Computer-Aided Engineering of RF Circuits with LINC2 System and Circuit Simulation

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(all figures are at end of article)

"The engineering profession applies the principles of mathematics, science, economics, ethics, and social sciences to use the materials and forces of nature for the benefit of mankind."[1]

This description of the engineering profession, prefacing the undergraduate curriculum in a recent bulletin of the school of engineering for a university in the west, elucidates the fact that those employed in the engineering profession are engaged in service for society for the benefit of humanity.

Thus, we would expect to find not only engineers but the tools they use to be employed in businesses, government and private practice of every kind to produce the products and services that we all have come to enjoy and in many cases to depend on. This article will explore this concept as it relates to how RF engineering software is making contributions to the field and consequently to society. We will review a small portion of the many ways and places the LINC2 RF/microwave design and simulation software has been used, looking back over the nearly quarter century since its inception. Then we will present a working design example to illustrate how the LINC2 suite of software tools can automate the circuit design process.

In Education: Over the past two and a half decades, the LINC2 design, synthesis and simulation software from ACS (Applied Computational Sciences) has been employed by students and educators in colleges and universities around the globe. A sampling of these include Johns Hopkins University APL (Applied Physics Lab), Laurel, Maryland; Georgia Tech, Atlanta, Georgia; Virginia Tech, Blacksburg, Virginia ; Max Planck Institute for Radio Astronomy in Bonn, Germany; Hanbat National University, Republic of Korea; Humber Institute of Technology, Toronto, Ontario, Canada; San Diego State University, and many more.

In Government: The LINC2 circuit design, synthesis and simulation software has been used in a number of government institutions across the country, from NAVAIR at Point Mugu, California to the NRL (Naval Research Laboratory) in Washington, DC. LINC2 has also found employment at the national laboratories, including Oak Ridge National Laboratory, Sandia National Laboratories and Lawrence Livermore National Laboratory. Spacecraft engineers also find the LINC2 software helpful in designing spacecraft at the NASA Glenn Research Center, Cleveland, Ohio and NASA JPL (Jet Propulsion Laboratory) in Pasadena, California.

In Industry: Far too numerous to mention are the many small businesses whose owners have found that with LINC2 they can save thousands of dollars on the purchase of RF and microwave circuit design software without compromising on the features and capabilities that they need. Large businesses are not insensitive to cost either and scores of large businesses have purchased the LINC2 software to supplement the CAE (computer aided engineering) software licenses that they already own. Large corporations that have incorporated LINC2 into their design processes represent nearly all sectors of industry, from aerospace, medical and bioengineering to consumer electronics of every kind and the cellular telephone industry.

Medicine and Drugs: For more than a decade LINC2 has been used in medical research, particularly in detection systems. For example, "NMR [Nuclear Magnetic Resonance Spectroscopy] is one of the most information-rich forms of biochemical, chemical, and molecular detection and analysis, and remains highly utilized in a wide range of health-related industries, including pharmaceutical research and drug discovery."[2] As early as December 1 of the year 2000, patent applications were being filed citing LINC2 as the RF software package employed to guide the design of these NMR detection probes which use small RF "microcoils." According to the patent filing, "Circuit modeling, e.g., using a commercial RF package such as Linc2 available from Applied Computational Sciences (Escondido, Calif.) can be employed to help guide the design" of these RF microcoils and their associated impedance matching networks, enabling "individual optimization of RF coil sensitivity to different nuclei (1H, 1H{15N}, 1H{13C}, etc.)."[3]

Next we present a textbook example, literally, of one way the LINC2 software might be employed to guide the design of the front end of an RF receiver. The following design example closely follows the problem worked out in Example 7.1 – Spur Levels in the book "Practical RF System Design" by W. F. Egan.[4]

Receiver Front End Example
A spurious response (or spur) in a communications receiver occurs when a signal is present at the output which is not a direct response to the desired input signal that the receiver is tuned to. Spurious responses can interfere with the desired reception. Moreover, there are many ways spurs can be generated, and their source can be both external (e.g., image, IF and half-IF) and internal (e.g., m x LO mixing with n x RF at the mixer or harmonics of digital/clock signals coupling into the RX path). To keep the presentation short and simple, this article will focus on the production of m(LO) x n(RF) spurs, how to analyze them and ultimately eliminate or reject them.

