Recipes for Printed Hairpin Filters

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Printed hairpin filters like the one in Figure 1 are popular for the lower microwave bands — they are used in all the KK7B no-tune transverters[1]. The filters consist of a series U-shaped ½λ resonators edge-coupled to their neighbors. Design of these filters has traditionally been somewhat empirical — cut-and-try. Jim Davey, WA8NLC (now K8RZ) worked with Rick Campbell, KK7B, to develop the hairpin filters for the no-tune transverters[2].

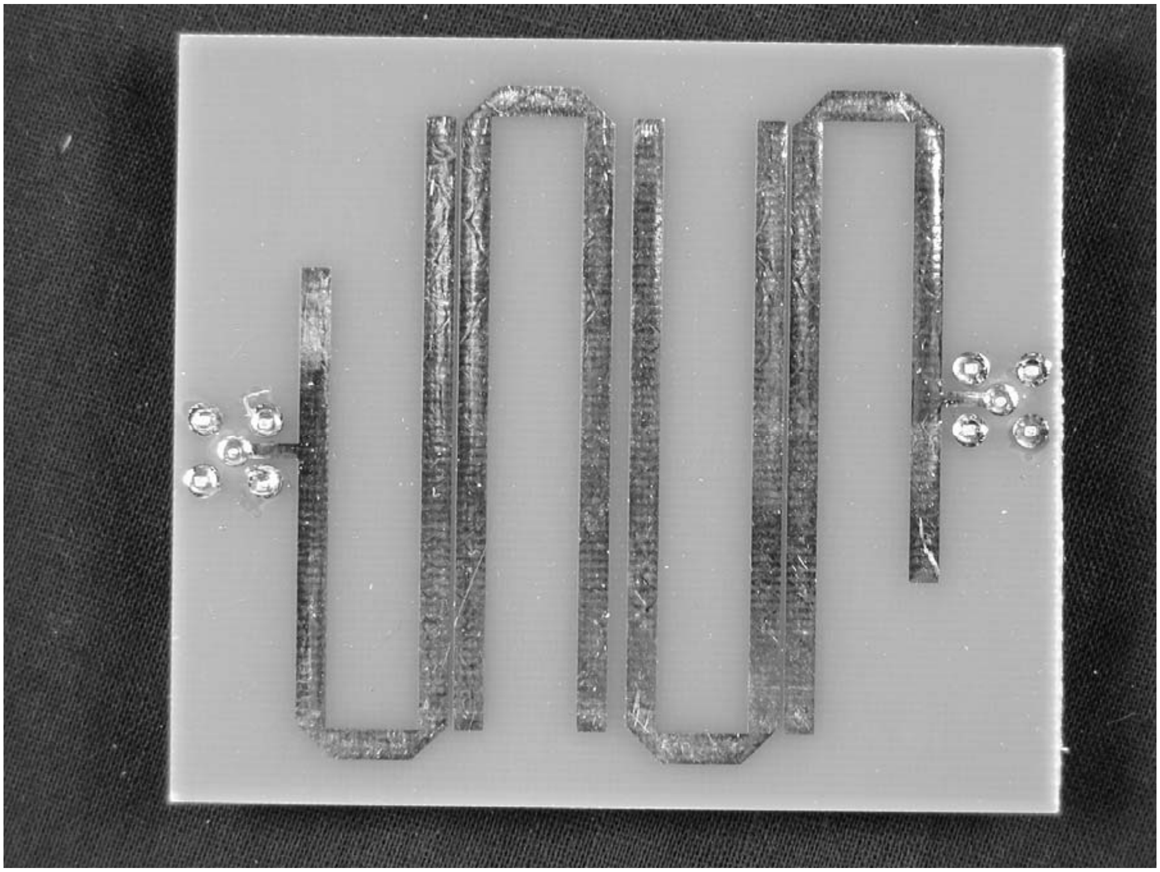

Figure 1 – Printed Hairpin Filter with tapped input and output

There are a number of papers in the literature describing design procedures for hairpin filters, but they seem to be long on matrix math and short on practical dimensions. Another alternative is software, but useful filter software is either very expensive or *really* expensive.

In 2003, I described[3] the design of printed hairpin filters like the one in Figure 2 using a free version (Student Version) of Ansoft Serenade and Harmonica software, with good results. However, this software is no longer readily available, and it has a learning curve that could deter many hams. The replacement free software, Ansoft Designer SV[4], has some powerful features, but the features needed for accurate filter design are not available in the free version.

