IMS2012 STUDENT DESIGN COMPETITION WINNER

LSNA Round-Robin Measurement Artifact

Development of a Large-Signal-Network-Analyzer Round-Robin Artifact

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There is an ever-increasing demand of high-efficiency and wideband microwave components and devices for wireless communication and sensing applications. However, this tendency generally pushes the devices forward to operate from linear to nonlinear regions of operation. Therefore, there is a requirement of an accurate measurement strategy to extract the nonlinear parameters of devices [1]. A large-signal-network-analyzer (LSNA) is a typical example of such measurement instruments for accurate modeling and characterization of the nonlinear properties of circuits and devices [2]–[3]. LSNAs measure the relative dependence of both magnitude and phase between different orders of harmonics (including the fundamental signal) that are generated by the nonlinearity of a circuit. Such a nonlinear model renders the circuit and system design process efficient and predictable. However, the accuracy of the nonlinear parameters strongly depends on the measurement accuracy of the LSNA itself. Therefore, the accuracy of the LSNA has to be checked and verified prior to performing the measurement of a nonlinear device.

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The objective of the inaugural LSNA Round-Robin Artifact Student Design Competition during the 2012 IEEE International Microwave Symposium (IMS2012) that was held in Montreal, Canada, supported by the Microwave Measurement Technical Committee of the IEEE Microwave Theory and Techniques Society (MTT-S), was to develop an artifact to complement an upcoming LSNA international round-robin between measurement facilities. This round-robin aims to verify that measurements made with different LSNAs in different laboratories yield the same results independent of measurement setups. For this purpose, a set of calibration standards and verification elements will be circulated between various laboratories. The proposed round-robin includes a calibrated power meter, a phase reference, and scattering-parameter calibration artifacts that are all precisely characterized at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. The proposed artifact is designed as one of the verification elements to confirm that an LSNA is able to provide correct harmonic measurement results. In the past, diodes with carefully measured characteristics have been used for this purpose. However, the diode's output impedances at fundamental and harmonic frequencies are sensitive to any temperature variations.

As from one measurement setup to another, the output impedances at the fundamental and harmonic frequencies may vary greatly; it is of primordial importance to propose a round-robin artifact that will not be sensitive to the output impedance.

Design Specifications and Goals

This Student Design Competition is intended to develop a two-port round-robin device that has rich nonlinear contents. The circuit is driven into the nonlinear region by a single-tone signal at $f_0 = 2$ GHz such that the output signal contains at least five measurable harmonics at frequencies nf_0, where $n = 1,2,3,4,5$, respectively. The output fundamental and harmonic components of the device should be insensitive to any change of the load reflection coefficient represented by Γ. In order to evaluate the two-port round-robin device, three different load reflection coefficients Γ_m (chosen by the judges at IMS2012) are presented to its output port, where $m = 1,2,3$ and the corresponding output phasors $b(nf_o, \Gamma_m)$ are measured. A standard deviation value as shown in the following formula is used to verify the performance of the device:

$$\sigma = \sqrt{\sum_{m=1}^{3} \sum_{n=1}^{5} \frac{|b(nf_0, \Gamma_m) - \bar{b}(nf_0)|^2}{|\bar{b}(nf_0)|^2}}, \quad (1)$$

where, $\bar{b} = \frac{1}{3}\sum_{m=1}^{3} b(nf_0, \Gamma_m)$. The target of the design is to keep the value of σ as small as possible. The smaller the value of σ, the better the isolation of the nonlinear device is from the variable load Γ_m, The incident power for the test has to be between –10 dBm and +10 dBm. The power level of the output signal and its harmonics should be sufficiently high to be measurable by the LSNA.

Design Preparation

This topic was included in the design competition for the first time, therefore no previous work is available for