It is required that a particular receiver be designed to receive signals with levels from -80 dBm to a maximum of -15 dBm at 1200.2 MHz. Additional requirements specify a 10 dB signal-to-spur ratio such that the maximum allowed spur referred to the input is -90 dBm (10 dB below the weakest desired signal). This requires any in-band spur to be 75 dB below the maximum (-15 dBm) input level.

Working out a solution to these requirements is a task for the LINC2 Visual System Architect (VSA), a system level simulator from ACS that includes spur analysis as well as cascade budget analysis. At this point we employ the system simulator (**Figure 1**) because we are interested in the accumulated effect of every system component on gain, linearity (which relates to the creation of spurs and their levels) and noise figure (NF), etc. The system simulator will show us what these parameters (gain, linearity/P1dB/IP3, NF, etc.) need to be at each stage, and this information can be used to design the physical circuit (e.g., low noise amplifier stage).

The LINC2 VSA (Visual System Architect) schematic is opened by selecting "System Design" from the LINC2 Tools menu as shown in **Figure 1**. The components pertinent to this analysis are shown entered into the VSA schematic in **Figure 2**.

The initial design starts with an IF at 2000 MHz by employing an LO of 799.8 MHz. If a spur is present, it will be strongest at the maximum RF input level, so we start with a signal level of -15 dBm at the input port and check the spur level in the 2000 MHz IF region.

Clicking Analyze and View > Spectrum Analysis yields the IF spectrum shown in **Figure 3**. From the VSA IF spectrum simulation (**Figure 3**), we see that there is a 2X3 spur (3*RF – 2*LO = 2001 MHz) identified by marker 2 appearing at a level 69 dB below the desired signal (marker 1). This worst case signal to spur ratio of 69 dB is 6 dB short of the 75 dB requirement. The deficiency is related to the mixer's non-linearity. The mixer could be replaced by another with better spur performance (at least for the 2X3 spur) or a mixer with a higher LO power rating could be used.

There are a couple of things that can be done without replacing the mixer. First, we can reduce the gain ahead of the mixer until the offending 2X3 spur is reduced another 6 dB relative to the desired signal. Secondly, we can choose another IF frequency (by changing the LO frequency) to place the IF in a spur –free region. We investigate the first option next.

Option 1: Reduce the front end amplifier gain until the signal to spur ratio is improved by 6 dB.

We can change the amplifier gain from the Spectrum Graph Tune menu by selecting Tune > AMP1, Gain. Then tap the down arrow key until the gain reduction yields the desired signal to spur ratio of 75 dB. This occurs when the amplifier gain is 2 dB as shown in **Figure 4.** (For simplicity, the gain of AMP1 represents the net gain of all components prior to the mixer).

We can now select Update Schematic from the Tune menu and rerun the simulation with this new gain value (2 dB) to see the effects on other system parameters through to the mixer output. With the schematic updated (for AMP1 Gain, Ga = 2 dB), we select Set > Output to add Gain and Noise Figure (NF) measurements. Clicking Analyze and View > Cascade Budget Analysis yields the results shown in the graph of **Figure 5**.

With the gain at only 2 dB ahead of a mixer that has a 10 dB conversion loss, there is not enough gain in the LNA (first stage) to hold the NF at 1 dB and thus it rises rapidly through the mixer to a total of 8.4 dB at the output. This would normally be an unacceptable result. Thus we turn to option 2; locating a spur-free region for the IF so that we can increase the gain to improve noise figure without incurring the consequences of increased spur level.

Option 2: Choose an LO frequency that places the IF in a spur-free region.

A most invaluable feature of the LINC2 VSA simulator is the ability to change the local oscillator (LO) frequency in Tune mode, interactively, while simultaneously observing all the resultant signals and spurs in a spectrum analyzer window. As the LO is moved, the IF moves, continuously providing new opportunities for a spur-free IF. With the LINC2 Visual System Architect (VSA) this can be done visually and interactively in real time.

First, the LNA (AMP1) gain is increased to 15 dB to bring the NF down. Then the LO is tuned while observing the IF move through regions of more or less spurs until we arrive at an acceptable IF that is relatively free of spurs. This is the case for an IF on the low side of an 1100.2 MHz LO as shown in **Figure 6** (**Figure 6** shows the spectral results for a maximum input signal of -15 dBm using an 1100.2 MHz LO).

