Microwave Filter Optimization Using Perfectly Calibrated Ports

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Abstract: The “tuning” methodology is illustrated. In this methodology, numerous ports are inserted into the filter resonators prior to EM analysis. Then tuning elements are connected into the filter by circuit theory. The filter is tuned (to meet requirements) by tuning only the circuit theory components. This is done in real time. The alternative is to modify the layout directly and to perform repeated EM analyses. The net result is that the filter can now be tuned at circuit theory speed with nearly full EM accuracy. Design closure typically decreases from about 2 weeks to 1 day.

Keywords: Design, Filter, Microwave, Optimization.

1. Introduction

In tuning methodology [1 – 3], additional perfectly calibrated ports (“tuning ports”) are inserted in and between filter resonators prior to EM analysis of the layout. Thus, instead of EM analyzing a 2-port filter repeatedly while trying to adjust the layout for desired performance; a 20 or 30 or 40+ port layout is EM analyzed once. Then tuning elements are connected into the filter by circuit theory (i.e., nodal analysis) connection to the tuning ports. The tuning elements can be circuit theory based, or EM based, or a combination. Ideally, the circuit theory tuning elements are only a small portion of the overall filter analysis results, with EM analysis responsible for most of the result. Thus, most of the filter is analyzed to full EM accuracy. Circuit theory error, due to the small circuit theory portion of the analysis, is small.

The circuit theory portion of the complete filter analysis can be tuned in real time, at circuit theory speed. If the changes needed for the final filter design are small, then tuning the circuit theory elements allows us to determine the final dimensions of the filter in

Fig. 1. To test an EM analysis, take any filter, split it into two pieces, then connect the two pieces together and see if you get the same result.
The net result is that the filter is now tuned at circuit theory speed with nearly full EM accuracy. Several closely related techniques are described in [4] and [5].

For full application, this technique requires Sonnet’s perfectly calibrated ports, [6] and [7]. However, it can actually be realized at lower frequency (where port calibration is not needed) using nearly any EM analysis tool. This technique can be immediately applied using any microwave design framework (e.g., Agilent, AWR, Cadence) that allows interoperability with an appropriate EM analysis tool. In practice, design closure typically decreases from about 2 weeks to 1 day. In addition, designers can now layout and design filters much more aggressively, for example, generating more compact designs that meet tighter requirements.

Even though port tuning has been available in its present form only for a relatively short time, port tuning methodology is seeing wide application. This is due to the huge reduction in time required for design closure with a typical two week design now being completed in one day. In this paper, we describe what port tuning is and how to test your EM tool to see if it can be used. We then describe an illustrative hairpin filter, where only resonator lengths are tuned. Then we close with an interdigitated filter at 60 GHz that illustrates how to tune coupled line separations, as well as resonator lengths.

2. Testing an EM Analysis for Port Tuning

The six resonator hairpin filter (Fig. 1, top) is split into two pieces, each piece analyzed separately, then recombined into one. This can succeed only if all 28 additional ports, internal to the resonators, are perfectly calibrated. If there is any error at all in the port calibration, then that error is duplicated four times in the middle of each resonator. The result when you connect the two half filters together can be catastrophic.

Note that we divided the filter so that all transmission lines are perpendicular to the dividing line. This is important because coupling between lines that are parallel to and on opposite sides of the dividing line is not included. For example, do not divide this filter in two vertically, between the legs of a resonator! An alternative test is to remove a rectangular chunk from the filter and analyze that chunk separately. Then, connect the separately analyzed chunk back into the filter and see if the response is the real time. The net result is that the filter is now tuned at circuit theory speed with nearly full EM accuracy. Several closely related techniques are described in [4] and [5].

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same as the entire filter. For this test, you will need perfectly calibrated internal ports.

If your EM analysis cannot pass this kind of test, it is unlikely to be useful for port tuning.

3. Insertion of Tuning Ports

In Fig. 3, we see an EM analysis set up for the entire hairpin filter. However, there is something strange in the center of the filter. There is a cluster of many ports in the center of each coupled line section. The first set of four ports are detailed in Fig. 4. Notice that we have taken out a very short length of coupled line. Then we added four ports. Of course, port calibration is critical here. These ports are internal ports using Sonnet’s perfectly calibrated (i.e., to within numerical precision provided no port connecting lines are over-moded) “co-calibrated™” ports. All ports in the same group (group A in this case) and are calibrated as a group. Even the effect of fringing fields that couple between the ports in the group are perfectly removed. In addition, all the ports use an exactly identical global ground reference.

To check that our port tuning is correct, we first add circuit theory coupled lines, Fig. 5. A detail of the circuit theory coupled line that restores the filter’s first coupled line section is shown in Fig. 6. This is done in AWR Microwave Office, however Agilent ADS and Cadence Virtuoso work just as well. The length of the circuit theory coupled line is the same as the length that we removed from the EM analysis (0.0025”) when we inserted the tuning ports. We connect this coupled line so that one line goes from port 3 to port 5 and the other line goes from port 4 to port 6, and we get the original response back, Fig. 2.

Since it is possible to hook up the schematic of Fig. 5 incorrectly, it is good design practice to make sure that when the circuit theory coupled lines are set to the same length as the lines that were removed from the EM analysis (for the tuning ports), that you get the original filter response back. Once you have confirmed your port tuning schematic, you may now tune and optimize your filter.

For example, the length of line that was removed from the EM analysis (to make room for the tuning ports) is 0.0025” long. When the length of all the circuit theory coupled lines (Fig. 5, 6) are set to 0.0025”, you should get the same filter response as when you analyzed the original 2-port filter.

