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Why FR-4 Is Often Inadequate for RF Design

By Ed Troy

Many times, designers want to use FR-4 for RF and microwave circuit designs. After all, it is less expensive than other materials, like Rogers 4350, and much less expensive than reinforced PTFE composite boards such as Rogers RT/Duroid 5870. However, sometimes it is necessary to spend the money for higher quality circuit board material and processing to get good, repeatable designs.

In this paper, to demonstrate the danger of using FR-4 for some designs, I will design a bandpass filter to work in the 2.4 GHz FCC Part 15 band which is typically used for WiFi, Bluetooth, Zigbee, cordless phones, and many other applications. The filter will be designed using the microwave filter design tool that is part of the Keysight (formerly Agilent) Genesys suite of RF and microwave design software. The pass band is defined as 2.4 to 2.483 GHz. I set an insertion loss goal of 3 dB. The filter program first designs a filter which is close to the desired performance, but it must be optimized to get the performance that is closest to the desired performance. In the case of the first filter, I used FR-4 with a dielectric constant of 4.5, a loss tangent of .010, and a thickness of 59 mils. The metallization is 1 oz rolled copper. Figure 1 shows the final, optimized performance.

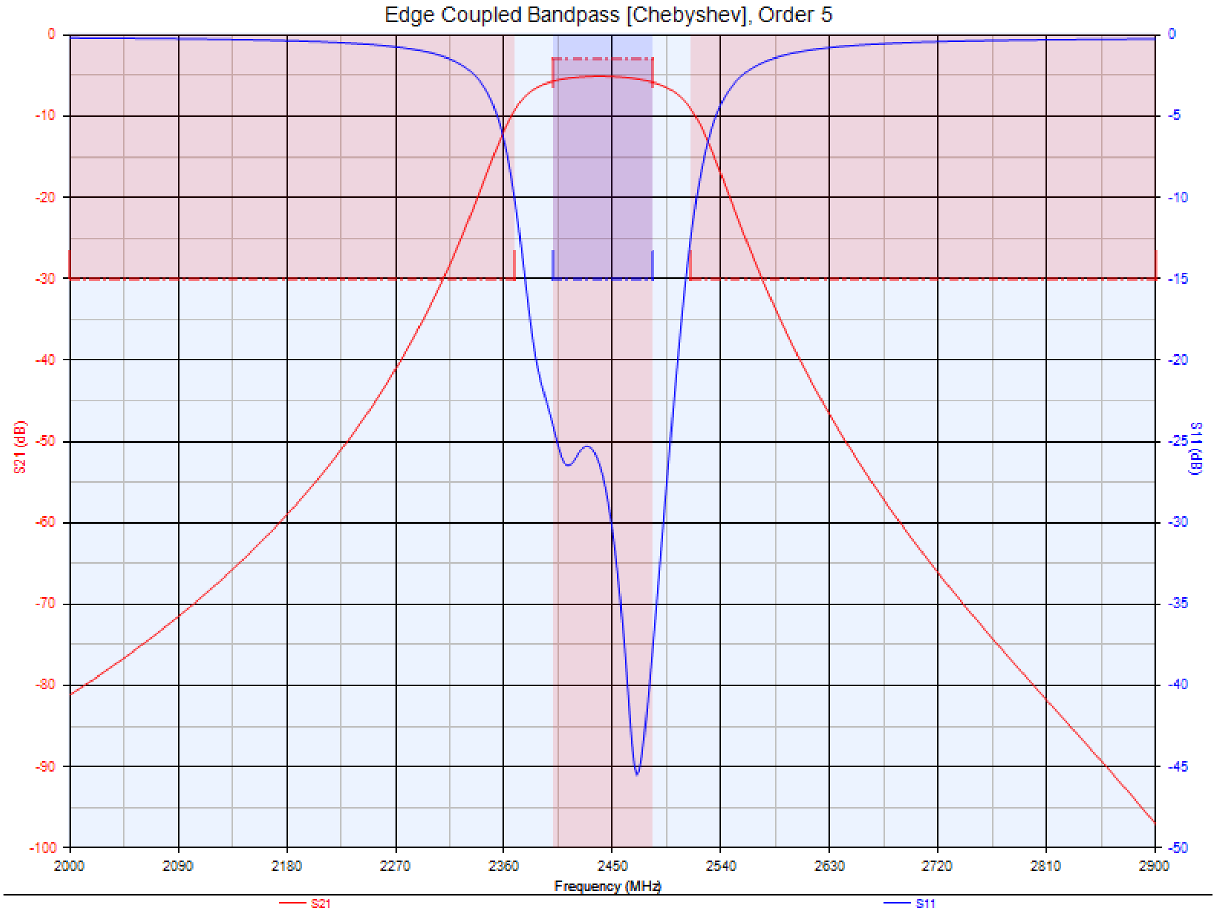

Figure 1 Optimized response of 2.4 GHz bandpass filter on FR-4

As we can see, it did not come very close to meeting the rejection goals, and the insertion loss is pretty horrendous at about 5 dB.

Next, we will look at the performance of that filter as the dielectric constant of the FR-4 varies over the "normal" range for FR-4, which is about ± 1.

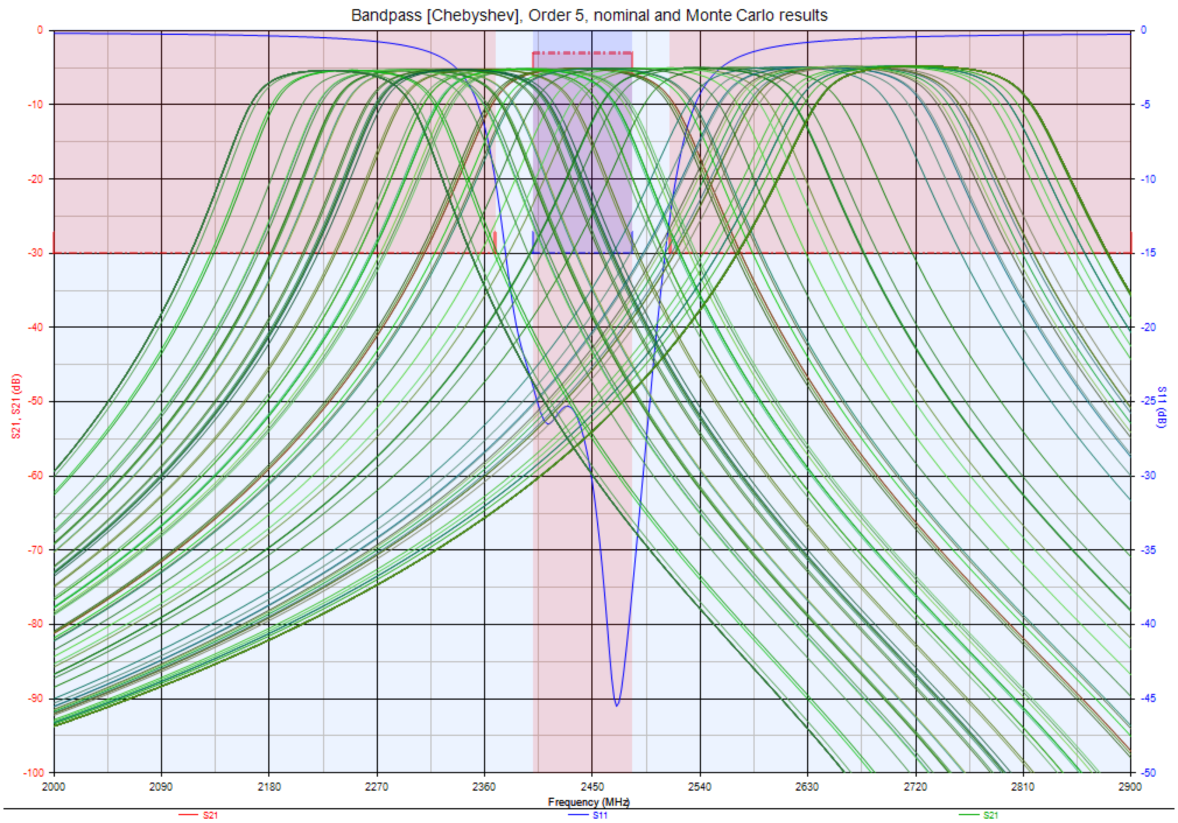

Figure 2 Performance of filter shown in Figure 1 when dielectric constant of FR-4 varied from 3.5 to 5.5