Filter Design

For my simple and cheap multiband transverters[5] like the one in Figure 2, I made printed hairpin filters for a number of frequencies. I did the initial design using the Planar EM simulator in Ansoft Designer (not included in the free version), then correlated the prototype performance to the predicted performance and adjusted the parameters to match the prototype results.

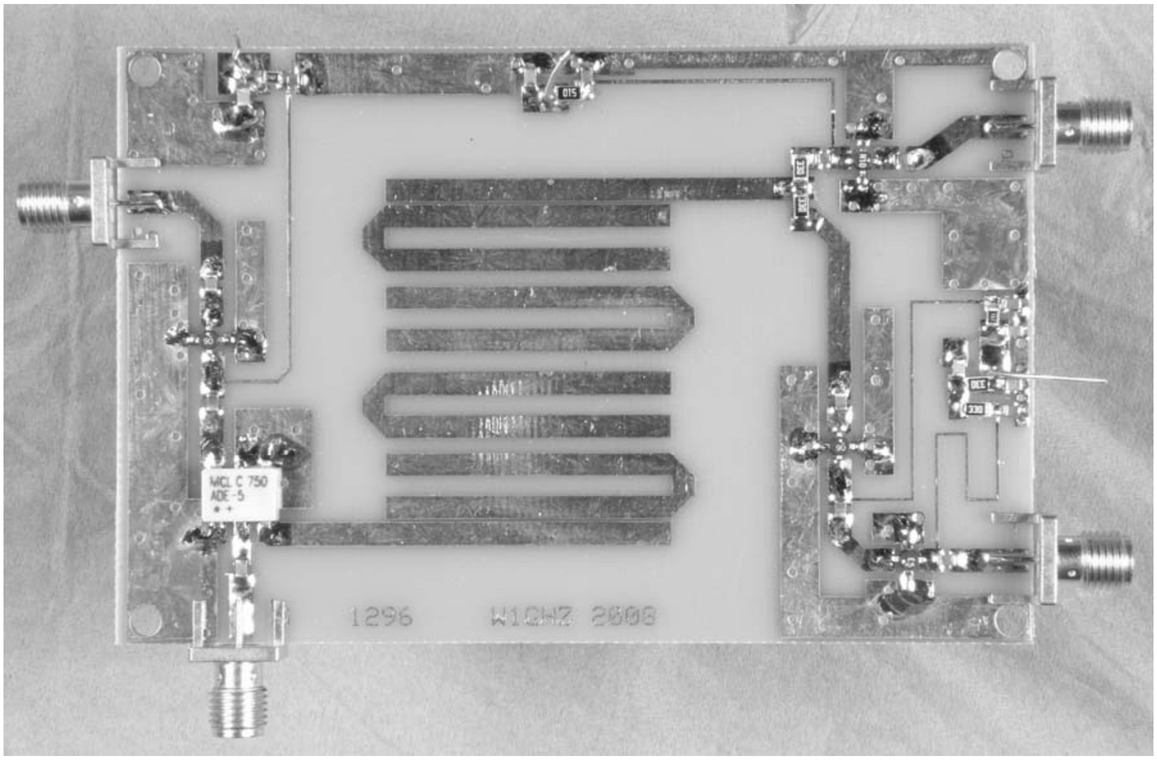

Figure 2 – 1296 MHz Transverter with printed hairpin filter

All my PC boards are made by ExpressPCB[6], using their free layout software. They provide excellent quality at an affordable price. Although the ordinary FR-4 dielectric is not specified for RF or microwave performance, the board have proven quite consistently reproducible. This allows me to make modest quantities of these transverter boards available at reasonable cost.

The FR-4 material consists of woven fiberglass cloth impregnated in an epoxy resin – the dielectric constant varies with the relative proportions of the two materials. The FR designation signifies that a flame retardant has been added – these are said to be lossy at microwave frequencies. FR-4 has a nominal dielectric constant of 4.5, which may vary from 3.9 to 4.6, and a nominal loss tangent of 0.02. The wide range of dielectric constant would make it difficult to design reproducible filters, which is why I stick to one source. Figure 3 shows that it would be difficult to make a hairpin filter for 1296 MHz with the wide range of dielectric constant.

