Automation and Real-time Verification of Passive Component S-parameter Measurements Using Loss Factor Calculations

An automated S-parameter testing approach, built around a LabVIEW program, is described that adds important capabilities to a microwave test setup. A real-time check on S-parameter data using total loss calculations is shown to be a good indicator of measurement quality. The program also automates multi-instrument control and the process of data storage by generating incremental filenames. This type of approach is essential for efficient acquisition and storage in data-intensive applications.

In developing microwave models, real-time verification of characterization data should be considered a priority to ensure its integrity. Sound models must be built upon accurate measurement data, and, as is generally the case, the 'garbage in – garbage out' principle applies to model extraction. Even if an instrument calibration is rigorously inspected prior to data acquisition, there are a multitude of things that can occur after calibration to seriously degrade data integrity — damaged connectors, bent probes, cable movement, improper die attachment, warped boards, temperature variation, etc. Sometimes the errors are difficult to detect and can best be identified using real-time data analysis.

Data storage is another aspect worthy of consideration, particularly when large amounts of data are involved. The development of a single, robust model that is representative of a microwave device typically requires measurements of 5 to 10 samples, often in multiple configurations and/or test fixtures. Thus, the characterization process can result in the generation of hundreds of data files. Under these circumstances, manual generation of filenames is almost certain to lead to errors, including an

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S-parameter data set being associated with an incorrect bias setting or configuration, for example. Further down the model extraction process, such errors will inevitably lead to a loss of engineering time and, possibly, incorrect models.

In this article, total loss calculations are shown to be good and useful indicators of measurement quality for passive microwave components. Such calculations can be performed in real-time and provide a single, visible 'snapshot' that is readily evaluated as, for most components, the forward and reverse loss factors should be substantially equal. A LabVIEW program has been written to automate the loss factor calculations, control multiple test instruments, and to implement an efficient data file generation and storage process.

LOSS FACTOR BASICS

The forward and reverse loss factors are calculated from passive component S-parameters as

$$\text{Forward Loss Factor (FLF)} = 1 - |S_{11}|^2 - |S_{21}|^2$$

$$\text{Reverse Loss Factor (RLF)} = 1 - |S_{22}|^2 - |S_{12}|^2$$

By these definitions, the loss factors are seen to equal the difference between a normalized input power and the power that is reflected and transmitted to the input and output ports, respectively. (Power loss can occur due to conductor, dielectric and radiation loss mechanisms.) For reciprocal devices $S_{21} = S_{12}$, the differences between the forward and reverse loss factor occur due to differences in $|S_{11}|$ and $|S_{22}|$. For ideal lossless components, the magnitudes of S_{11} and S_{22} are equal, but they can deviate from one another whenever loss is present.

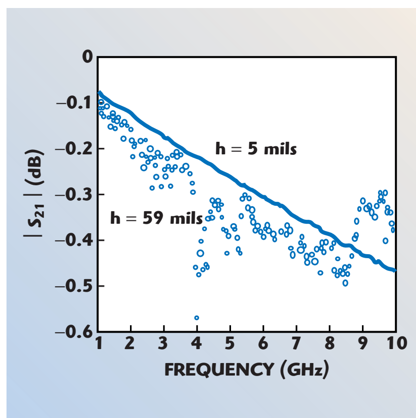


Fig. 1 S_{21} of a delay line used during a TRL calibration on FR4 substrates of different thickness.

For passive components such as capacitors, inductors and resistors (and diodes), the electrical behavior is most often symmetrical ($S_{11} = S_{22}$); thus, the difference in the forward and reverse loss should be negligible. Significant deviations in the forward and reverse loss can be observed when a component begins to radiate, a commonly observed phenomenon, particularly for inductors. However, the main objective of this article is to illustrate how real-time monitoring of loss factor behavior becomes a useful tool for detecting measurement inconsistencies when, all things functioning properly, the component should exhibit symmetrical characteristics.

MEASUREMENT EXAMPLES

The variation of the loss factor with frequency can often be used as a measure of data integrity. For most passive devices, the loss factor tends to increase with frequency with peaks near resonant points, such as the cutoff frequency of a filter or a self-resonance of an RLC component. A trend other than this generally indicates a measurement problem that can stem from a poor calibration, poor quality test fixtures, or other defects such as those mentioned at the beginning of this article.