Clearly, this filter would be useless in any kind of a production environment. In fact, the only way you could have any hope of producing a filter that even came close to working would be to measure the dielectric constant of your board material before etching the copper to be sure it was, indeed, 4.5. Figure 2 only shows the various S21, or insertion loss, plots. It does not show return loss, S11, but it is obviously going to be all over the place as well. I did not show it only because it would uselessly clutter up the graph. Also, this Monte Carlo simulation did not take into account variations in the thickness of the board, over-etch or under-etch of the copper pattern, or variations in the loss tangent. Those factors would only make the situation worse.
Next, I designed the same filter using Rogers RT/Duroid 5870. This is a very high quality microwave dielectric material. It has a dielectric constant of 2.33 ±.02. It has a loss tangent of .0012 (which is an order of magnitude better than that of the FR-4) and a thickness of 62 mils. Again, I used 1 oz rolled copper for the metallization. (Actually, the dielectric constant of 62 mil RT5870 is 2.333 according to a calculator program from Rogers Corporation called MWI-2014, but I am ignoring that for this paper. However, if you wanted to actually build this filter, it would be prudent to use that value in you design effort.)

Figure 3 shows the simulated performance of the optimized filter. This is clearly a huge improvement. The insertion loss is about 3 dB, 2 dB better, and the rejection is much better.

