Perfectly Calibrated Internal Ports in EM Analysis of Planar Circuits

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***Abstract* — Perfectly calibrated internal ports have recently been developed for high frequency electromagnetic analysis of planar circuits. This capability has never before been available. As such, microwave designers are only just now learning the value of such ports. This overview paper describes new and extremely efficient design methodologies that are now practical. For example, if properly prepared, an entire circuit can be EM (electromagnetically) analyzed once and the precise analysis of all subsequent modifications (tuning, tweaking) of the circuit provided essentially instantly. Another capability enabled by perfectly calibrated ports is compact model synthesis. These capabilities are illustrated with examples.**

***Index Terms* — Compact model, electromagnetic analysis, method of moments, port calibration.**

I. INTRODUCTION

We first define a "port" in EM (electromagnetic) analysis and why, and how, it is calibrated. Most existing port calibration algorithms are approximate. These algorithms are "good enough" for many applications, but fail in critical situations. Exact port calibration is required for certain exceptionally efficient design methodologies. Examples of perfect port calibration include splitting a complex filter in half, filter tuning, precise insertion of SMD (surface mount devices), and use in RFIC (radio frequency integrated circuit) design.

II. WHAT IS A PORT?

A port is two terminals: signal and ground. Ports are used to interface the results of an EM analysis with circuit theory tools. In one way to represent a port, the designer specifies a path (for a line integral) from the signal terminal to the ground terminal. The problem is that the Z_0 (characteristic impedance) must be independently determined. Fortunately, the Z_0 can be "good enough" for many situations. But small Z_0 errors (especially for lossy thick substrates) insert non-physical error into the final result. Such approximate results mean the techniques described here can not be applied.

Another kind of port is the "gap" port. A gap port introduces both inductance and capacitance; imagine a tiny bond wire with a tiny voltage source connecting the gap edges. We have the same problem if the "gap" is between the end of a line and nearby perfectly conducting wall.

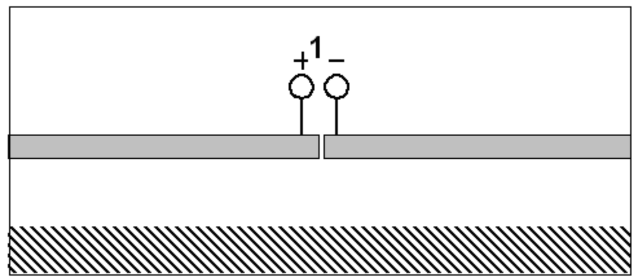

Fig. 1. Side view of a series connected infinitesimal gap port. The negative terminal could also be a perfectly conducting sidewall, which would provide a perfect ground reference.

For my EM analysis work, my ports are always an infinitesimally narrow (zero width) gap in a conductor. One side of the gap is deemed to be the signal terminal and the other side is the ground. A voltage source is then impressed across the gap. Fig. 1 shows a side view of a gap port in series in a conductor. When the port is on the edge of the circuit, the port's ground terminal is conducting sidewall of a shielded EM analysis yielding perfect ground reference.

Now there is no need to arbitrarily select a path from signal to ground. In addition, there is no port inductance because the imagined bond wire has zero length. However, the gap still has fringing capacitance across itself and there is fringing capacitance to nearby gap ports.

For box sidewall ports, the exact port calibration problem was solved in 1991 [1]. The calibration is perfect to within numerical precision provided the port connecting lines are not over moded and is completely valid for multiple closely spaced ports.

The calibration works very much like a VNA (Vector Network Analyzer) calibration. It analyzes two standards and exactly removes any and all port discontinuity, including capacitive fringing fields coupling to nearby ports. Typical port discontinuities are on the order of 0.1 pF. This is small. However, if the techniques described in this paper are to be used, even tiny port calibration errors are unacceptable.

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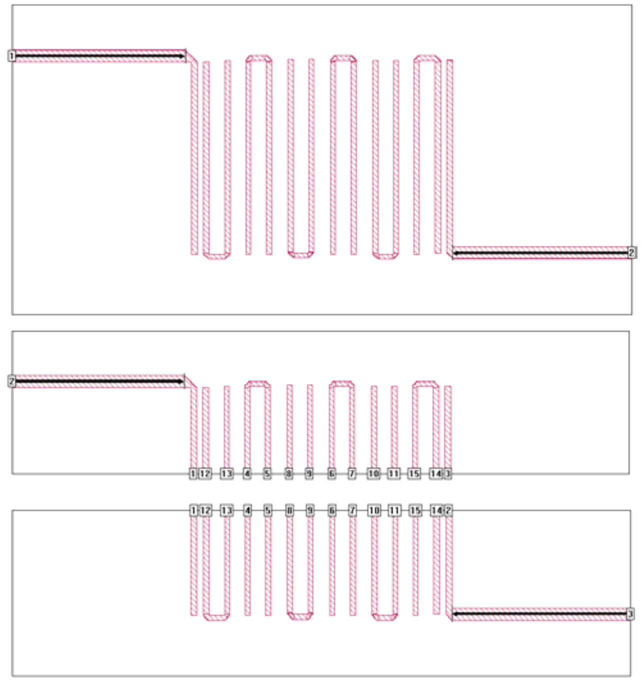

