Fast and Efficient RF Amplifier Design Using LINC2 Automated Circuit Synthesis

by Dale D. Henkes, ACS

Considering the advancement in computer aided engineering (CAE) software today, it would certainly seem evident that the most direct approach to RF circuit design would be to employ circuit synthesis software to automate the design process. Circuit synthesis software, as the term is used here, is not to be confused with circuit simulation. While computer aided engineering software aids or assists in the engineering effort, for example through simulation of an existing schematic, circuit synthesis actually creates the circuit schematic in the first place.

The circuit synthesis program that can be considered to be true design automation (rather than simply an engineering tool to assist in the design process) employs all the "rules", algorithms, circuit theory and other design methods, knowledge and expertise built into the software in such a way that an automated mapping is performed between the user entered specifications and the completed schematic. The software thus renders a schematic that meets the design specifications without further human intervention or thought.

One specialized form of circuit synthesis software that is well known to most RF engineers is filter synthesis software. A majority of electrical engineers today will recognize the familiar user interface of the typical filter synthesis program. Even the casual user is likely to know, almost instinc-tively, how to navigate the software's user interface in order to select a desired filter type and topology and specify the frequency response objectives. One might rightfully ask why this kind of software technology (the essential form and flow of the filter synthesis user interface) might not be employed to synthesize other kinds of circuits besides filters. Indeed, multi-purpose circuit synthesis software does exist and is available in the LINC2 Pro software suite from ACS (Applied Computational Sciences at www.appliedmicrowave.com).

In addition to filter synthesis software, capable of designing both lumped and distributed filters (in microstrip or stripline), the LINC2 Pro design automation software offers a comprehensive suite of automated circuit synthesis software.

The LINC2 Pro design automation suite includes an extensive offering of both passive and active circuit synthesis software. For designing passive circuits and components, LINC2 offers the following:

- Lumped and distributed impedance matching networks that match any real or complex source and load Impedances
- Resonators, including special high Q transmission line resonators (in microstrip or stripline with modeled losses)
- Balanced and unbalanced attenuators

ACS, Con't from pg XX

- Directional couplers
- BALUNS (matching any unbalance impedance to any balanced imped-ance, real or complex)
- Simultaneous bilateral impedance matching to the ports of passive devices
- For designing active circuits, LINC2 offers the following:
- Low Noise Amplifier (LNA) design using lumped or distributed compo-nents
- Single and multi-stage amplifiers designed for balanced and unbal-anced terminations
- Single and multi-stage balanced amplifiers (quad combined)
- Single and multi-stage push-pull amplifiers (including differential inputs and outputs)
- All matched to the user's choice of real or complex source and load impedances
- User's choice of distributed or lumped impedance matching net-works for input and output match-ing networks and any inter-stage matching of multi-stage amplifiers

Consider the following design gates, or steps, that the design engineer may pass through in the design cycle of an RF circuit such as an RF amplifier.

1. Develop the desired operational characteristics, i.e. circuit perfor-mance specifications.
2. Select the circuit topology that can best meet the design specifications (Balanced, single- or multi-stage, differential or single-ended, etc.).
3. Synthesize the circuit schematic (automatic circuit synthesis).
4. Analyze the circuit's electrical per-formance (circuit simulation).
5. Optimize the circuit's electrical per-formance (using the circuit simula-tor's built-in optimizer).
6. Verify performance through simula-tion or statistical yield analysis (i.e., Monte Carlo analysis).
7. Lay out and route the printed circuit board (PCB) using PCB CAD tools.
8. Build and test the finished product to verify operational performance relative to the design specifications.

Notice that there are at least three steps in this design cycle that includes a verifi-cation process (namely steps 4, 6 and 8). If the design is not correct, or is deficient from the start, then unacceptable results will likely be revealed at any one of the subsequent steps in the design cycle, espe-cially those that involve evaluation of the circuit's performance, either by simulation or testing of the finished physical product. Obviously, the further into the design cycle that we go before a problem is revealed the more costly it will be for us in time and material since we will have to go back to earlier steps to correct the situation, and in some cases this means going all the way
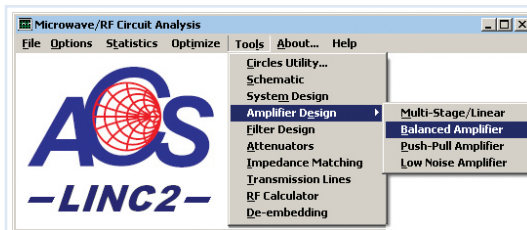
Figure 1: The LINC2 Tools Menu

back to the beginning and starting over.