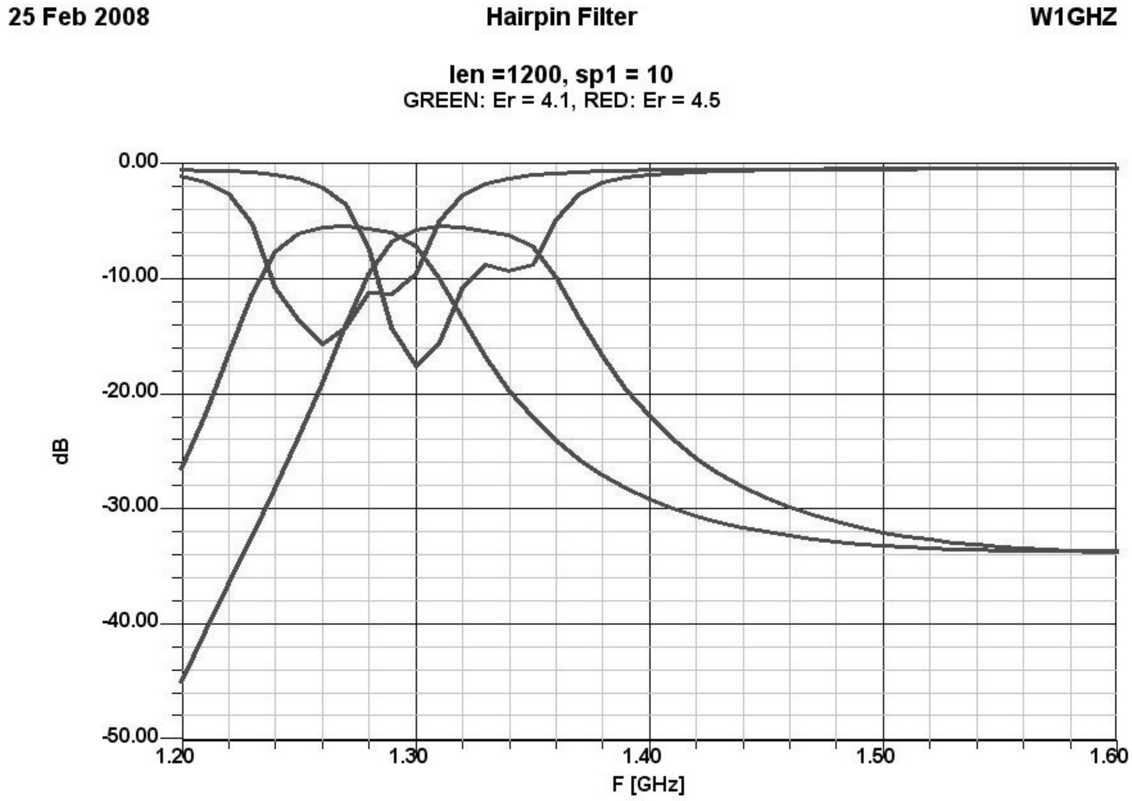

Figure 3 – Effect of Dielectric Constant on printed hairpin filter frequency

My previous hairpin filter experiments, using Ansoft Serenade, suggested that the dielectric constant for the ExpressPCB boards was about 4.1, so I designed the filter centered at 720 MHz shown in Figure 4. Measured results, shown in Figure 5, show that the center frequency is lower than simulated,suggesting that the actual dielectric constant is higher, but 720 MHz is still within the passband so the filter was usable. I later adjusted the dimension to cover 720 to 760 MHz so the filter is usable for the LO of a 902 MHz transverter as well.