By not defining an IF bandwidth (**Figure 2** does not include an IF filter), the problem has been kept general so far. Consequentially, we can see from the expanded IF region (lower Spectrum Graph in **Figure 6**) that there are no spurs in any potential IF bandwidth less than 200 MHz wide (<100 MHz either side of the 100 MHz IF center frequency). The nearest spur, 100 MHz above the IF, is approximately 65 dB below the maximum IF signal (**Figure 6**). This is a vast improvement over the previous IF (at 2.0 GHz) which had a significant spur only 1 MHz away from the IF center (**Figure 3**). However, the -65 dBc spur is 10 dB short of the requirement. But this is now very easy to remedy with an IF filter. As shown in **Figure 7**, we can add a simple 30 dB (rejection) band-pass filter after the mixer and get nearly 20 dB of margin (minus the filter loss).

With the addition of the IF filter, the spur at 200 MHz drops to -94 dBc as shown in **Figure 8**. This provides 19 dB of margin to the -75 dBc requirement. And whereas the noise figure was 8.4 dB using the IF of option 1 (**Figure 5**), this IF scheme improves the noise figure to very nearly 2 dB as shown in **Figure 9**.

The frequency plan (LO and IF selection) corresponding to a satisfactory gain, NF and spur budget is now complete. The detailed circuit design of the LNA can now commence.

LNA (Low Noise Amplifier) Design Example
In the process of employing the LINC2 VSA system simulator to select a workable frequency plan, and work out other system level requirements, the software is also developing the stage-by-stage requirements that can be used to direct the low level circuit design of each stage in the RF chain. The low noise amplifier (AMP1) in **Figure 7** met all our stated requirements so we can use it, and the parameters attached to it, as specifications for the next phase of the design—the low level circuit design.

From **Figure 7** the candidate transistor must have a minimum noise figure, Fmin, less than 1 dB with an associated gain of approximately 15 dB. Regarding linearity, the device will have an input P1dB = 0 dBm and an input third order intercept point IIP3 = +9.64 dBm.

LINC2 LNA design is started by selecting "Amplifier Design > Low Noise Amplifier" from the Tools menu. Loading the s-parameters, including embedded noise parameters, for the NESG2021 candidate device into the LINC2 LNA design tool and selecting the operating frequency opens the LNA design environment shown in **Figure 10**.

The Circles utility of **Figure 10** indicates that the selected NPN SiGe transistor is potentially unstable at the 1200 MHz operating frequency. This is evident by stability circles that are displayed intersecting the Smith Chart in both the input and output planes. There are at least a dozen methods for LNA design or analysis included in the LINC2 LNA Circles utility, including one devoted entirely to device stability analysis and remedial solutions.

The LINC2 Circles utility can automatically stabilize the potential instability of the device or transistor by employing the user's choice of several methods. For this example a 240 Ohm load resistor is inserted in series with the output terminal. This action stabilizes the transistor and drops the gain from a potentially unstable excess of 22.8 dB (**Figure 10**) to an unconditionally stable 15.24 dB (**Figure 11**). As will soon be shown, 15.24 dB of gain will be just enough to account for the anticipated loss in the input and output matching networks and still meet our 15 dB requirements for the completed LNA.

Designing a low noise amplifier at the transistor level often involves the application of an intentional mismatch at the input in order to present the transistor with the optimal source impedance for minimum noise, Fmin. This "noise match" reduces the gain available from the overall amplifier. There may be additional reasons why a "noise match" that incurs a conjugate mismatch, may be undesirable (from an external or system point of view). Thus, LINC2 LNA design provides alternative design methods for automating various trade-offs between gain, noise figure and input, as well as output or return loss. For this example, the optimum noise match was selected (**Figure 11**).

Selecting "Transmission Line > Stub and TRL Cascade" from the Match menu automatically synthesizes the RF LNA schematic shown in **Figure 12** with ideal series and shunt transmission lines. The initial synthesized circuit schematic is immediately ready to analyze to verify the amplifier's performance (by simply clicking "Analyze"). Simulating the circuit with ideal transmission lines will give a very good indication of the amplifier's performance. But the transmission lines are electrical models (characteristic impedance, Z0, and electrical length in degrees, etc.) and we cannot directly lay out the printed circuit board with electrical models; we need physical microstrip models. Fortunately, LINC2 can automatically convert all the transmission lines in the circuit schematic to microstrip or stripline in a single step.