What is needed is a solid foundation on which the subsequent processes will build upon. LINC2's circuit synthesis applica-tions help ensure that the initial schematic will represent the best circuit going for-ward in the design cycle. LINC2 does this by using exact circuit synthesis instead of approximations. Moreover, LINC2 cre-ates the best circuit by directly mapping the performance specifications into a new schematic rather than starting with a leg-acy design that needs unknown modifica-tion, such a modifying a reference design from a device data sheet to fit a new set of operating specifications.

This article will demonstrate, through the following amplifier design example, the virtually seamless approach that the LINC2 software employs in automating nearly all the steps and processes in the design cycle. LINC2 design automation will be employed from the moment the circuit's operational specifications are entered (step 1) through final verification that the design will meet the expected electrical performance (step 6 above) and is therefore ready to lay out and fabricate the printed circuit board.

Balanced Amplifier Design Example

The design of an RF amplifier in a two transistor balanced configuration will be presented here to illustrate the design pro-cess. A few target specifications will serve as design goals for the LINC2 Pro amplifi-er synthesis module:

- Amplifier topology: Single-ended two transistor balanced amplifier
- Device: Wideband bipolar NPN low noise transistor (NXP BFG591)
- Gain: 11.5 +/- 0.5 dB
- Bandwidth (1 dB): 625 MHz to 1250 MHz (one octave BW)
- Distributed input and output match-ing networks: Microstrip
- Input and output return loss: > 10 dB from 625 MHz to 1250 MHz

Creating the Initial Circuit Design using LINC2 Circuit Synthesis

LINC2 balanced amplifier synthesis is started by selecting Amplifier Design > Balanced Amplifier from the Tools menu (**Figure 1**). This action pops up the Design Specifications Form as shown in **Figure 2** (output matching tab shown). The Design Specifications Form allows the user to control the details of various aspects of the design. The user can specify the frequency, port impedances, stability criteria, topolo-
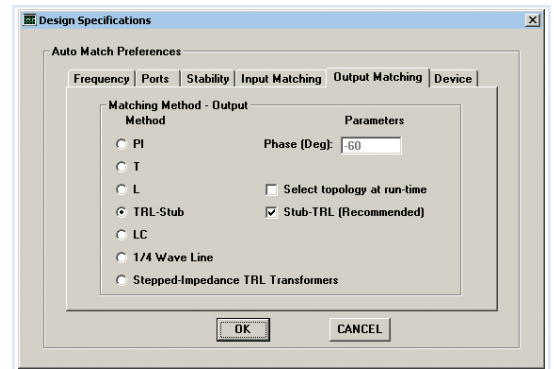
Figure 2: LINC2 Design Specifications Form - Output Matching Tab
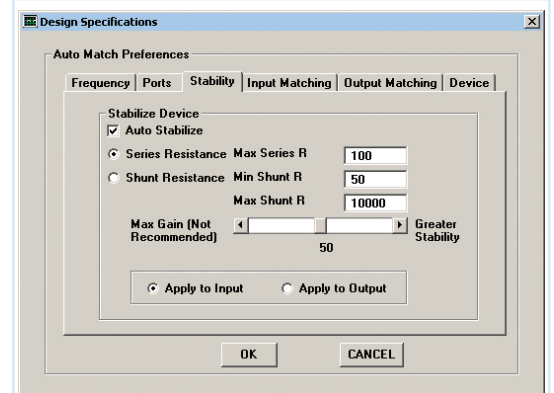
Figure 3: LINC2 Automatic Device Stabilization