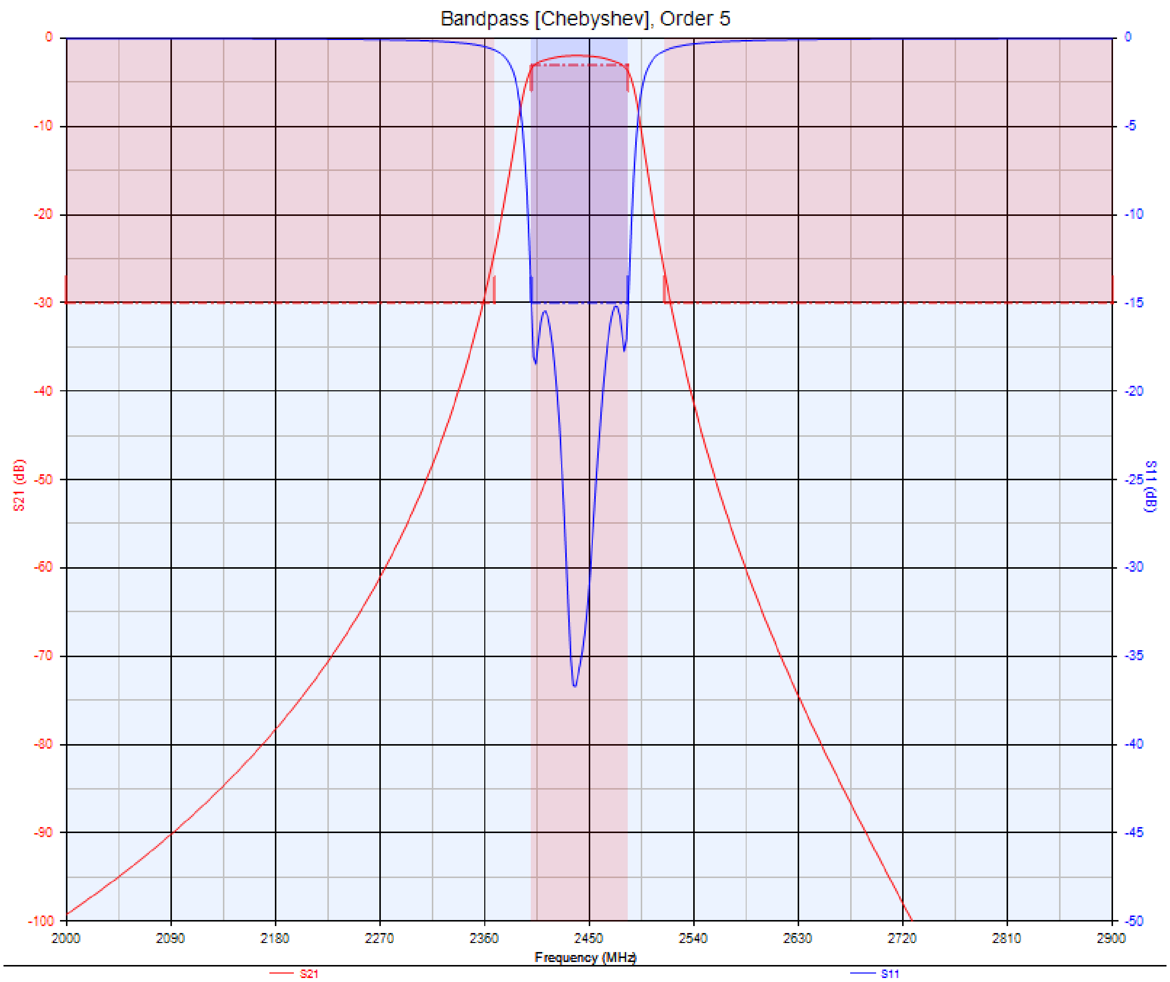

Figure 3 Simulated performance of optimized filter on RT/Duroid 5870 material

Now for the real test, and a critical reason for choosing materials with a more consistent dielectric constant. I performed a Monte Carlo analysis on this filter, again varying only the dielectric constant. But, in this case, we only had to vary it over a range of ±.02, instead of ±1. The result is dramatically better, as shown in figure 4.