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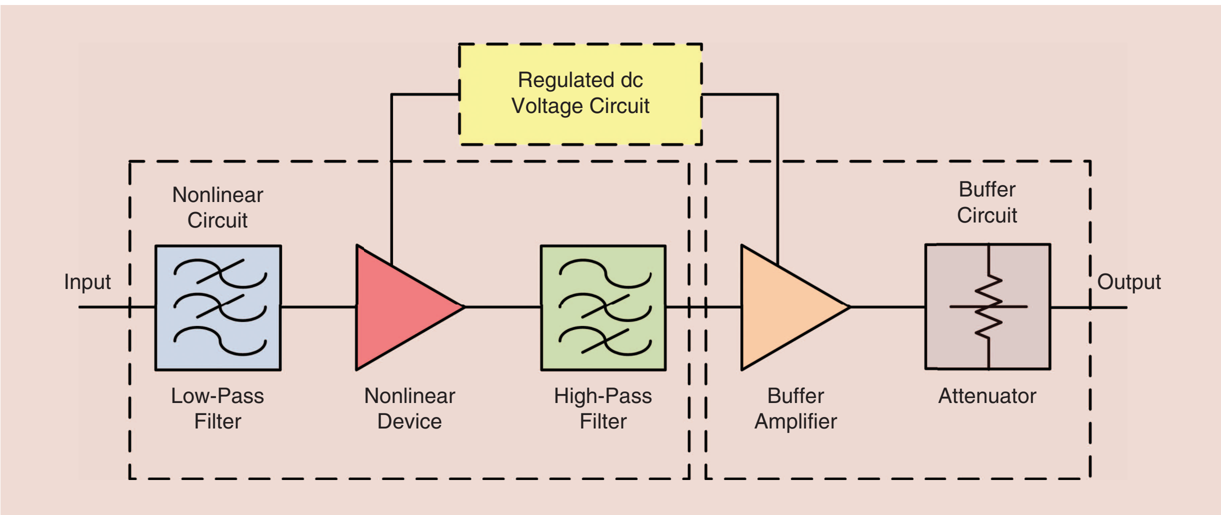

Figure 1. *Block diagram of the proposed round-robin artifact.*

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reference. After an in-depth analysis of the competition rules and consideration of different design approaches, the problem was divided into two parts, the generation of a nonlinear signal and the desensitization of the artifact relative to the output load. So the proposed design consists of two circuits, a nonlinear circuit and a buffering circuit. Also, considering the instrumental objective of the artifact, the electromagnetic interference (EMI) issues have to be taken into consideration. For this reason, a third circuit is implemented to stabilize the dc voltages supplied to the active circuits, and a shielding casing is used.

The first step of the project was to design a circuit rich in harmonics. The second step was to design a second stage isolating the first stage and amplifying the signal to obtain a harmonic level around 0 dBm at the output for an accurate measurement using the LSNA. The gain of this second stage can be obtained considering a budget link of the overall circuit. The third step consisted in designing the dc voltage supply and shielding casing.

Proposed Design

In Figure 1, a block diagram of the designed round-robin device is presented. It is a two-port network, which consists of three circuits: 1) a nonlinear circuit consisting of a low-pass filter, a device which is rich in nonlinear content and a high pass filter; 2) an output circuit consisting of a buffer amplifier and an attenuator for the isolation purpose; and 3) a dc voltage regulation circuit.

Nonlinear Circuit

This circuit is designed to generate the required harmonics. It is designed separately without considering issues due to the sensitivity of the output load. This circuit is based on an amplifier driven into its nonlinear region consisting of a low-pass filter at its input and a high-pass filter at its output. The bias of the amplifier was made tunable in order to optimize the level of harmonics. The nonlinear model of the nonlinear device was not available to the authors. The optimal input power level and bias was obtained by measurement.

Low-Pass Filter

As can be seen from Figure 1, the low-pass filter is placed in the beginning of the design chain. Its main function is to block any leakage of higher-order harmonics generated by the nonlinear device from entering into the input port. The low-pass filter selected for the design is from TDK DEA162700LT-5014A1, which has a 3 dB corner frequency of approximately 3.8 GHz.

Nonlinear Device

A monolithic InGaP HBT MMIC Amplifier from Mini-Circuits Gali-39 is selected as a nonlinear device to