Differences in the variation of loss factor with frequency are shown herein by comparing data for a 5.6 pF 0603 capacitor, as measured on 5-mil-thick and 59-mil-thick FR4 substrates. The S_{21} data for a delay standard of a multi-line thru-reflect-line (TRL) calibration,[1] performed prior to the capacitor measurements, is shown in ***Figure 1***. The data taken on the 5-mil substrate shows a uniform, monotonic decrease as expected, while that for the 59-mil substrate is relatively noisy. In particular, the 59-mil data shows spikes at ~4 and ~8.5 GHz. The measured S-parameters for the capacitors are given in ***Figure 2***. While there are noticeable

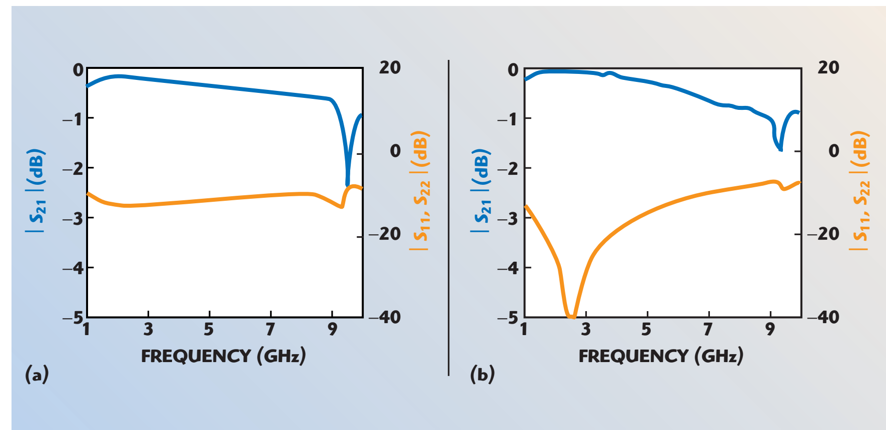


Fig. 2 S-parameters for a 5.6 pF 0603 capacitor on (a) a 5-mil FR4 substrate and (b) a 59-mil FR4 substrate.

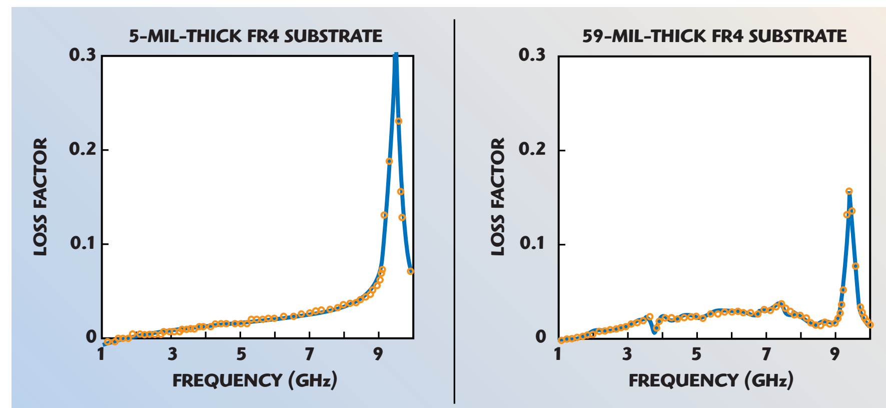


Fig. 3 Forward (solid line) and reverse (circles) loss factor measured on a 5.6 pF 0603 capacitor.

differences between the substrates due to ground-related parasitic effects,[2] the data for each has uniform variation and excellent symmetry between S_{11} and S_{22}. The variation in the loss factor, however, reveals an inconsistency in the 59-mil data. While the 5-mil data shows the expected increase in loss factor (and a spike near the resonance) the data on the thicker substrate has a small spike near 4 GHz and decreases near 8.5 GHz, as shown in ***Figure 3***.

In this example, the calibration data on the 59-mil substrate clearly indicated an upper frequency limit for trustworthy data, and the problem arising in the loss factor behavior could be anticipated. Less obvious sources of error, such as poor probe contact to an uneven test fixture, are also possible and can easily result in similarly bad data. The main point here is that the non-physical behavior — decreasing dissipation near 8.5 GHz — is more apparent in the loss factor than it is in the S-parameters. Identifying this upper frequency limit is important if one is attempting to obtain high precision data.

Even when the loss factor increases monotonically with frequency, asymmetry between the forward and reverse properties can be indicative of a measurement problem. Measured S-parameters for a 1.0 pF 0201 capacitor, as measured on a 5-mil substrate, are shown in ***Figure 4***. Analyzed individually, either set of S-parameters has uniform variation and no obvious inconsistencies. However, the data on the left has nearly identical S_{11} and S_{22} characteristics, while the data on the right shows some asymmetry. A comparison between the two also indicates that S_{21} for the asymmetric data set is lower than the symmetric data by approximately 0.6 dB at the high end of the frequency band.