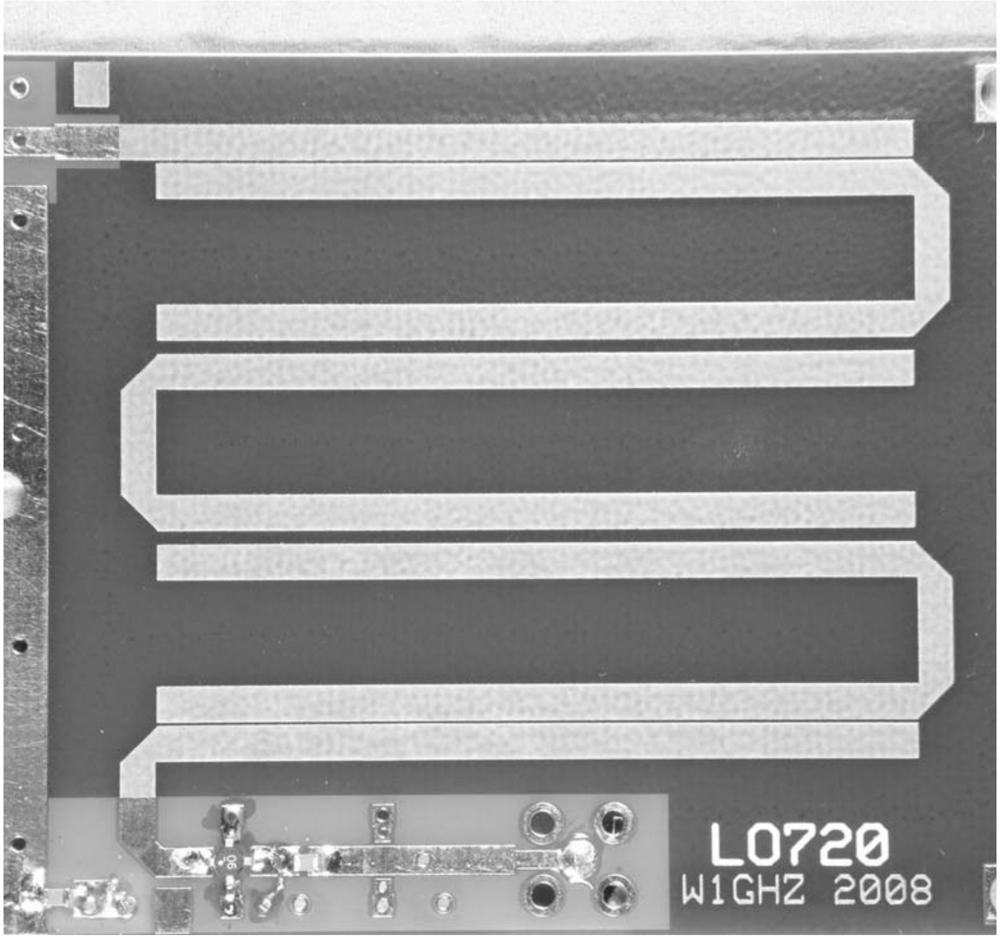

Figure 4 – 720 Mhz Printed Hairpin Filter with coupled input and output

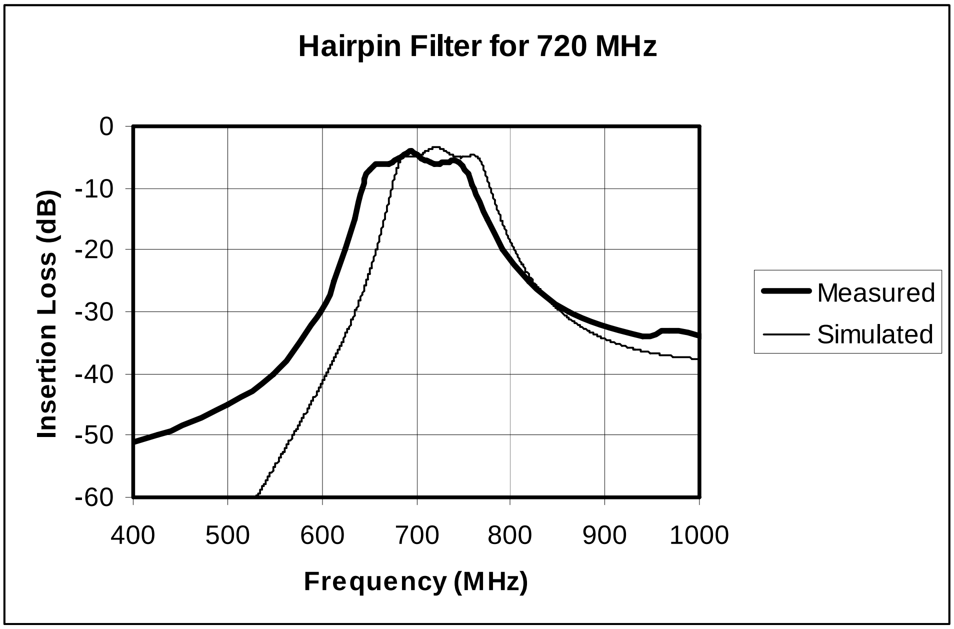

Figure 5 – Frequency response of 720 MHz hairpin filter

However, I needed a better handle on the dielectric constant to be able to design filters that work the first time. I went back to Ansoft Designer and varied the dielectric constant to match the measured data; Figure 6 shows some of the correlation curves. It appears that the best dielectric constant is 4.25 to match Ansoft Designer with ExpressPCB boards. This number may not be the best match for other software or PCB suppliers.