Figure 4: LINC2 Device Selection Tab

gy and type of input and output matching networks (such as whether to use lumped or distributed networks), device selection and the inter-stage matching network if a multi-stage design is selected. For example, **Figure 3** shows the contents of the stability control tab. The LINC2 amplifier synthe-sis program can automatically stabilize any potentially unstable active device or tran-sistor in the process of creating the circuit schematic. The user can simply do noth-ing and accept the defaults or take control of the process and guide the program in the application of certain amplifier stabil-ity enhancements. This flexibility allows the low noise amplifier (LNA) designer the option of specifying that any resistive loading (which may be required to render the device unconditionally stable) will be applied to the device output and not at the input where it will degrade the noise fig-ure. Conversely, a power amplifier design-er may choose stability enhancement that loads the input rather than at the output network in order that output power is not sacrificed for stability.

The impedance matching options shown in the Output Matching tab of **Figure 2** are representative of the options that are

ACS, Con't on pg XX

ACS, Con't from pg XX

also available (from the Input Matching tab) for matching the amplifier's input port to the amplifier's first stage transistor(s). A number of lumped and distributed networks are available for matching port impedances to the active amplifying device(s). In keeping with our design goals, distributed networks are selected for input and output matching. In this example, a quarter-wave line was selected from the options under the Input Matching tab while the Stub-TRL method was chosen for the output match (**Figure 2**).

Choosing "Select topology at run-time" provides more control over the design by allowing for more details about a particular topology to be specified during the synthesis process. By not selecting the default we could have elected to make a couple of additional decisions regarding the application of components designed to make the input quarter-wave line more effective in the presence of the complex impedances encountered at the active device input. Lumped or distributed elements in series or shunt orientation can be applied at the device terminals to cancel the device reactances. Alternatively, the user can place the reactance on the left, right or on both sides of the quarter-wave line by simple selection of an immittance inverter.

One of the additional ways in which the user can guide the design is in the choice of the frequency response of the matching networks (low-pass, high-pass or band-pass). In this design, networks are chosen so as to produce a low-pass response when optimized for the overall balanced amplifier. This helps to flatten the frequency response and delivers the additional benefit of suppressing harmonics.

After specifying the amplifier's operating frequency, port impedances (usually 50 Ohms but any other impedance can be specified), stability enhancement, and
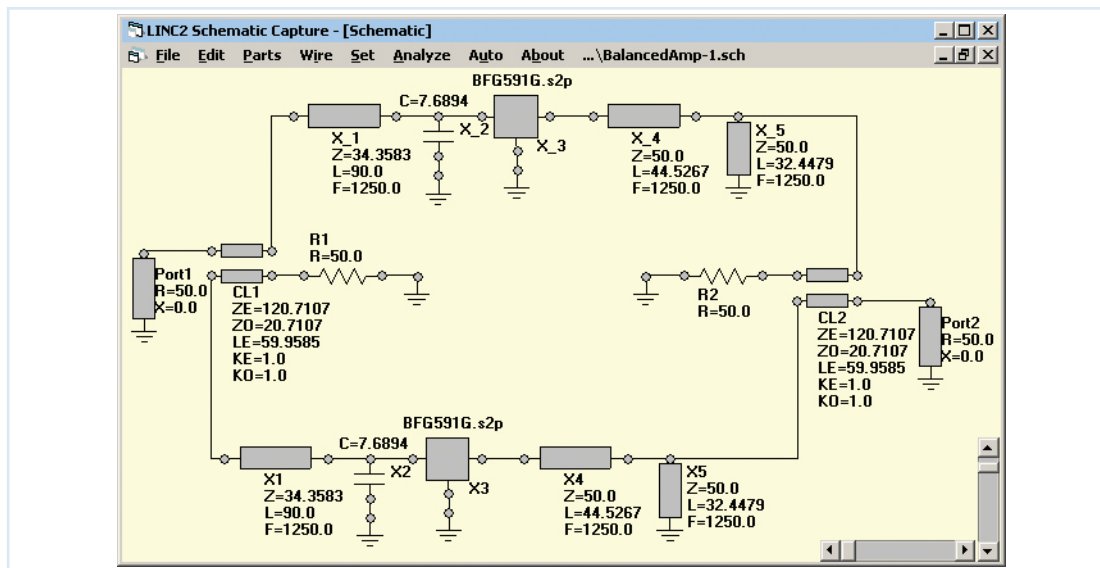

Figure 5: LINC2 Synthesized Amplifier Schematic

input/output matching, the only other option that remains to be selected is the type of active device that will be employed. For this example, the two-port s-parameters for the BFG591 NPN transistor are selected from the Device tab (**Figure 4**).