The difference between the data sets is more readily recognized by a comparison of the loss factors (see ***Figure 5***). The symmetric S-parameters show nearly identical forward and reverse loss factors. However, the forward and reverse dissipation calculated from the asymmetric data set are different, and the loss is 60 to 70 percent higher than the symmetric results at the upper frequency limit. These two data sets were obtained from the same part and test fixture during different measurement sessions, with equal-quality instrument calibration. Thus the differences can be attributed to an inadvertent cable movement, probe placement differences, or similar post-calibration circumstances.

Given the preceding examples, it is worth mentioning that asymmetric S-parameters, and corresponding differences in the forward and reverse loss factor, are not necessarily incorrect. ***Figure 6*** shows the S-parameters for a 24 nH 0603 chip inductor, as measured on 14-mil and 5-mil FR4 substrates. The data from the 14-mil substrate shows noticeable asymmetry beyond 5.5 GHz, while the 5-mil data shows a difference only near 8 GHz. These effects are due to radiation loss, which is frequently shown

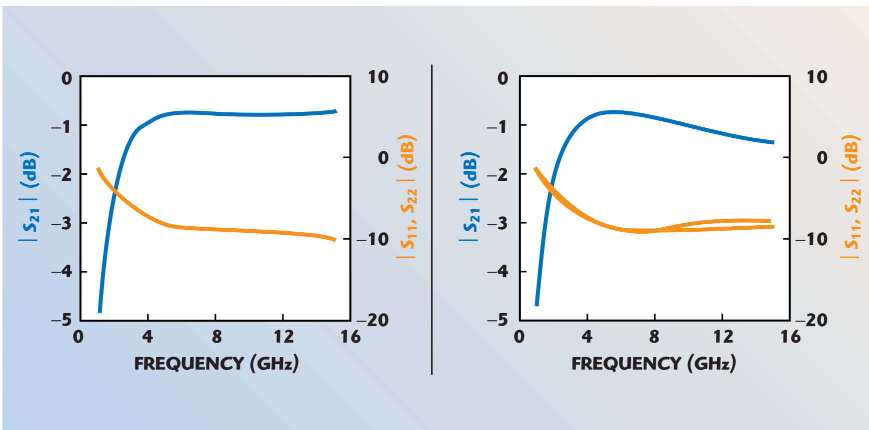


Fig. 4 Two measurements of S-parameters for a 1.0 pF 0201 capacitor on a 5-mil-thick FR4 substrate.

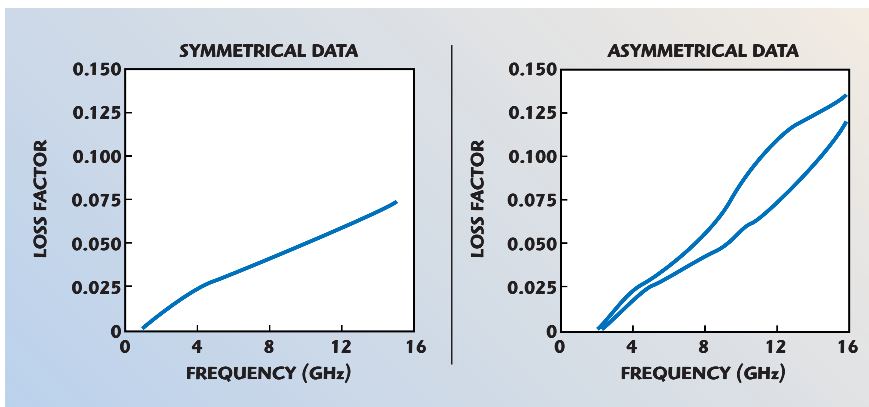


Fig. 5 Forward and reverse loss factors for a 1.0 pF 0201 capacitor on a 5-mil FR4 substrate.