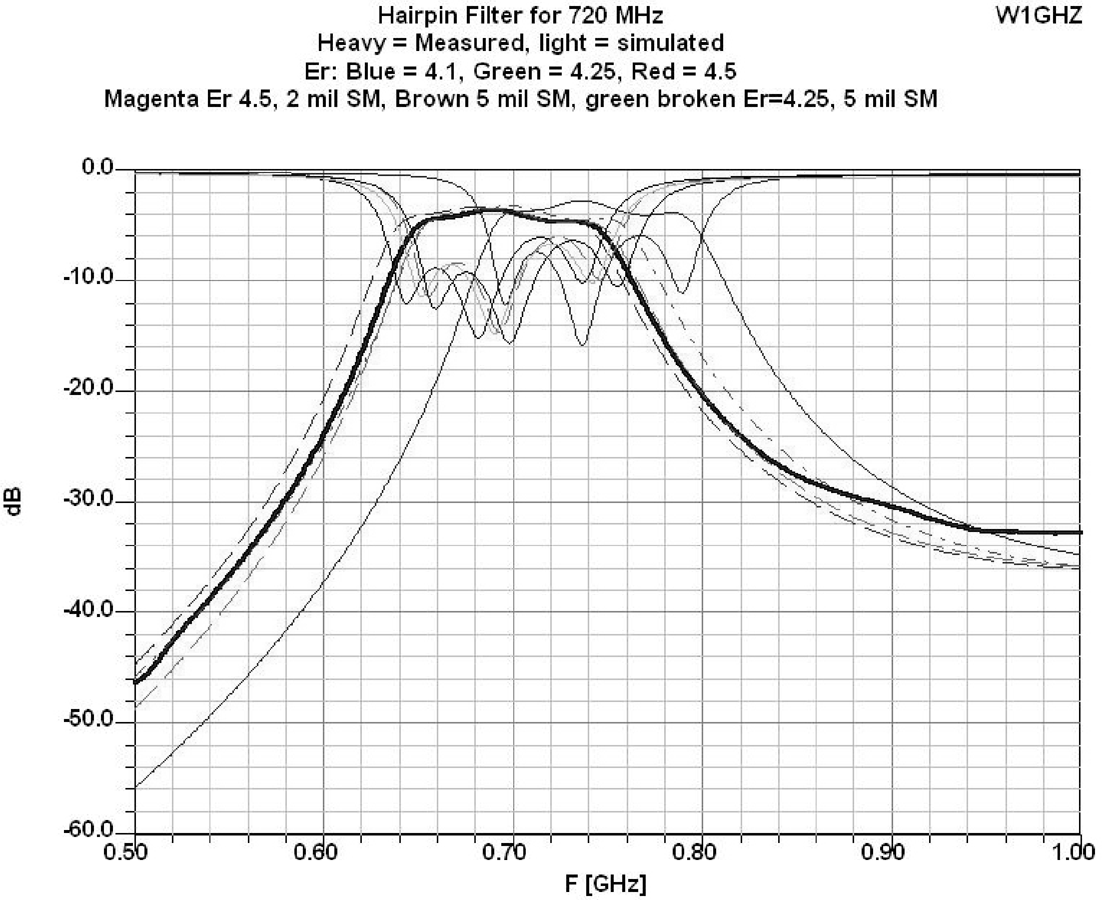

Figure 6 – 720 MHz hairpin filter curves for Dielectric Constant correlation

The filter in Figure 4 has soldermask over the copper, giving it the green color. This plastic film protects the copper, but I don't have a good handle on its thickness or dielectric constant, so I omitted soldermask from higher frequency filters.

Once we have some confidence in the software, we can try to optimize the dimensions. The 720 MHz filter has some ripple in the passband, in both measurement and simulation. This suggests that the filter might be overcoupled. Varying the spacing between the hairpin controls the coupling; Figure 7 shows how the bandwidth changes with spacing, without significantly increasing the loss – the FR-4 material does have a bit of loss, but remember: ***gain is cheap***.