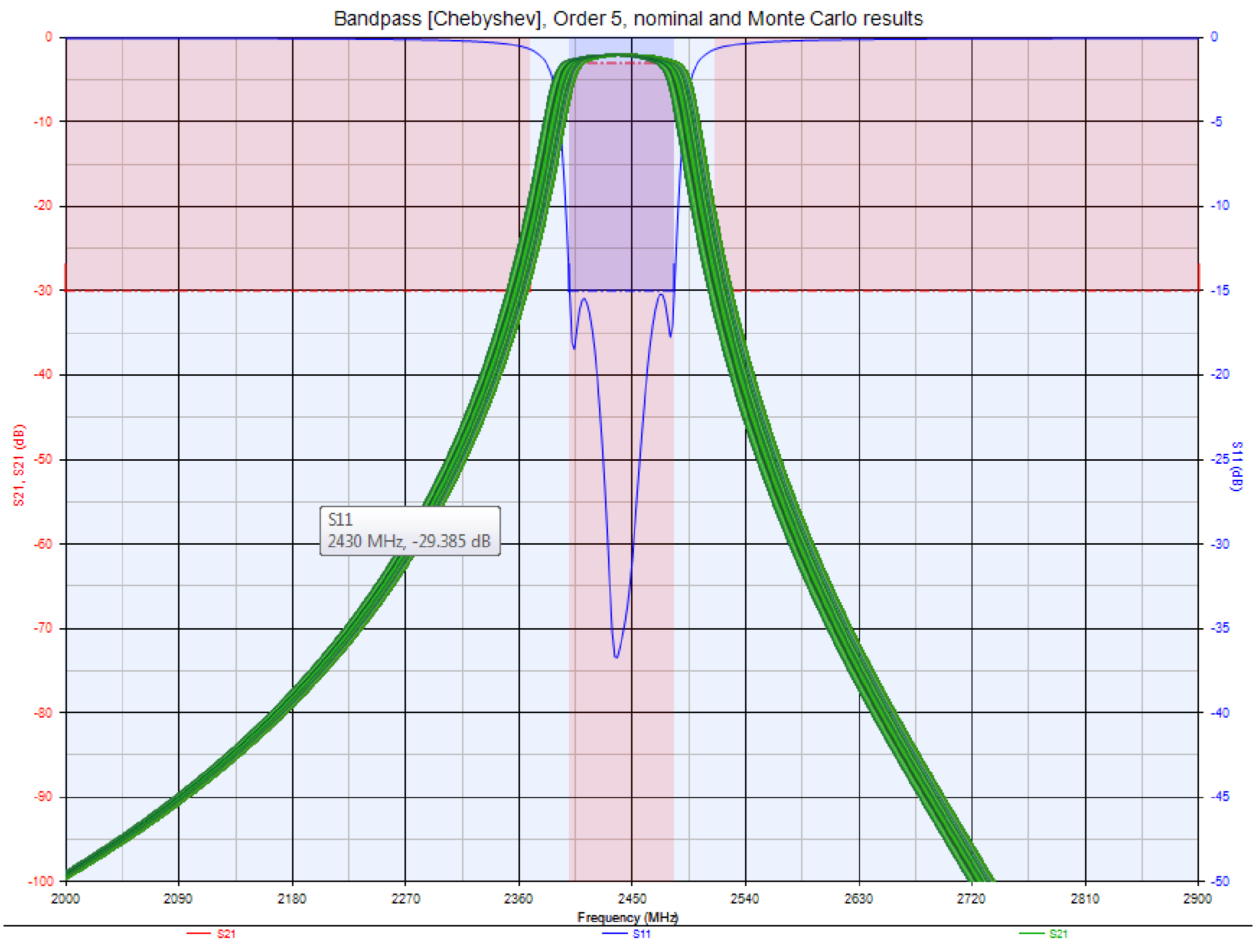

Figure 4 Monte Carlo analysis of RF/Duroid filter

This is a filter that might actually work for a real product that could be reliably re-produced. Of course, this filter does not meet the pass band and stop band requirements, either, but it is sure a lot closer. But, those limits were arbitrarily set. In a real design, this might be adequate. If a better pass band or stop band response was required, then the filter would need more poles. This would make it larger, and it would increase the insertion loss, somewhat, but those are the trade-offs that are necessary when designing microwave filters. Alternatively, other materials, with even lower loss, could be used. This would tend to sharpen the stop band rejection and decrease the insertion loss. Thus, it might be possible to meet the design goals without having to go to more poles. If smaller physical size was required, a material with a higher dielectric constant could be used.

Figure 5 shows the results of an electromagnetic simulation using Momentum GXF from within Genesys on the same graph as the original optimized linear simulation of the RT/Duroid filter. It clearly shows that before attempting to actually manufacture this filter, the design would have to be optimized within an EM simulation program to obtain proper performance. (EM simulation results are in green and orange.)

Figure 6 shows what the filter would look like. This circuit board is about 4.8" x 3.9".