Clicking "Auto > Convert T-Lines To…> Microstrip" pops up a substrate definition dialog box for specifying the board material. For this example, Rogers RT/duroid® 6010LM 25 mil laminate is selected. Immediately the microstrip circuit of **Figure 13** is created. All the transmission lines in the initial LNA circuit of **Figure 12** are automatically converted to the microstrip circuit of **Figure 13** while shunt stubs TL1 and TL4 are here utilized as bias feed lines for the power supply; these become MLI3 and MLI4, respectively, in the schematic of **Figure 13**.

Clicking "Analyze" and "View Plot" runs the circuit simulation and displays the LNA gain and output return loss performance as shown in **Figure 14**. **Figure 14** indicates that after accounting for the loss in microstrip and board material the LNA still maintains 15 dB of gain at the 1200 MHz operating frequency. The output return loss is greater than 36 dB while the input is matched for minimum noise figure (< 1dB). This completes the circuit design of an LNA that meets the system level requirements discovered using the LINC2 Visual System Architect software.

Summary

Many products involving RF consist of multiple stages. For example, the signal path in a radio receiver may pass first through a filter, low noise amplifier, a mixer or down-converter and possibly an IF stage consisting of filtering and more amplification at the intermediate frequency. The characteristics of each stage interact with the characteristics of the other stages, necessitating the proper balance of the stage-by-stage parameters in order to meet the overall product specifications. The product design must therefore begin at the system level because the parameters of each individual stage remain fluid until the cascade budget analysis indicates that the product specifications are fulfilled.

When the system simulator arrives at a workable solution, all the parameters of each stage (gain, NF, IP3, P1dB, etc.) have been determined for each individual stage and the design turns to creating the circuit level implementation of each particular stage. The LINC2 software provides the design solution at both the system and circuit levels so that the overall product design can properly flow from high level design using the LINC2 VSA to low level circuit design using LINC2 Pro circuit synthesis and simulation. This article demonstrated this concept of design flow by first considering the frequency plan and other high level issues, such as total noise figure and a spurious free dynamic range, and then proceeding to the detailed design of the LNA.

The LINC2 VSA was used to identify the spurs of interest and their relative amplitudes. It is a fairly easy matter to predict the frequencies of the spurs but it is significantly more difficult for the simulator to determine the exact amplitude of every spur. There are a number of reasons for this; some lie in the hardware itself (e.g., unaccounted for leakage paths) while others depend on the simulator and the type of models used. LINC2 offers several types of mixer models with varying degrees of approximation to any given type of real mixer.

In the LINC2 VSA, the simplest mixer model accounts for gain/loss, NF, and non-linearity in the budget simulation but not frequency translation. All other LINC2 mixer behavior models include some form of frequency translation. Only the advanced model, still under development and used here in this presentation, models the frequency translation in addition to spurs created by the LO to RF interaction. Another approximation is that the simulator's model parameters are constant over frequency whereas that is usually not the case for real mixers (over extremely wide bandwidths). There are a number of filter models in the components pallet that can be used to model the frequency response. Nevertheless, the VSA simulator can be a very useful tool in determining the location of the spurs in almost any kind of spur situation.

Conclusion

The Visual System Architect from ACS adds many built-in simulation functions for producing the stage-by-stage cumulative system budget analyses that are essential for successful system design, analysis, system performance verification and report generation. Full spectral domain analysis provides a spectrum analyzer view of the signals and spurs at any point in the system.

While providing many new design and analysis capabilities for designing at the system level, the VSA program maintains a common user interface with the ACS LINC2 circuit simulator. With the VSA addition to the LINC2 Pro circuit design and simulation software suite, system level designs created with the Visual System Architect can proceed to the detailed circuit design level, all within a common integrated user interface. Thus RF and microwave circuit design can be appropriately driven by high level system design that links product specifications to circuit level specifications and subsequently to detailed circuit designs that meet product requirements.

At the circuit level, LINC2 provides high performance RF and microwave design and simulation. In addition to schematic based circuit simulation, optimization and statistical yield analysis, LINC2 Pro includes many value-added features for automating design tasks, including circuit synthesis. Filter synthesis, amplifier circuit synthesis (including LNA synthesis), the automated synthesis of impedance matching networks and coupler design are just some of the LINC2 Pro automated synthesis modules.

More information about the ACS Visual System Architect and LINC2 Pro can be found on the ACS web site at www.appliedmicrowave.com.