Earlier we selected the Balanced Amplifier topology. This amplifier topology uses two identical transistors in a balanced configuration, so only one device type is selected from the Device tab as shown in **Figure 4**. At this point, clicking OK automatically generates the initial synthesized schematic shown in **Figure 5**.

Optimizing the Amplifier for Broadband Response

By employing LINC2 circuit synthesis, we went from entering a few design specifications to an initial circuit schematic (**Figure 5**) in the matter of just a few minutes. Now, by simply clicking the Analyze button we get an immediate RF performance analysis for the initial synthesized amplifier circuit. Already, the frequency response is significantly broadband

Figure 6: LINC2 Optimizer Goals

at 56.8% for the 3dB bandwidth centered at 1250 MHz. We next want to apply our final design goals onto this initial circuit by running the LINC2 optimizer. Based on our original design goals, we want the optimizer to extend the bandwidth to an octave and flatten the gain to within +/- 0.5 dB of the 11.5 dB gain requirement.

Before employing the optimizer to flatten the gain we will convert all the ideal TRL (transmission line elements characterized by their impedance and electrical length) to physical microstrip. This will ensure that the optimizer is optimizing the final physical circuit and not some initial highly idealized representation of it. Fortunately the process of converting ideal transmission line elements to their physical equivalents (microstrip or stripline) is also completely automated in LINC2. Clicking Auto > Convert T-Lines to > Microstrip requires only that we specify the substrate material. In this case we choose 32 mil Rogers® RO4003C laminate. Effortlessly, all the electrical lines in the schematic are converted to physical microstrip. The schematic, with all lines converted to microstrip and bias feeds added, is shown in **Figure 7** (after optimization).

The design is now ready to optimize. The optimization goals are entered as shown in **Figure 6**. To flatten the gain we made the lower limit equal to the upper limit (setting each to 11.5 dB). After optimizing, the optimized component values are saved into the schematic (**Figure 7**). **Figure 8** shows the optimized frequency
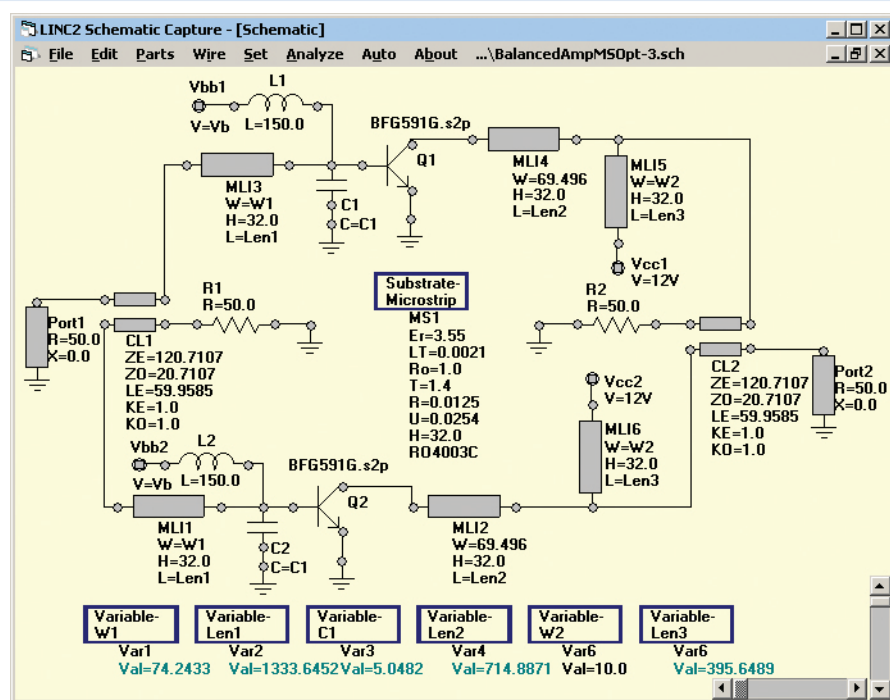
Figure 7: Optimized LINC2 Balanced Amplifier Schematic