Fig. 2. The six resonator hairpin filter (top) is split into two pieces, each piece analyzed separately, then recombined into one. This can succeed only if the 28 additional ports, internal to the resonators, are perfectly calibrated.

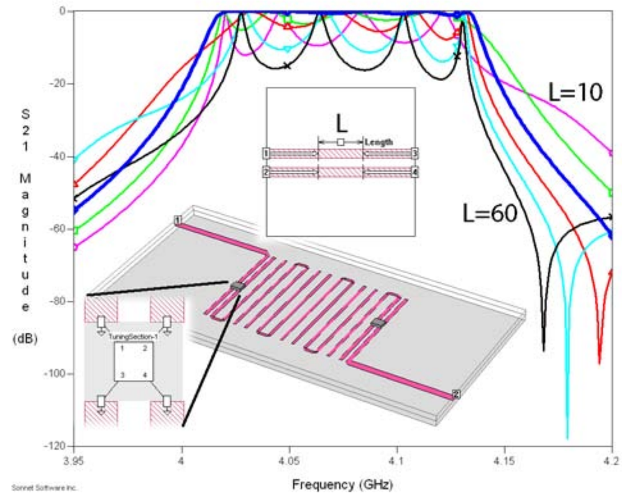

Fig. 3. The six resonator hairpin filter has two sets of perfectly calibrated ports (one set detailed, lower left) placed in the input and output coupled sections. A length, L, of coupled line (central inset) is inserted into each set of ports. As L is varied from 10 to 60 mils, step of 10 mils, new results are instantly available. The thick blue line (L=30) corresponds to the filter of Fig. 2. Notice the over 100 dB dynamic range.

III. Internal Port Calibration

In the course of a design, the microwave engineer might place multiple gap ports internal to a circuit, far from nearby perfect-ground-reference sidewalls. These internal ports also have a port discontinuity. The internal port calibration problem is now solved exactly [2] and is commercially available [3]. Various “torture tests” are presented in [4]. As with sidewall port calibration, the internal port calibration perfectly calibrates groups of internal ports. This capability has never before been available to the microwave designer.

Important note: if radiation is present during the calibration procedure, then the calibration is no longer perfect. Thus, the approaches described in this paper can not be reliably used with unshielded EM analysis.

IV. The Split Filter Example

This six resonator hairpin filter, Fig. 2 top, is available on-line [3]. First, download SonnetLite, install, and click on Help->Examples->Filters.

This filter analyzes quickly, and only four frequencies are needed (the rest are interpolated), so there is no need to analyze faster. Rather, our purpose is to illustrate how one might handle a more difficult filter.

First split the filter in half (Fig. 2, bottom). Then each half (now with 15 ports each) is analyzed electromagnetically and connected back together. Note that perfect port calibration is critical. Each resonator of the split/recombined filter has four port discontinuities. Any port calibration error in this sensitive region results in failure. With perfect calibration, the full filter and the split/recombined filter responses are visually identical [4].

Most planar EM analysis is limited by matrix inversion time, which increases with N^3. Thus, cutting N (the number of subsections) in half, cuts the analysis time by eight times. Since there are two halves, the overall analysis is four times faster. Note that, in this case, the two halves are identical. Appropriately connecting one half of the filter with itself, thus invoking symmetry, yields a full eight times speed-up.

The process of splitting a circuit, analyzing each portion, and reconnecting is tedious and error prone. Fortunately, the process is automated. The user draws the splitting line, clicks on “Subdivide Circuit,” and then clicks “Analyze”. The entire process described in this section requires three minutes.

V. Tuning Methodology

When the EM analysis is complete, the initial result is rarely satisfactory. With perfect port calibration, tuning, or “tweaking” is easy.

For illustration, let’s tune the length of the input and output coupled line section in the filter above. We insert four internal ports as shown in Fig. 3 (lower left detail).