References
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  "Microfluidic device with multiple microcoil NMR detectors enabling fluidic series communication", United States Patent, Peck et al., Patent No.: US 7,141,978 B2, Date of Patent: Nov. 28, 2006, Filed Jul. 14, 2005. See also "Microfluidic device with multiple microcoil NMR detectors and field gradient focusing", United States Patent, Peck et al., Patent No.: US 6,822,454, November 23, 2004.

  "Practical RF System Design" by William F. Egan, Copyright © 2003 by John Wiley & Sons, page 175.

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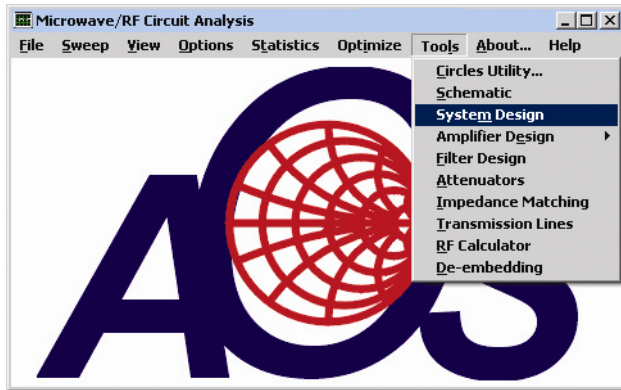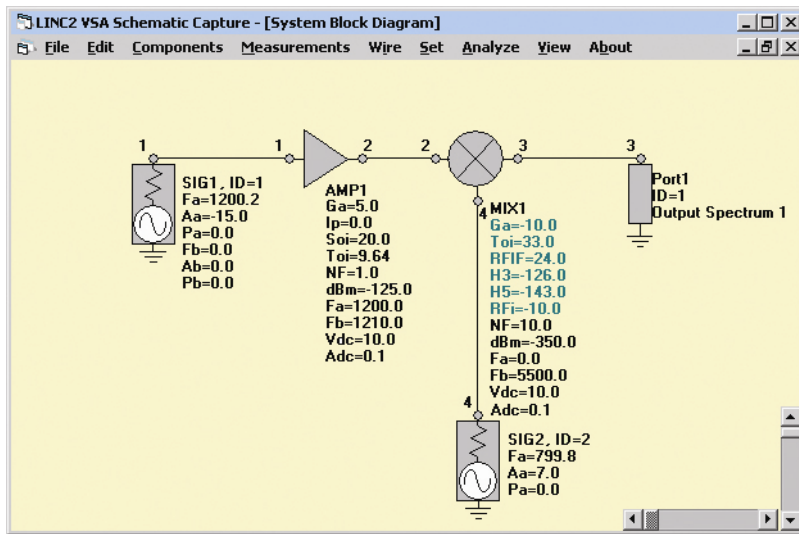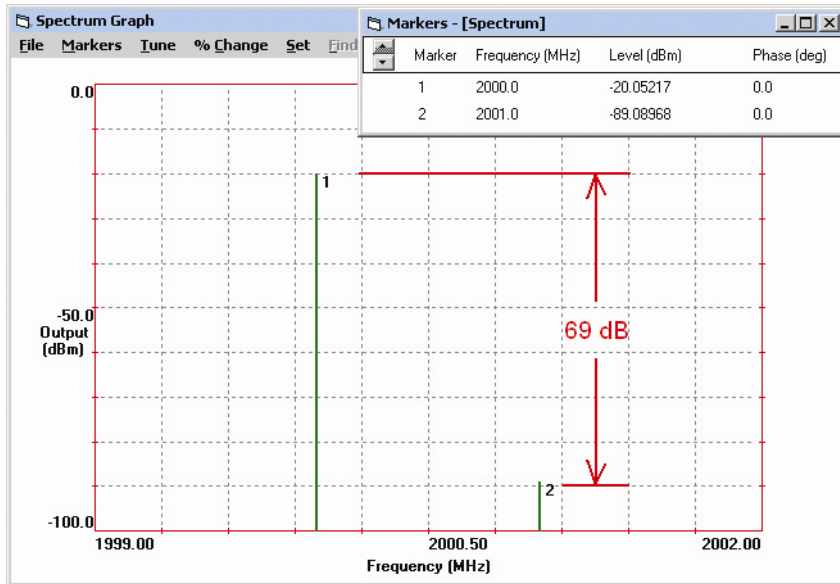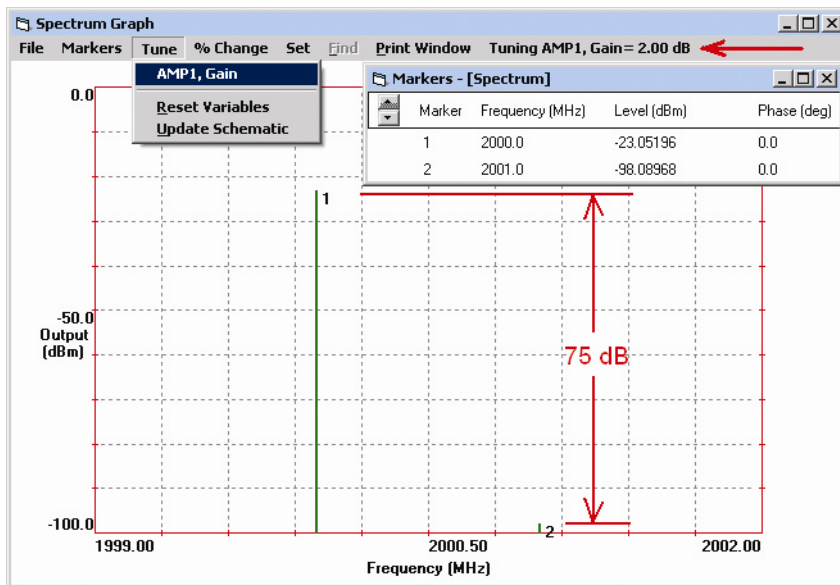
Figure 1