Now, you can optimize and/or tune the filter. Most microwave design frameworks have a tuning tool. You are given a slider bar to vary component values in real time. For example, if you increase the length of one of the circuit theory coupled lines from 0.0025” to 0.0035 inch, you will see the response of the filter as if that coupled line section were 0.001” longer. If you decrease the length of the circuit theory coupled line section to 0.0015”, you now see what the filter response will be if that coupled line section were 0.001” shorter. You can even set the circuit theory coupled lines sections to negative length…that is just fine for circuit theory. Keep in mind that you are making all these changes in real time. There are no further EM analyses!
4. Tuning Coupling Between Resonators

We have seen how to tune resonator lengths. How do we tune coupled line separations? To see one way of doing this, we return to transmission line basics, Fig. 7. In the top left of this figure we see a circuit theory coupled line. We have set the even mode impedance to infinity. This means that the transmission line ground plane is an infinite distance away and no power can be propagated in the even mode. Thus, this coupled line is like a parallel wire transmission line (like TV twin-lead). The impedance of this transmission line is the odd mode impedance of the coupled line. For the odd mode, current goes out one line and returns on the other. Since the far end (the right end) is open circuited (the x’s), this is an open circuited stub. The Smith chart shows what happens to an open circuit impedance (beginning of arrowed line) that is transformed along 45° of transmission line (i.e., counter-clockwise along 90° of Smith Chart). It becomes a capacitor.

The important observation here is that the odd mode on a 45° length of open circuited coupled line looks just like a capacitor. The capacitor value does indeed depend on frequency, as we discuss below. The reason we choose 45° is because that is half of a 90° long coupled line. Filters are often composed of 90° coupled line sections and we are going to use either two capacitors, or two 45° odd mode open circuited stubs to tune each half of each 90° long coupled line section in a filter.

In the schematic of Fig. 8, the shaded areas have all been laid out and passed to EM analysis. Internal perfectly calibrated ports in the EM analysis allow connections to the circuit theory tuning elements (with a white background). Here, we have a short length of circuit theory coupled line (only a very small percentage of the total calculated filter response is due to circuit theory). This length of coupled line tunes the length of the coupled line section.

Now, we also have tuning capacitors. These capacitors simulate changing the separation between the coupled lines in the EM analysis. We optimize all the circuit theory tuning elements to give us the desired filter response. Then, we change the length of each coupled line section to correspond to the length of line added (or subtracted) by the tuning coupled line. Next, we must figure out how much to change the coupled line separation so that we get the same effect as the optimized tuning capacitors shown here.

In the right half of Fig. 9 (ports 3 and 4) we have a circuit theory model of the original coupled line. The value of the tuning capacitor has been set by the designer seeking to meet filter requirements. On the left side, we have a circuit theory coupled line that we can tune. We tune the separation of left hand
coupled line (with no tuning capacitor) to give the same S-parameters as the right hand coupled line (with original separation + tuning capacitor). We then modify the separation of the coupled line section in the filter layout to match that of the, now tuned, left hand coupled line.

Prior to fabrication, you should probably do a confirming EM analysis of the entire filter with the new dimensions. Even though we use circuit theory for a very small portion of the complete filter, circuit theory can indeed introduce errors. If the confirming EM analysis does not meet your requirements, then you can repeat the above process. First create a new tunable EM analysis using the new dimensions. When you repeat the tuning process, circuit theory will be an even smaller part of the entire response and a confirming EM analysis should be almost exactly what you want.

Using capacitors to tune coupling between resonators works best for narrow band filters. This is because what we really need is a capacitor that varies as a function of frequency. Is there such a component? Certainly. In fact, it is in Fig. 7, the 45° long open circuited stub. Just substitute it for the capacitors of Fig. 8 and 9 and tune its odd mode impedance.

5. Example Filter

Fig. 10 shows an example 60 GHz interdigitated filter with tuning ports already inserted. Circuit
theory tuning elements are inserted by means of an AWR Microwave Office schematic in Fig. 11. Note that open circuited tuning stubs, all placed on the right hand side of the schematic, are used to tune the coupling between resonators. Capacitors could have been used, but the bandwidth of this filter is wide enough, we really need to use the frequency variable capacitors, described above, to get an accurate optimized bandwidth.

Fig. 12 shows the initial, untuned response. Also shown is the EM analysis of the original 2-port filter (i.e., no tuning ports), confirming that the tuning model is correct. (Be cautious, it is possible to have errors in the tuning model that are not caught by comparison to the confirming EM analysis.) Differences between the tuning model and the confirming EM analysis are due to the circuit theory models starting to fail for this filter. Circuit theory is failing because the frequency is too high and the substrate is too thick. A good filter can still be built, it is just that use of circuit theory must be kept to an absolute minimum. In extreme cases, we can substitute EM analysis for the circuit theory tuning elements.

Fig. 13 shows the result of the second iteration of the tuning methodology. A second iteration was required because of the circuit theory model error leading to slightly incorrect layout modifications. For the second iteration, it is important to keep the optimization changes to minimum. This keeps the circuit theory portion of the overall filter analysis to a minimum, and thus also keeps circuit theory error to a minimum. The full, 2-port EM analysis of the filter with the new dimensions shows that our filter design is complete.

6. Conclusion

The various forms of the port tuning methodology are being rapidly and widely adopted throughout industry as designers start to realize the incredible power of this approach. Using port tuning, a designer can come to closure on a filter design in about one day, rather than about two weeks as is common using older methodologies. This new methodology allows optimization to occur at circuit theory speeds, and with near full EM accuracy. We illustrate this technique using a hairpin filter at 4 GHz and an interdigitated filter at 60 GHz.

References