ACS, Con't from pg XX

response. The simulation results plotted in the graph of **Figure 8** indicate that the gain meets the goal of 11.5 +/- 0.5 dB over the octave bandwidth from 625 MHz to 1250 MHz.

Circuit Performance Verification – Yield Analysis

LINC2 statistical yield analysis employs Monte Carlo simulations (random variations of component values) to determine the likely yield for a large number of samples. The goals for the desired outcome are entered as shown in **Figure 9**. Minimum values (lower limit), maximum values (upper limit) or both can be entered for any design goal, and the frequency range over which the goal applies can be specified. In this case we have specified the goal that the magnitude of S21 (M21) should remain within a 1 dB window around 11.5 dB.

All components selected for tuning or optimization are listed in the Tolerances menu. The default tolerance is +/- 5%, but each component value can be selected individually from the menu and its tolerance can be changed to any other value. The tolerance value for all components can be set to any range by selecting Reset Tolerances from the Set menu. In this example, the range for all microstrip width dimensions were set to +/- 13% for a total dimensional tolerance range of 26%. The lumped capacitor values were also set to +/- 10%.

Clicking Calculate Yield performs the yield analysis over the specified number of samples. In this case the sample size was set to 2000. Yields for the individual goals are displayed next to the goal while the total yield is displayed at the bottom of the statistics window (**Figure 9**). The total yield shows the number of successful results over the total number of trials performed. The percentage of successful trials is also

displayed. Selecting Show Graph in the Graph menu, prior to running the simulation, displays the results for each trial run graphically as shown in **Figure 10**.

For the balanced amplifier circuit of **Figure 7**, the yield for two thousand samples is 98.5% for a peak to peak gain variation of no more than 1 dB over the octave bandwidth (625 MHz to 1250 MHz). A subsequent Monte Carlo run showed that with only a slight tightening of the dimensional tolerances of the microstrip (from +/- 13% to +/- 10%) a 100% yield was produced.

Performance Summary

When all component parameter variations were held with +/- 10% of their nominal values, the yield analysis indicated 100% yield on a sample of 2000. Though not shown in **Figure 9,** a subsequent analysis indicated that all the original design goals, including amplifier input and output return loss, were also met.

One of the characteristics of the balanced amplifier is good input and output return loss, primarily over the bandwidth of the quad hybrid couplers (CL1 and CL2 in **Figure 7**). **Figure 11** indicates that a minimum of about 12 dB return loss is achieved over the octave amplifier operating bandwidth. The 90 degree 3-dB splitter and combiner couplers modeled had a center frequency of 1250 MHz. Simulation indicates that when the couplers are replaced by couplers designed for the band center (around 900 MHz), this balanced amplifier has a minimum of 21.5 dB return loss over the entire octave bandwidth.
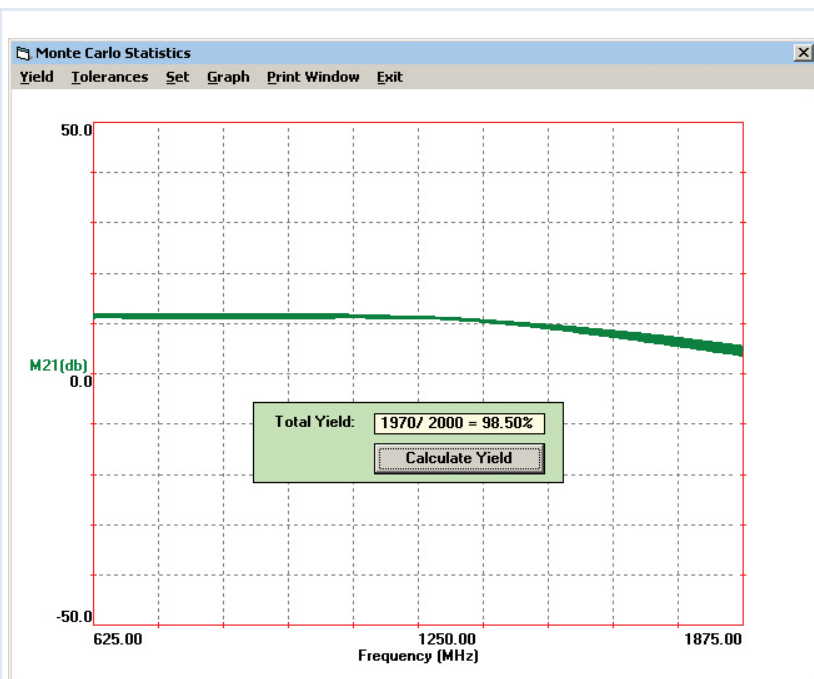
Summary and Conclusions