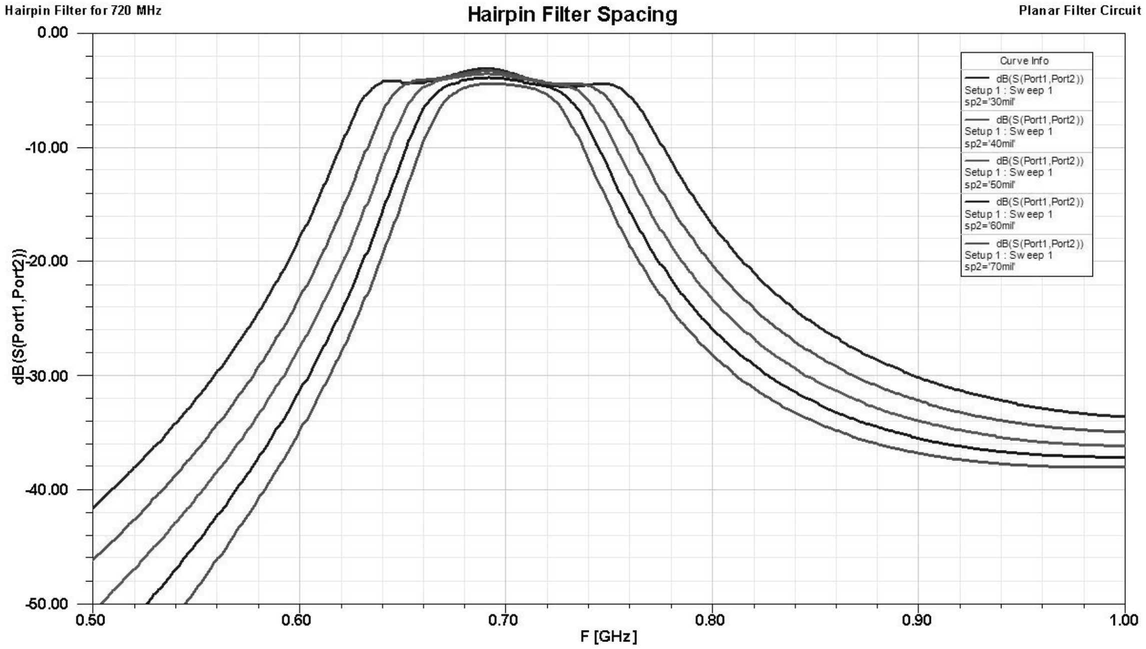

Figure 7 – Effect of hairpin spacing on filter frequency response

I varied all the dimensions and found that there was no clear optimum, just a set of tradeoffs. After I found a pleasing combination, I rounded off the dimensions to the nearest 10 mils and ran it again to make sure it was still close. Using round numbers is arbitrary – results would be roughly the same if I used 0.25 mm instead of 10 mils as a round number – but round numbers sure make layout easier.

The most critical dimension is the spacing of the input and output lines. The filters in Figures 2 and 4 use closely coupled ¼ λ lines, while the filter in Figure 1 uses tapped input and output. I found that the closely coupled lines provide a better VSWR. I chose a spacing of 10 mils to make it more reproducible; a tighter spacing of 6 to 8 mils would give slightly better performance, but the dimension would be more critical. ExpressPCB seems to be able to hold the 10 mil dimension consistently, which would be difficult with hand-made boards – the tapped input and output is probably better for homebrew boards. All the original no-tune transverters use tapped input and output for hairpin filters.

Once the critical dimension is fixed, the others are adjusted for desired performance – all dimensions interact. The results are good – Figure 8 shows that the measured performance of the highest frequency hairpin filter that I have made closely matches the predicted performance. Note that the stopband rejection is much greater on the low-frequency side. This is typical of the coupled input and output; for the tapped input and output, rejection is greater on the high-frequency side.