Figure 2

Figure 3

Figure 4
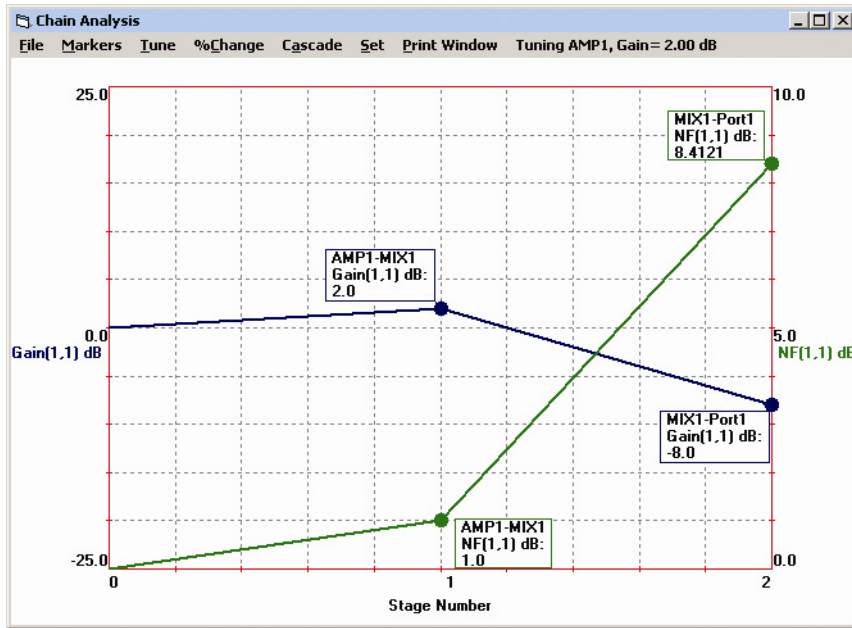
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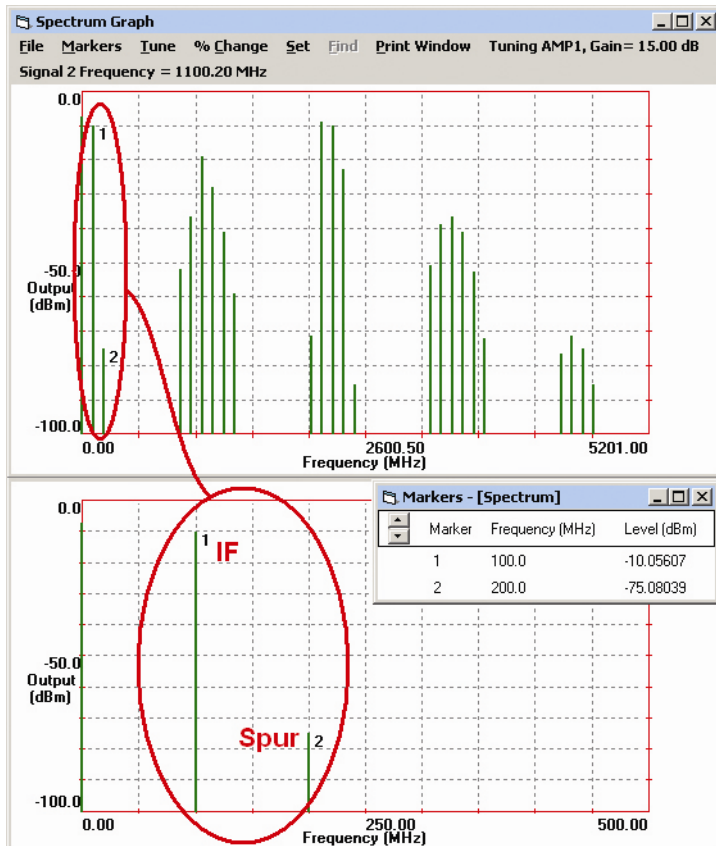
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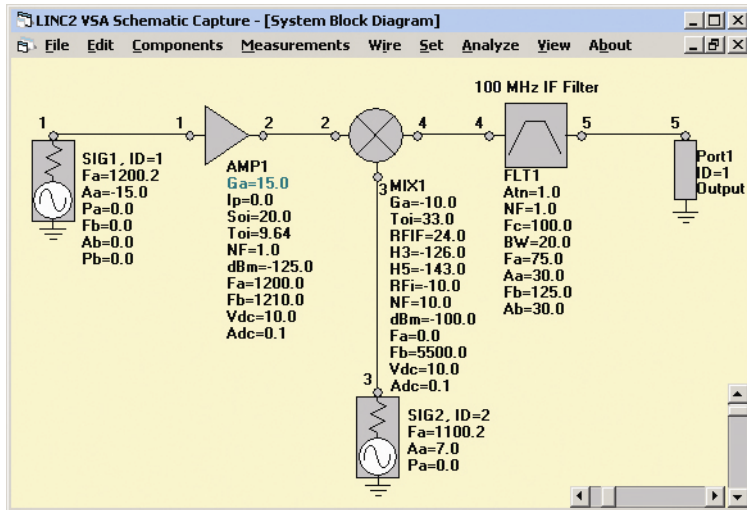