A design procedure was presented in which circuit synthesis is used to create the initial circuit for subsequent analysis and optimization. A wideband balanced amplifier circuit designed using the LINC2 program demonstrated that virtually complete design automation can be realized when design software inte-
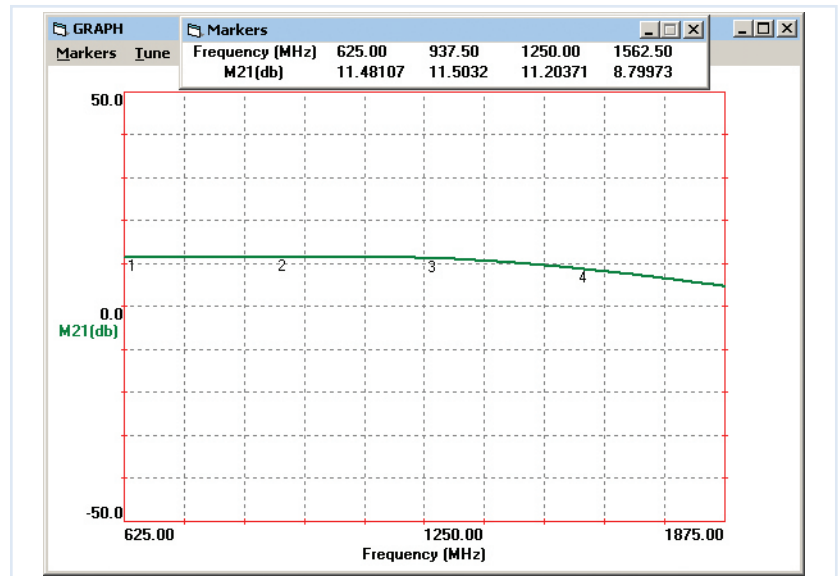
Figure 8: Gain Response for the LINC2 Designed Balanced Amplifier
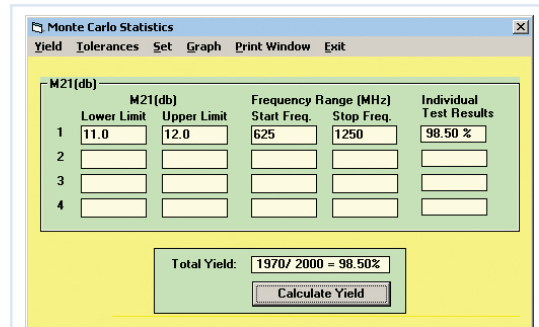
Figure 9: LINC2 Yield Goals

grates circuit synthesis with schematic capture, simulation, optimization and design verification through statistical yield analysis.

It was mentioned earlier that LINC2's exact circuit synthesis helps to provide a circuit schematic that will be the basis for a solid foundation on which the subsequent design cycle processes can build upon. If the circuit thus synthesized is the final product then the first step, acquiring the operational specifications, may be dictated contractually by the customer or by market survey. But if this circuit is one component in a system or cascade of components, that make up the overall product, then it is most important to have derived the correct component specifications before embarking on the synthesis of the specific circuit (a balanced amplifier in this case). The LINC2 software suite also provides a solution here as well.