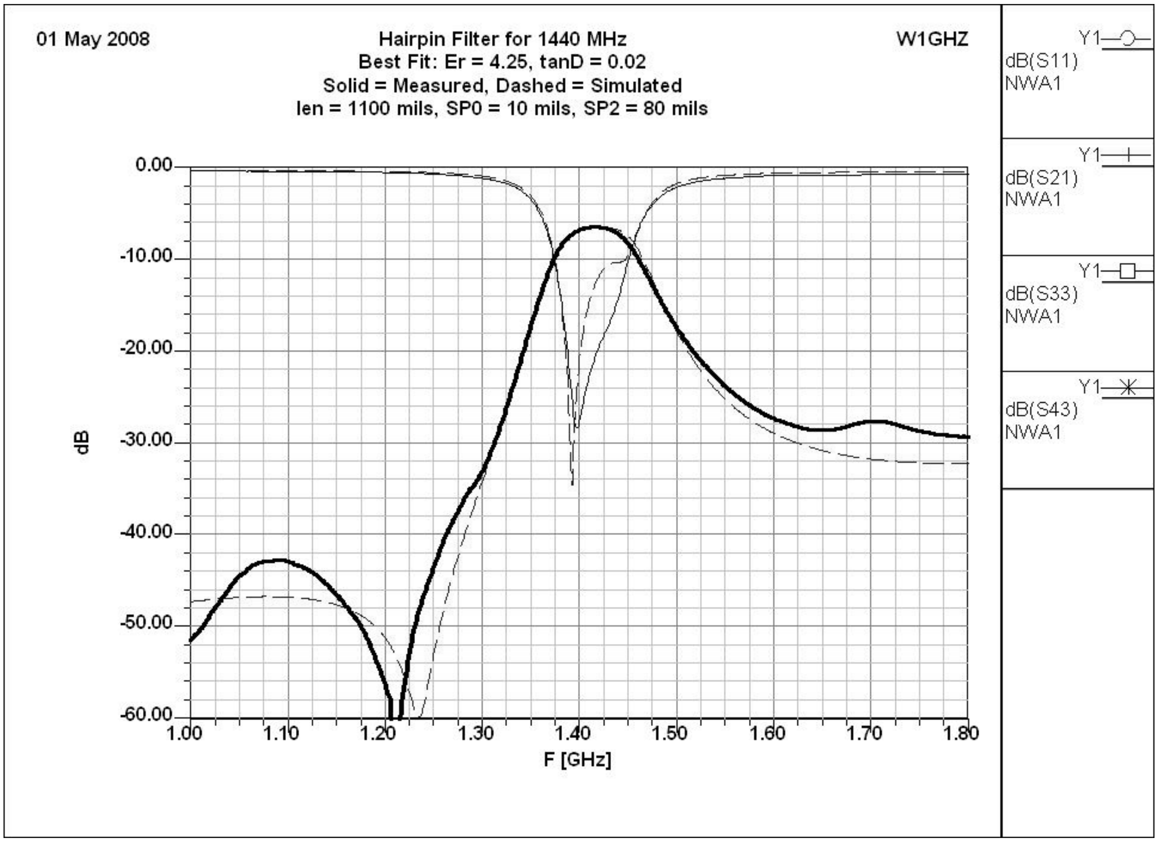

Figure 8 – Measured frequency response matches simulation

Hairpin Filter Recipes

I have made and tested hairpin filters for 902, 1152, 1296, and 1440 MHz, all using the same dimensions, changing only the length of the hairpin legs. The dimensions are identified in Figure 9, and listed in Table 1. The dimensions in Table 1, and the curve of frequency vs. length in Figure 10, provides a simple recipe for filter design.

The filters are symmetrical – one end is a mirror image of the other – so only one end has dimensions identified. Filters with four hairpins, like Figure 2, have one additional dimension, **SP3**, the center space between the two inner hairpins.

