO}A_{BB}\cos[(\omega_{LO} - \omega_{BB})t]\right] - \left[A_{LO}A_{BB}[\phi_{LO}(t) + \phi_{BB}(t)]\sin[(\omega_{LO} - \omega_{BB})t]\right] \quad (8)$$

Here, the first term in the larger square bracket is the signal content, and the second term (in the larger square bracket) is the noise content from $\Phi_{BB}(t)$ and $\Phi_{LO}(t)$ variations, which are modulated by a carrier 90 degrees out-of-phase from the actual carrier. Equation 7 can be separated into output signal power (P_{OUT}) and output phase noise power (PN_{OUT}), in terms of BB and LO inputs, as Equation 9 and then Equation 10.

$$P_{OUT} \alpha (A_{LO}A_{BB})^2 \quad (9)$$

$$PN_{OUT} \alpha [A_{LO}A_{BB}\phi_{LO}(t)]^2 + [A_{LO}A_{BB}\phi_{BB}(t)]^2 = PN_{LO} + PN_{BB} \quad (10)$$

Assuming the modulator noise (N_{MOD}) is constant with regards to the input power, a constant term could be added to PN_{OUT} to obtain the total output noise (N_{OUT}), as Equation 11 shows:

$$N_{OUT} = PN_{OUT} + N_{MOD} = PN_{LO} + PN_{BB} + N_{MOD} \quad (11)$$

As the modulator noise is estimated at 13-MHz offset, the baseband noise variations $\Phi_{BB}(t)$ (at the output of the BB low-pass filter) can be assumed to be small ($PN_{BB} \approx 0$). Thus, the total output noise can be considered as the result of Equation 12.

$$N_{OUT} = PN_{OUT} + N_{MOD} \sim PN_{LO} + N_{MOD} \quad (12)$$

From Equation 12, it can be concluded that N_{OUT} consists of two terms: the first term PN_{LO} ($\approx PN_{OUT}$) increases dB-to-dB with an increase in input power, and the second term N_{MOD}, which is constant with the input power. It could also be concluded that at lower input powers (or output powers), PN_{LO} is negligible, and the total output noise is dominated by N_{MOD}.

Figure 7 shows the output noise versus output power from approximately –16 dBm to approximately 9 dBm at 13-MHz offsets for RF carrier frequencies 450 MHz, 750 MHz, 900 MHz, 2140 MHz, 2700 MHz, and 3500 MHz. Figure 7 is the same as Figure 32 in Ref. 1. It can be seen that at higher output powers, N_{OUT} is dominated by PN_{LO} noise, which increases linearly with input power and at lower output powers; N_{OUT}, on the other hand, is dominated by the constant N_{MOD}.

Thus, using these conclusions, both PN_{LO} and N_{MOD} can be estimated. Figure 8 shows the estimated PN_{LO} and N_{MOD} along with the measured output noise for a 900-MHz carrier signal at 13-MHz offset. At a 900-MHz carrier signal, a PN_{LO} of approximately –156.5 dBc/Hz and an N_{MOD} of approximately –161 dBm/Hz is estimated.

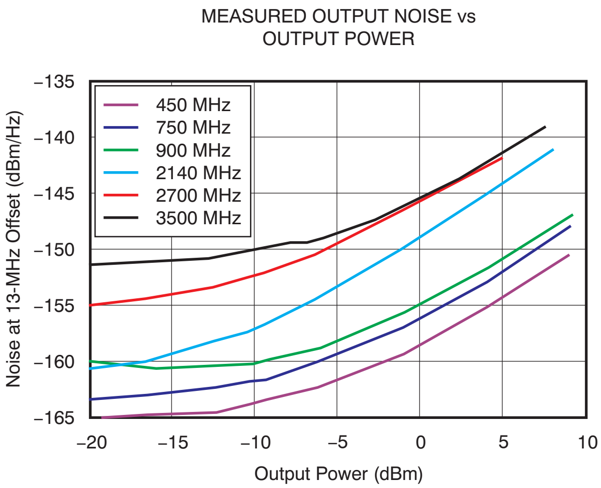


Figure 7. Measured Output Noise vs Output Power at 13-MHz Offset

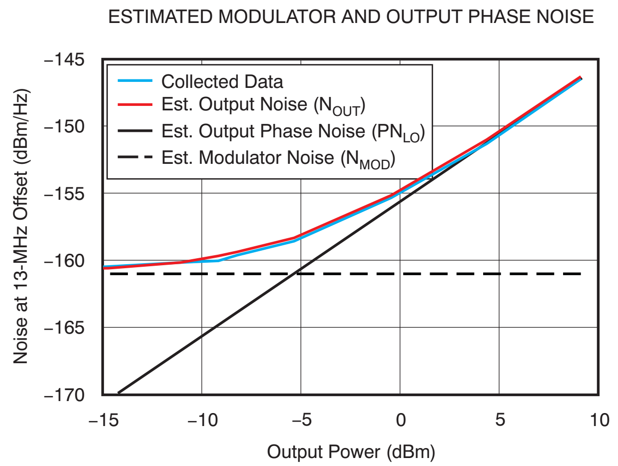


Figure 8. Estimated Modulator and Output Phase Noise for 900-MHz RF at 13-MHz Offset

Figure 9 shows the modulator noise estimated for different carrier frequencies at a 13-MHz offset. It can be observed that the TRF372017 estimated modulator noise increases from –165 dBm/Hz at 450 MHz to 152.5 dBm/Hz at 3500 MHz.

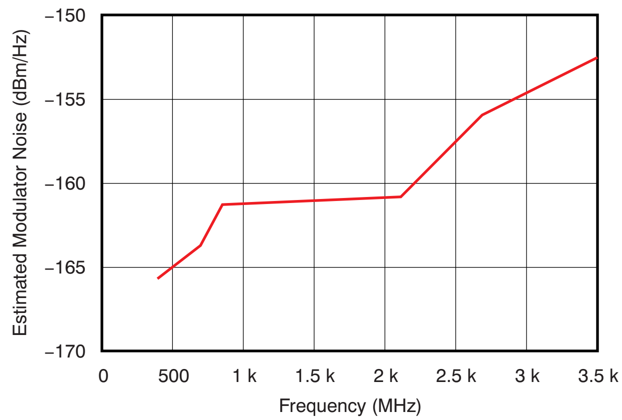


Figure 9. Estimated Modulator Noise (N_{MOD}) at 13-MHz Offset Across Different Carrier Frequencies

4 Summary

A noise analysis of the TRF372017 is provided along with the experimental set-up used to obtain the output noise plots in the product data sheet. The significance of using a baseband low-pass filter and an RF bandpass filter in noise measurements is shown. The estimation of modulator noise from the measured output noise is discussed.

5 References

1. TRF372017 Integrated IQ Modulator PLL/VCO product data sheet. Literature number SLWS224. Available for download at www.ti.com.
2. TRF372017 Evaluation Module user guide. Literature number SLWU068. Available for download at www.ti.com.
3. Pozar, D. (2004.) *Microwave engineering*. New York: Wiley & Sons, Inc.

Revision History

Changes from Original (March, 2011) to A Revision	Page
• Corrected units in Figure 9	8

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

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