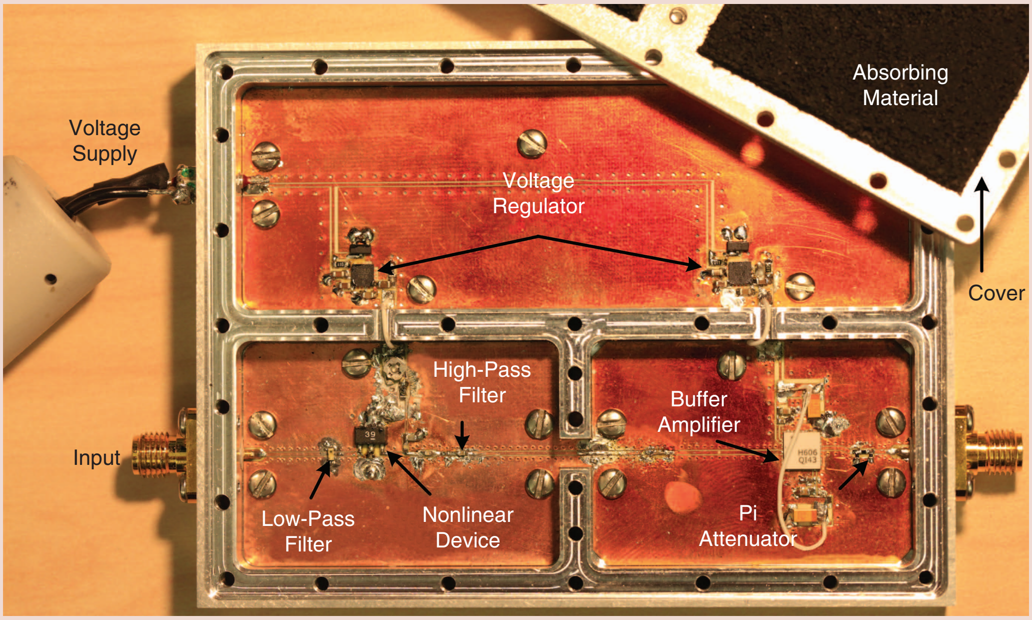

Figure 2. *The fabricated round-robin-artifact.*

verify the performance of the LSNA. When driven into the nonlinear region, Gali-39 is capable of producing an output that is rich in measurable nonlinear content. The typical gain of Gali-39 at 2 GHz is 19.7 dB, and the maximum output power at 1 dB compression point is 10.5 dBm, thus requiring only –9.2 dBm of input power to drive the device into its nonlinear regime.

High-Pass Filter

The output signal generated by the nonlinear device contains signals at frequencies nf_0, where $n = 1,2,3 \ldots$. Usually, the strength of the signal at the fundamental frequency f_0 is much higher than the corresponding harmonics. In order to measure the strength of the harmonics precisely, it is desirable to make the levels of the fundamental and its harmonics as close as possible. Therefore, the cut-off frequency of the high-pass filter is selected in such a way that the signal at the fundamental is attenuated and the corresponding harmonics fall into the pass band of the filter. This is also equivalent to creating a mismatch condition for the fundamental signal f_0, where the reflected signal will drive the device into further nonlinearity, thereby increasing the strength of the output harmonics. Thus, the high-pass filter has basically two functions: first is to reduce the strength of the signal at the fundamental frequency f_0, and second is to boost the strength of the harmonics in order to bring their signal power close to the fundamental signal power. The high-pass filter operation is obtained by connecting two 0.4 pF capacitors in series. The capacitors used in the design are ceramic surface mount UQCL2A0R4BAT2A capacitors from AVX Corporation.

Buffer Circuit

The second step of the design was to design an output circuit that isolates the nonlinear device from the output load and amplifies the generated signal to obtain a sufficiently high-level signal. The isolation provided by this second stage is given by the wideband buffer amplifier and the attenuator.

Isolation Wideband Buffer Amplifier

In Figure 1, a wideband buffer amplifier is connected to isolate the nonlinear circuit from the load connected at the output-port of the round-robin device. The buffer amplifier used in the design is HMC606LC5 from Hittite Microwave Corporation. The device is a gain-block with matched 50 Ω input and output impedances.

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The amplifier has an approximate gain of 13 dBm at 2 GHz. The device output 1 dB compression point is at +15 dBm. It is necessary to maintain this device well below the nonlinear region of operation in order not to overlap the harmonics generated by the Gali-39. It is found by measurement that the buffer amplifier is not sufficiently insensitive to the output load, therefore the use of an attenuator is necessary after the amplifier.

π-Attenuator

The final part of the design block diagram in Figure 1 is a fixed 6 dB attenuator. The attenuator is designed is a π-network built by a suitable combination of resistors. The attenuator reduces the total power of the incoming signal without distorting its waveform. It is a reciprocal device, which offers the same level of attenuation for the signals travelling in both directions. Therefore, any reflected signal produced due to the mismatch is further attenuated before it reaches the device`s input port. Thus, its main function is to