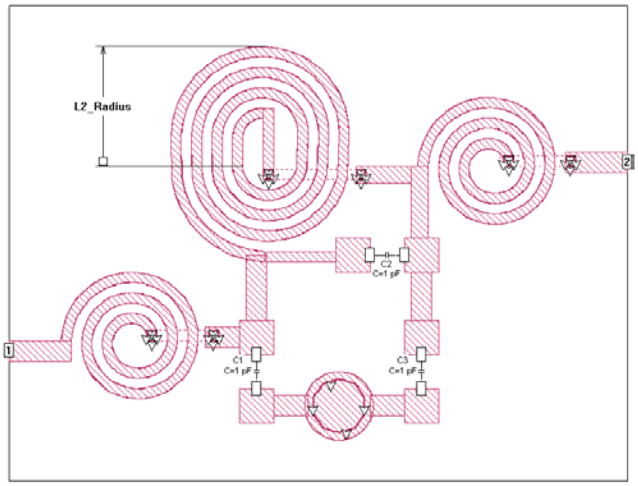

Fig. 4. A lumped low-pass filter includes three SMDs, modeled here as ideal capacitors. A more sophisticated model or measured data is easily entered as well. For highest accuracy, the reference planes in the EM analysis should be at exactly the same location as the reference planes for the SMD data.

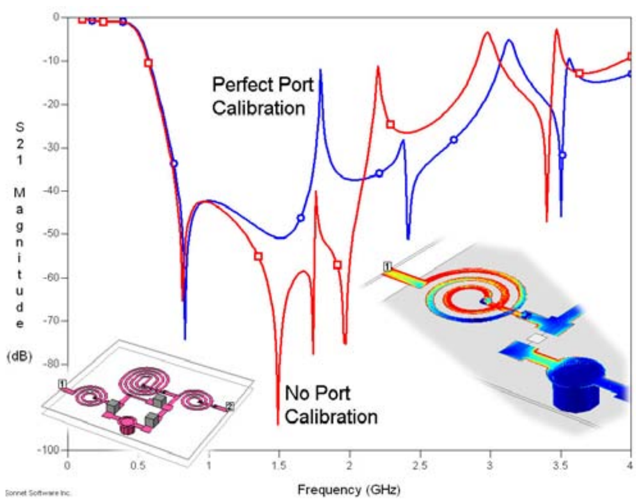

Fig. 5. A low pass elliptic filter with three SMD capacitors. Perfect port calibration is not needed below 1 GHz, but above 1 GHz, a substantial difference is seen. Note that the current flowing from through the ideal capacitor (small white square) to the ground via is included in the current distribution.

The results for different lengths, L, are shown in Fig. 3. In this case, we inserted EM analysis data for a short L length of coupled line (Fig. 3 central inset). After the initial complete EM analysis, successive tuning results (as we vary L) are available instantly. A similar technique is described in [5].

A coupled line from any circuit theory program could be inserted as well. This allows invocation of any available circuit theory optimizer, with circuit theory speed and EM accuracy. The extreme power of this methodology is completely changing how we do high frequency design. In practice, we see filter design cycles drop from two weeks to one day using this approach.

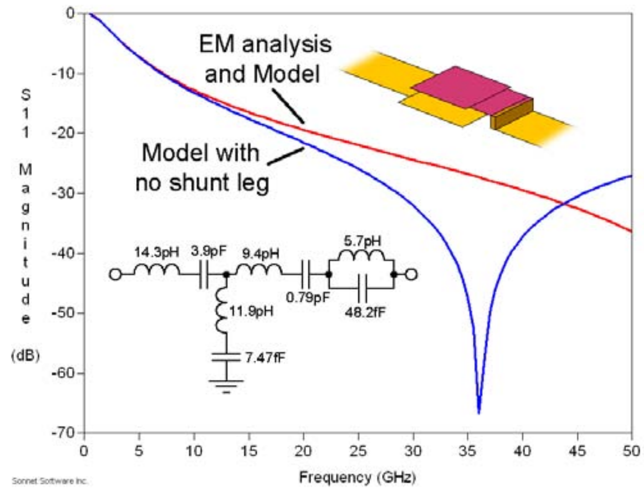

Fig. 6. A simple series capacitor on GaAs requires some sophistication to model. All components shown are significant. For example, removal of the shunt leg with the tiny 7.47 fF capacitor results in the model incorrectly becoming a perfect short circuit at the first series resonance just above 35 GHz.

VI. SMD Model Insertion

During the design process, SMD (surface mount device) models and/or measured data must be inserted into EM analysis of the entire circuit. If working at low frequency, approximately calibrated ports can provide acceptable results. However, critical applications, especially at high frequency, require perfect calibration.