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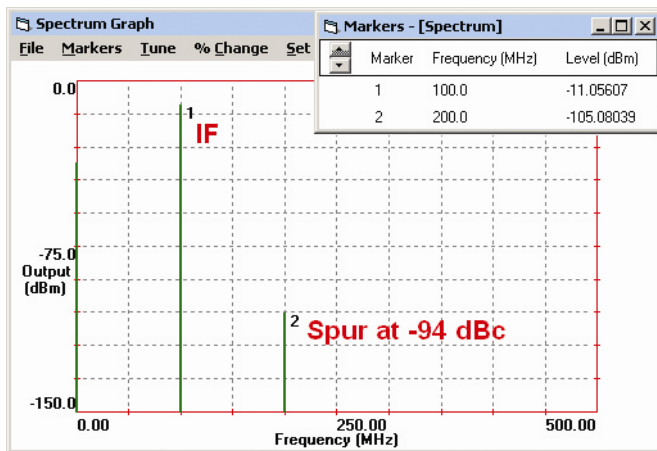
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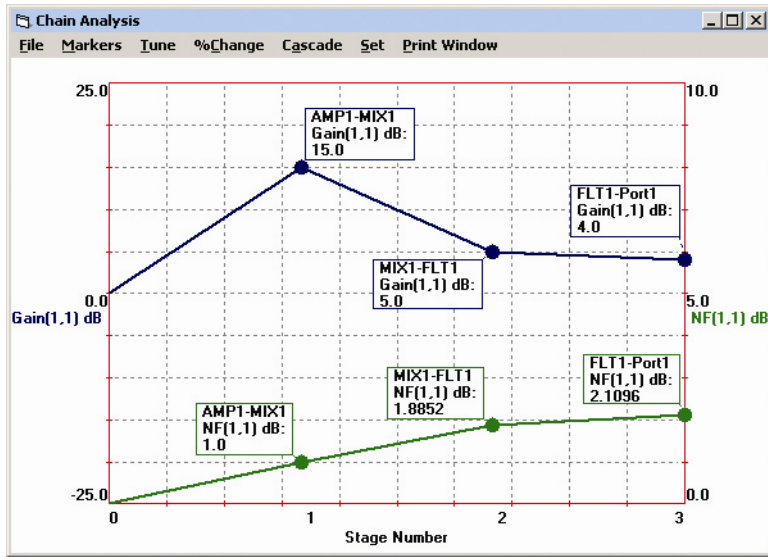
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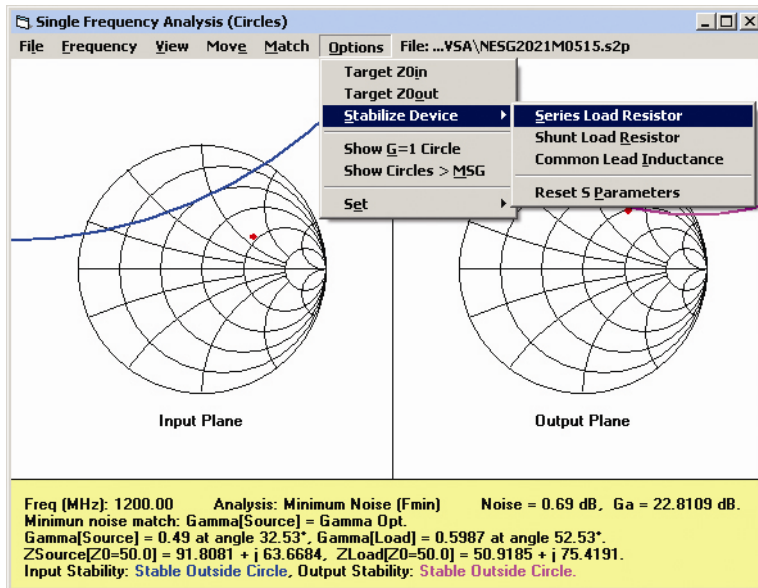