With the addition of the LINC2 Visual System Architect (VSA), system level designs created with LINC2 VSA can flow down component operating requirements to the product's composite circuits allowing the designer to proceed to the detailed circuit design level with confidence that the individual circuit design will meet overall system or product requirements. The Visual System Architect from ACS includes the cumulative system budget analyses that are essential to successful system design and other tools for optimizing at the system level to ensure that a product
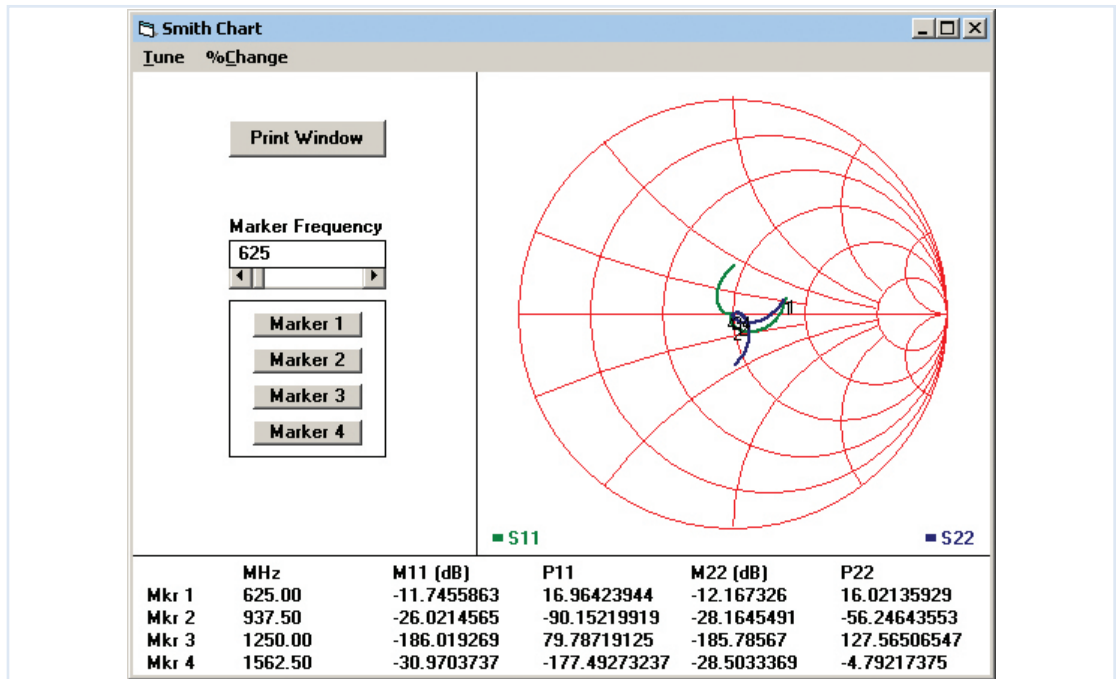
Figure 10: LINC2 Statistical Yield Analysis

ACS, Con't from pg XX

will comply with required specifications before valuable resources are committed to detailed circuit design and prototyping.

LINC2 is a high performance, low cost, RF and microwave design and simulation program that includes many value added features for automating design tasks, including circuit synthesis. More information about LINC2, LINC2 Pro and LINC2 Visual System Architect can be found on the ACS web site at www.appliedmicrowave.com. 🔵

RO4000® series is a trademark of Rogers Corporation.

All trademarks and registered trademarks are the property of their respective owners.

• ACS •

Figure 11: Return Loss for the LINC2 Designed Balanced Amplifier

	MHz	M11 (dB)	P11	M22 (dB)	P22
Mkr 1	625.00	-11.7455863	16.96423944	-12.167326	16.02135929
Mkr 2	937.50	-26.0214565	-90.15219919	-28.1645491	-56.24643553
Mkr 3	1250.00	-186.019269	79.78719125	-185.78567	127.56506547
Mkr 4	1562.50	-30.9703737	-177.49273237	-28.5033369	-4.79217375