Fig. 4 shows a low pass elliptic filter using three SMD capacitors. In this case, the reference planes are set at the inside edge of each pad, thus including the entire pad in the EM analysis. SMD data and EM port calibration should use the same reference planes. For this example, the SMD data should not include mounting pads as the mounting pads are already included in the EM analysis.

Fig. 5 shows the result with and without port calibration. Below 1 GHz, port calibration is not needed. The rejection band, above 1 GHz, shows substantial sensitivity to port calibration. While it might be possible, depending on stop-band requirements, to use approximate calibration, perfect calibration is clearly preferred.

Notice the current distribution in Fig. 5. The effect of the SMD capacitors on the current is included; current flows through the capacitor to the ground via. The current distribution also shows good isolation between the two connections to the via suggesting that separate vias will not improve stop band rejection. This is in fact true.

A key advantage of including ports in an EM analysis, rather than the actual SMD structures, is that different

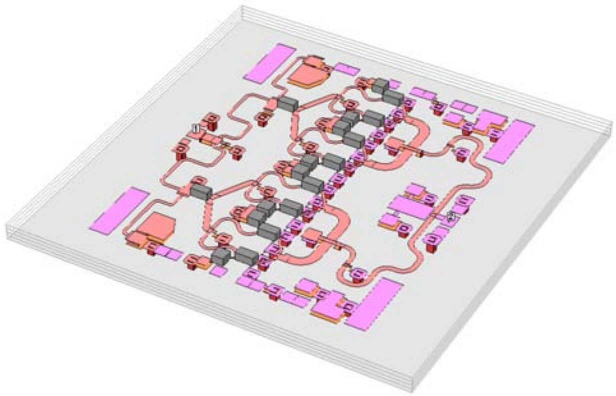

Fig. 7. For RFIC design, all transistors, capacitors, and resistors can be removed, substituting perfectly calibrated ports (small grey boxes). Now, results for design modifications are available instantly. No further EM analysis required.

SMD candidates can be quickly substituted and evaluated at circuit theory speeds and with EM accuracy.

VII. Compact Model Synthesis

By taking an analysis to high frequency, we can dramatically demonstrate the importance of perfect port calibration. Fig. 6 shows a capacitor on GaAs analyzed with perfect port calibration illustrating a new compact model synthesis [6] (patent pending). The synthesis needs no knowledge of the geometry being modeled and the user need not guess model topology in advance. However, perfect port calibration is required; approximate port calibration renders the technique useless.

Fig. 6 also shows the synthesized model; its response is visually identical to the EM result. Note that removal of the tiny 7.47 fF shunt-to-ground capacitance yields unacceptable results (the series inductor has small effect). This sensitivity is due to the fact that without the shunt to ground capacitance, the model incorrectly becomes a perfect short circuit at the first series resonance, just above 35 GHz. We have also found that the more commonly used "pi" model has difficulty properly representing the shunt to ground admittance ($=Y_{11}+Y_{12}$) at resonance.

Why is perfect port calibration needed? First, an extra nH or pF in the ports simply obliterates the model. Second, this synthesis approach fails when there is even the smallest non-physical error, as there is with most port calibration techniques. And third, the high frequency accuracy of this model would be wasted if inserted into an EM analysis with approximate ports.

VIII. RFIC Component Based Design

For RFIC (radio frequency integrated circuit) design, we often like to EM analyze the entire circuit. For example, stability analysis of an amplifier requires evaluation of output to input matching network coupling. This means that internal ports must be used for the transistor. However, even small port discontinuities can completely invalidate analysis at high frequency and high power. Perfect port calibration is critical.

Now that we can remove the transistor and substitute perfectly calibrated ports, we can also remove all resistors and capacitors and substitute perfectly calibrated ports, Fig. 7. With care, we can even remove inductors. In addition, adding "tuning" ports, as in Fig. 3, allows lengths of critical transmission lines to be adjusted as well.

With this approach, only an initial EM analysis of the RFIC interconnect is needed. All components are then inserted and tuned using any circuit theory tool. Thus design modifications (either manually, or under automatic optimizer control) are available at circuit theory speeds. The old way of tuning, changing the layout and doing a complete EM re-analysis, is no longer viable.

IX. Conclusion

Perfectly calibrated internal ports are a new, never before available capability within EM analysis. The impact of this new capability is just now being explored by microwave designers. We describe above using perfectly calibrated ports for split/recombine filter analysis, for inserting perfect tuning ports to fine-tune, or "tweak", the final result, for insertion of SMD models directly into an EM analysis, for providing data to high accuracy compact model synthesis, and for rapid RFIC design and optimization. Perfectly calibrated ports promise to have a substantial impact on microwave design methodology.

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