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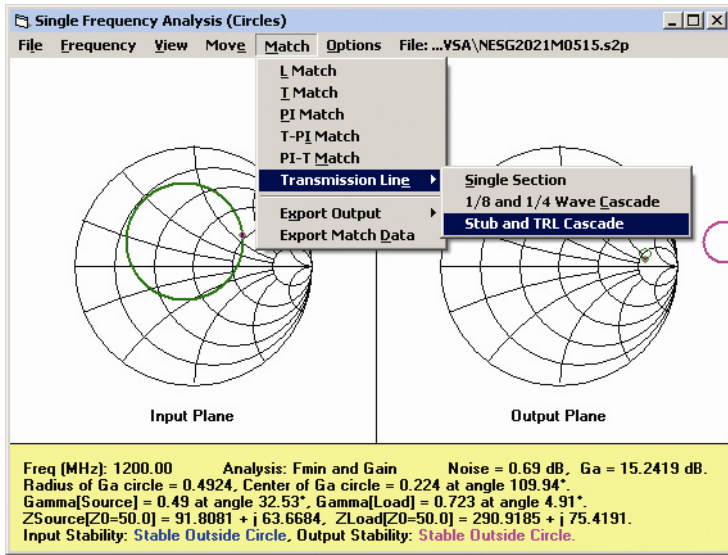
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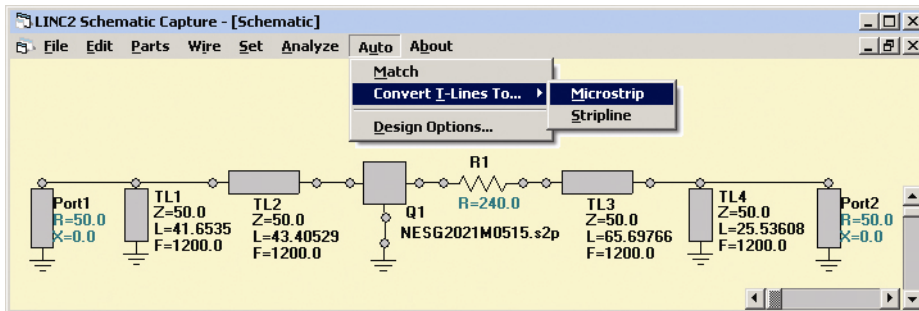
Figure 12

Figure 13

Figure 14