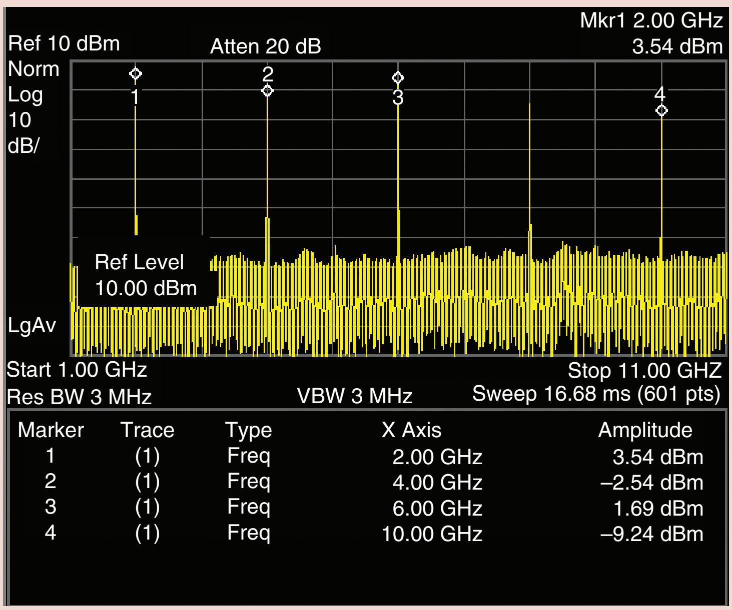

Figure 3. *The measured spectrum of the proposed round-robin artifact with a single-tone 2 GHz / +10 dBm input signal.*

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improve the matching condition between the input and output port of a device for any changes in value of the terminated load.

Regulated dc Voltage Circuits

To avoid interference noise coming in the supplied voltages to interfere with the LSNA measurement, each active device is powered by a voltage regulator HMC860LP3E from Hittite Microwave Corporation. Also, a coaxial cable and an EMI ferrite are used to avoid noise coming from the voltage supply cable.

Figure 2 illustrates the fabricated round-robin artifact that is fabricated on Rogers RT/duroid 4350 B substrate, having a permittivity of $\epsilon_r = 3.48$. The thickness of the substrate is 10 mils. As can be seen from Figure 2, the circuit is accommodated inside a metal box consisting of three cavities in order to avoid the effects of external and internal interferences. A metal housing is designed to cover the circuit. In order to avoid unwanted resonance effect produced due to the cavities, absorbing materials from Emerson & Cuming Microwave Products are attached on the cover. A common dc bias is used to supply the power for both nonlinear (Gali-39) and wideband buffer (HMC606LC5) amplifiers. Since the Gali-39 requires less biasing voltage compared to the HMC606LC5 amplifier, a variable resistor is used for Gali-39 to control its input bias voltage and therefore tune its nonlinear properties.

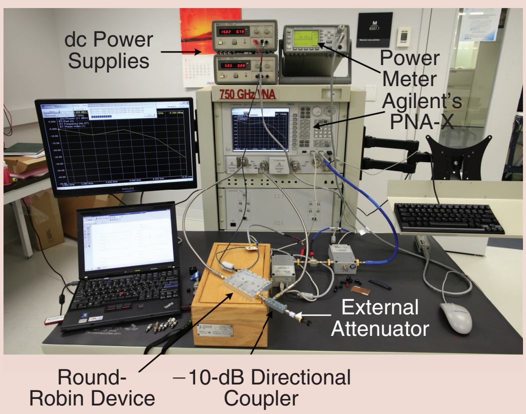

Figure 4. *The measurement set-up of the proposed round-robin artifact using Agilent's PNA-X network analyzer.*

Measurement Results

The measurement of the round-robin device consisted of two steps. The first step consisted of tuning the Gali-39 polarization voltage to obtain the desired nonlinear signal using a spectrum analyzer. Once the desired signal was obtained, a nonlinear vector network analyzer (NVNA) was used in order to characterize the nonlinear properties of the round-robin artifact when terminated with different loads from the measurement of the X-Parameters.

Output Spectrum Measurement

In Figure 3, a measured output spectrum of the round-robin device is displayed. An SMIQ signal generator from Rohde & Schwartz generating a sinusoidal signal at 2 GHz with the input power level of +10 dBm is connected at the input of the device. The output of the device is connected to an Agilent's E4440A spectrum analyzer. The signals at the fundamental frequency and its harmonics are clearly visible and measurable. Between the fundamental signal and the harmonics, there are no significant differences in output power values. It can be seen that the fundamental signal power is at 3.54 dBm while the output power of the fifth harmonic is at –9.24 dBm. Hence, the maximum difference between the two power levels is approximately equal to 12.78 dB. As explained in the previous section, the output power spectrum of Figure 3 is achieved after a careful design of the high-pass filter, the buffer amplifier, and the attenuator.