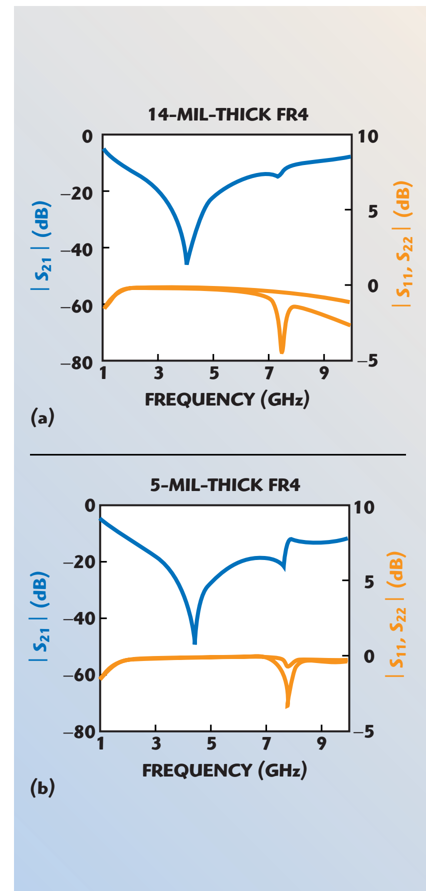
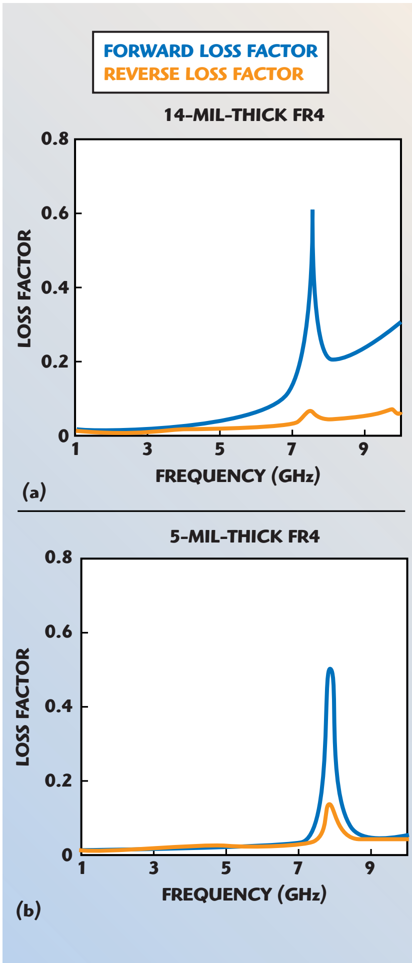
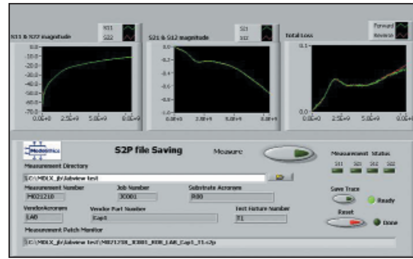


Fig. 6 S-parameters for a 24 nH 0603 inductor on (a) 14-mil and (b) 5-mil-thick FR4 substrates.



▲ *Fig. 7 Loss factors calculated from S-parameters for a 24 nH 0603 inductor on (a) 14-mil and (b) 5-mil-thick FR4 substrates.*



▲ *Fig. 8 Sample screen from the LabVIEW measurement-control program.*

to be highly dependent on the substrate to which the part is mounted and on the side of the part to which the RF signal is injected. The corresponding loss factor data (see ***Figure 7***) demonstrates that on the thicker substrate 60 percent of the incident power can be lost in one direction, while only 10 percent may be lost from the other. These radiation properties have been experimentally validated by others.[3]

MEASUREMENT AUTOMATION

The best time to validate experimental data is when the measurements are being made. Errors that are caught down-stream, perhaps stemming from an equipment problem that occurred after calibration, can result in a significant amount of lost engineering time. Currently, however, most software that is commercially available for microwave measurements and data extraction does not allow user-defined equations to be generated for data analysis purposes.

A LabVIEW program was written in order to implement real-time loss factor analysis, as well as an automated filename generation algorithm. A sample front-panel screen shot is shown in ***Figure 8*** and the elements of the program are summarized in ***Table 1***. Information-rich filenames are created by concatenating parameters such as internal job number, component description and test fixture identifiers. Additional features of the program enable GPIB-control of bias supplies and various meters to facilitate active device characterization from a central command point.

TABLE I

ELEMENTS OF THE LabVIEW PROGRAM

Stage	*National Instruments Library VIs*	*Description*
Initialize VNA	AW372XXA INT open VNA.vi	initialize GPIB communication with the VNA
Setup channel format	CH graph type.vi	set up each channel in the desired display and data format
Measure button	while loop	wait to proceed until the "measure" button is pushed
Sweep frequency	AW372XXA DAT frequency values.vi	obtain frequency points from VNA
Sample channels	AW372XXA DATA get trace.vi	obtain data 4 times (once for each parameter)
Calculations	standard "numeric" and equation functions	perform desired calculations
Display data	XY graphs	standard XY graph display
Data format and saving	while loop, write file	wait to proceed until "save" or "reset" is pushed and save if needed

CONCLUSION

Loss factor calculations using measured S-parameters are simple to perform, and provide useful insight into data quality for passive, reciprocal components. Loss factor ties the port-matched transmission and reflection coefficients together, is symmetric for a physically symmetric component and should generally increase with frequency (except after a peak near resonance). Since myriad problems can arise during high frequency measurements to degrade the accuracy, tracking a parameter whose general properties are known a priori is a valuable aid when measurement precision is critical. ■

ACKNOWLEDGMENT

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