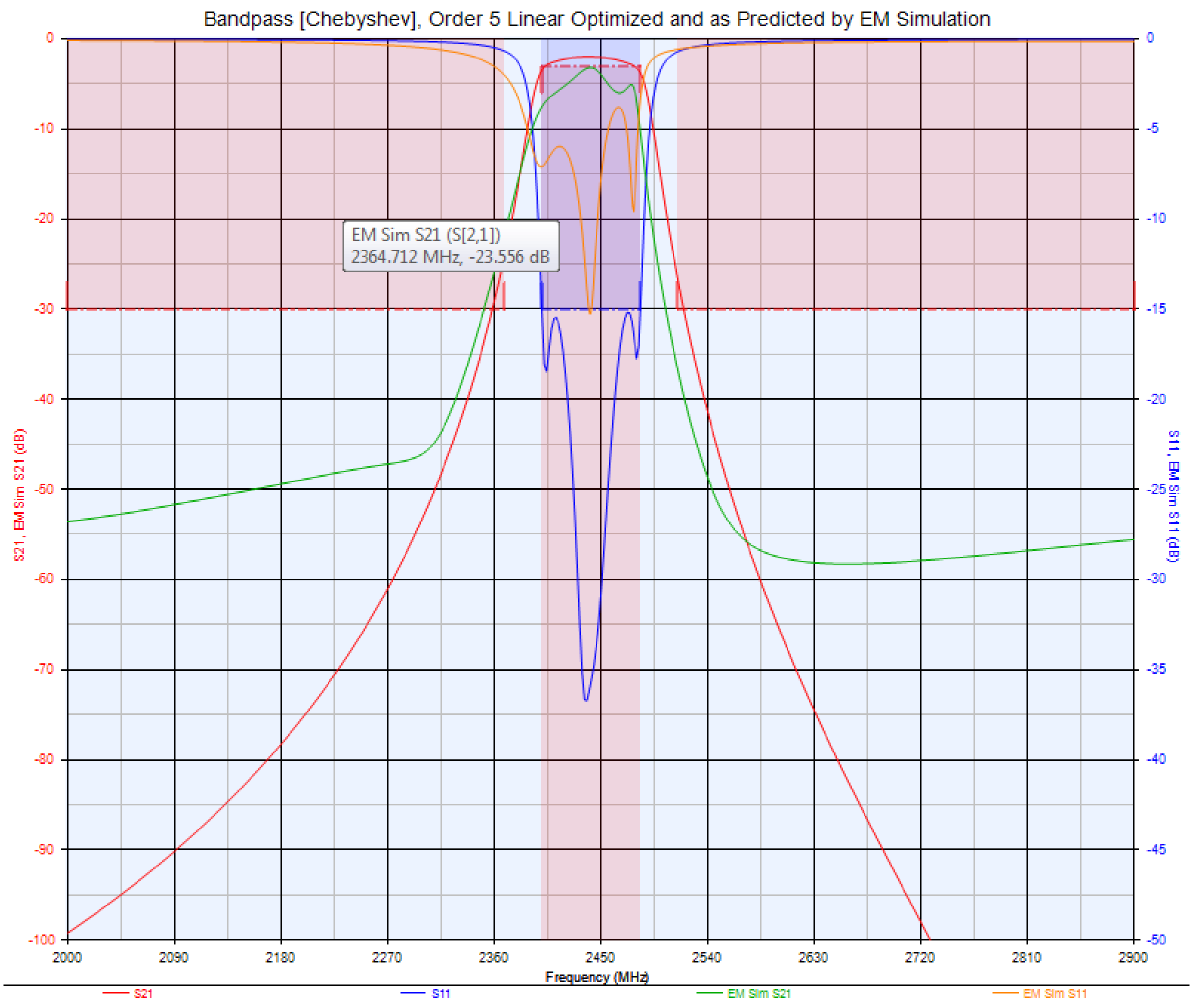

Figure 5 RT/Duroid 5870 linear and EM simulation predictions

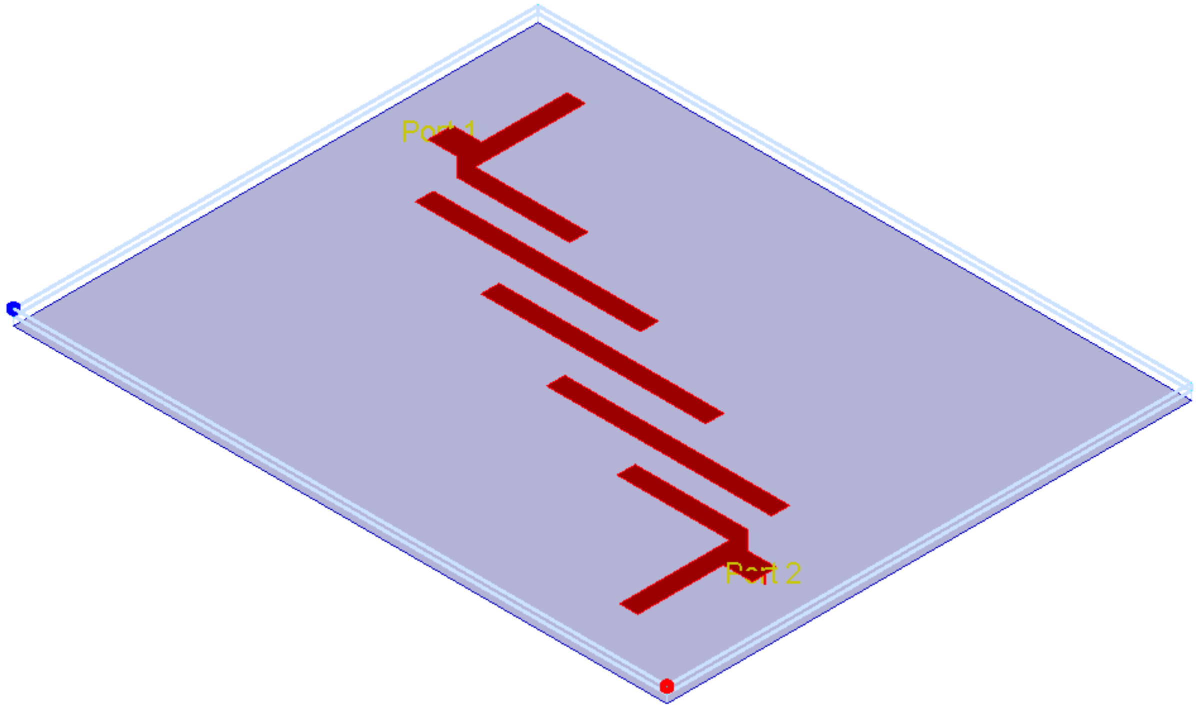

Figure 6 Physical appearance of RT/Duroid 5870 bandpass filter

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