As illustrated in Figure 3, the measured spectrum of the round-robin device using the spectrum analyzer only provides the magnitude of the output power in dBm. It does not contain any phase information of the fundamental signal and the harmonics. Therefore, based only on Figure 3, it is not possible to

TABLE 1. Measurement data of the round-robin device using PNA-X.

$b(nf_0, \Gamma_m)$	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$
$m = 1$	0.00216–0.00142i	–0.0072+0.00128i	–0.00147+0.0015i	0.00083–0.00019i	0.00010+0.00011i
$m = 2$	0.00217–0.00143i	–0.0073+0.00129i	–0.00149+0.0015i	0.00084–0.0002i	0.00011+0.00011i
$m = 3$	0.00216–0.00143i	–0.0073+0.00129i	–0.00149+0.0015i	0.00083–0.00019i	0.00012+0.00012i

obtain the circuit's harmonic output phasor $b(nf_0, \Gamma_m)$ values in order to calculate the standard deviation σ as given by (1).

Measurement of the Output Phasors Under Different Loading Conditions

In Figure 4, a measurement setup of a round-robin artifact using Agilent's N5247A PNA-X NVNA is presented. As mentioned previously, the device's nonlinear behavior cannot be fully characterized by using standard spectrum analyzers. The PNA-X series network analyzer as illustrated in Figure 4 is capable of accurately measuring the nonlinear behavior of the device under test. It is capable of measuring not only the amplitude of the signal but also its phase information.

The measurement setup consists of the round-robin device whose input is connected to the Port-1 of the PNA-X and its output is connected to the incident port of a –10 dB coupler. At the through port of the coupler, a shorted attenuator is connected and at the Port-2 of the PNA-X the coupling port of the directional coupler is connected to the Port-2 of the PNA-X. Different output loading conditions are created by changing the values of the attenuator connected at the output of the coupler. For example, a 1.5 dB attenuator that is short-circuited produces a load reflection coefficient value of 0.5. With this setup, measurements were performed for three different cases of the output load. In the first two cases, attenuator values of 10 dB and 16 dB were connected at the through port of the coupler, which was further terminated by a broadband short termination. The output travelling waves $b(nf_0, \Gamma_m)$ at the fundamental and its harmonic frequencies have the dimension of the square root of power.

In the third case, a broadband 50 Ω load was directly connected at the output terminal of the coupler. The input power of the PNA-X was set to +11 dBm, and corresponding phasor values of five harmonics for three different cases of the output loading were measured. For a better matching condition, a 16-dB attenuator was connected at the output port of the round-robin device. In Table 1, the measured phasor values for various loading conditions Γ_m and harmonic values nf_0 are listed. After substituting the data presented in Table 1 into (1), the value of standard deviation σ is calculated to be 0.083. The value of σ measured in the IMS design competition was 0.0062 for the same round-robin device. The difference between the two results is due to the difference of the actual load impedance used in IMS and our measurement. In our measurement, a bidirectional coupler and attenuators were used, but this approach of generating different loading conditions is rough. In order to obtain a precise load impedance and repeatable results, an electric tuner would have been more suitable.

Thanks to a high output signal level at the fundamental and harmonics, a high-value attenuator can be used to efficiently isolate the artifact from the load and still obtain a sufficiently high output signal for accurate measurement with an LSNA.

Conclusions

This article presents the design and measurement results of the contest-winning LSNA round-robin artifact. The proposed two-port device was designed with respect to the objective of complementing an upcoming LSNA international round-robin between measurement facilities. The proposed device consists of three parts, a nonlinear circuit generating the required five harmonics based on a monolithic InGaP HBT MMIC amplifier, an output circuits based on a wideband amplifier and attenuator, which role is to amplify the signal generated by the nonlinear device and isolate the nonlinear device from the output load, and finally, a stabilized dc supply circuit based on voltage regulator chips typically used for instrumentation. To avoid noise interfering with the measurement, EMI considerations were taken into account. The overall device is shielded within a casing composed of three cavities to isolate each circuit. This casing also helps as a heat sink to stabilize the artifact in temperature. The proposed device is validated by measurements. Thanks to a high output signal level at the fundamental and harmonics, a high-value attenuator can be used to efficiently isolate the artifact from the load and still obtain a sufficiently high output signal for accurate measurement with an LSNA.

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