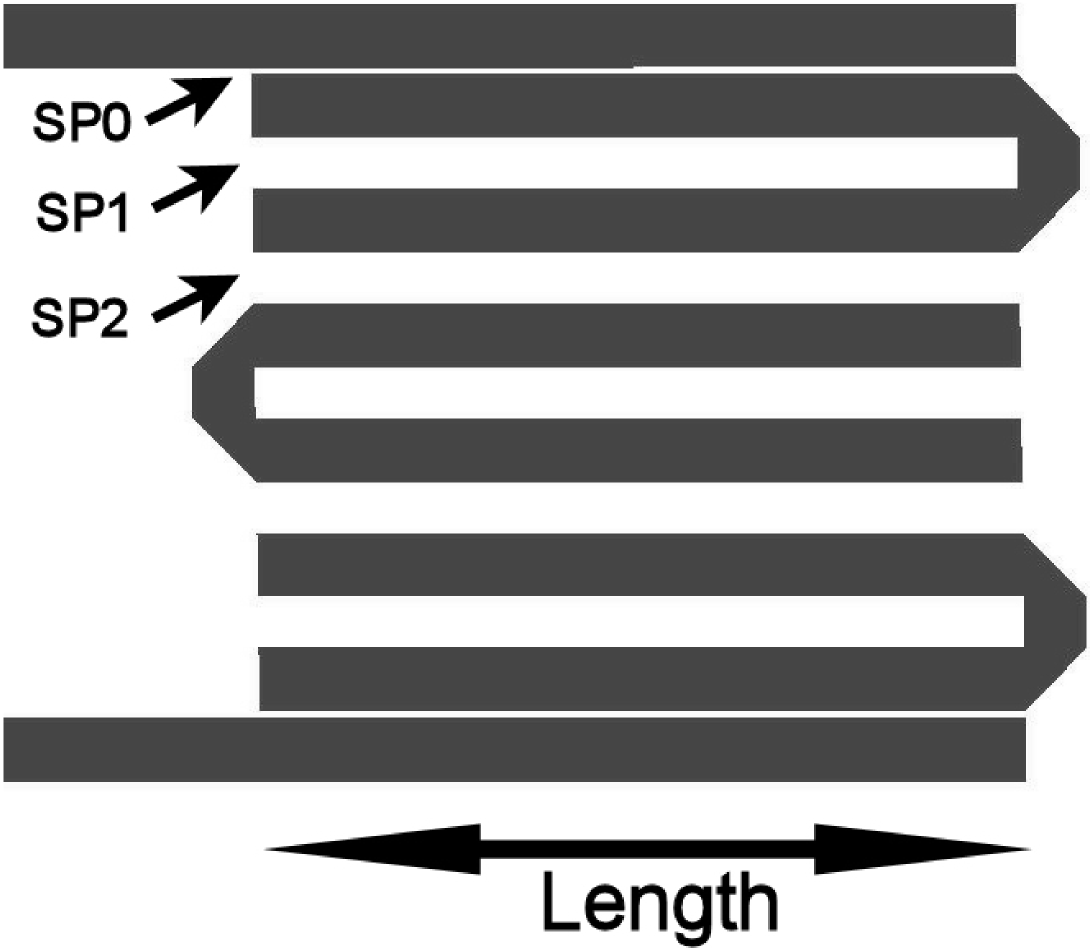

Figure 9 – Locations of Dimensions in Table 1

Dimension	3 Hairpin	4 Hairpin	
S0	10	10	mils
S1	80	80	mils
S2	80	60	mils
S3	na	80	mils
Line Width	100	100	mils
Length	Center Frequency – Fig 10		
			W1GHZ

Table 1

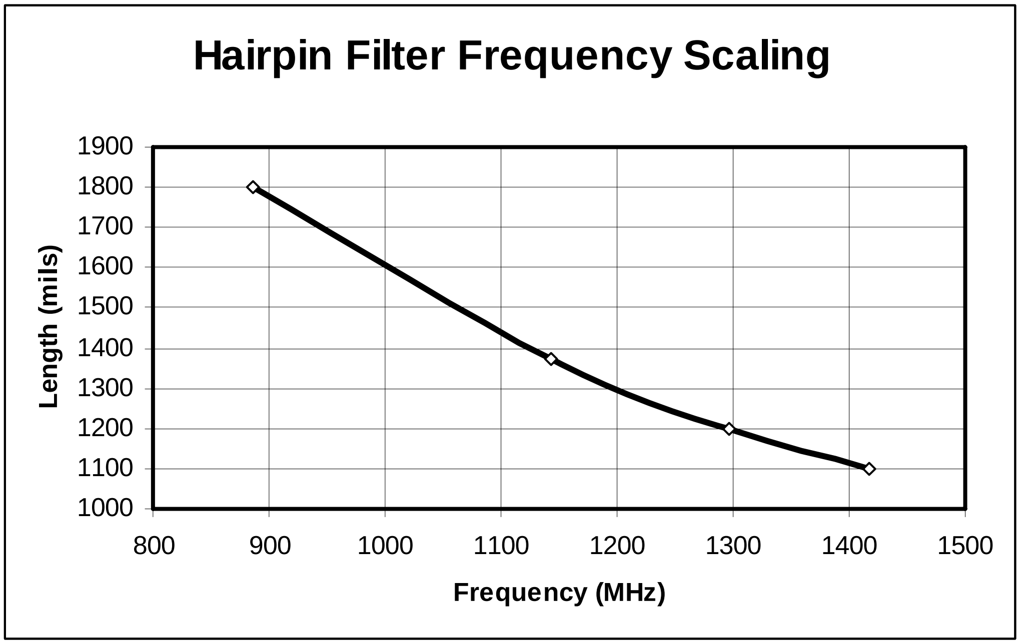

Figure 10 - Hairpin Filter Center Frequency vs. Length Dimension

Filter Performance

I made printed hairpin filters for 902, 1152, 1296, and 1440 MHz using the dimensions in Table 1 as part of the cheap and simple transverters. To test them, I simply cut up transverter boards and added SMA connectors. The performance of the three-hairpin versions is shown in Figure 11 – loss is about 6.5 dB.

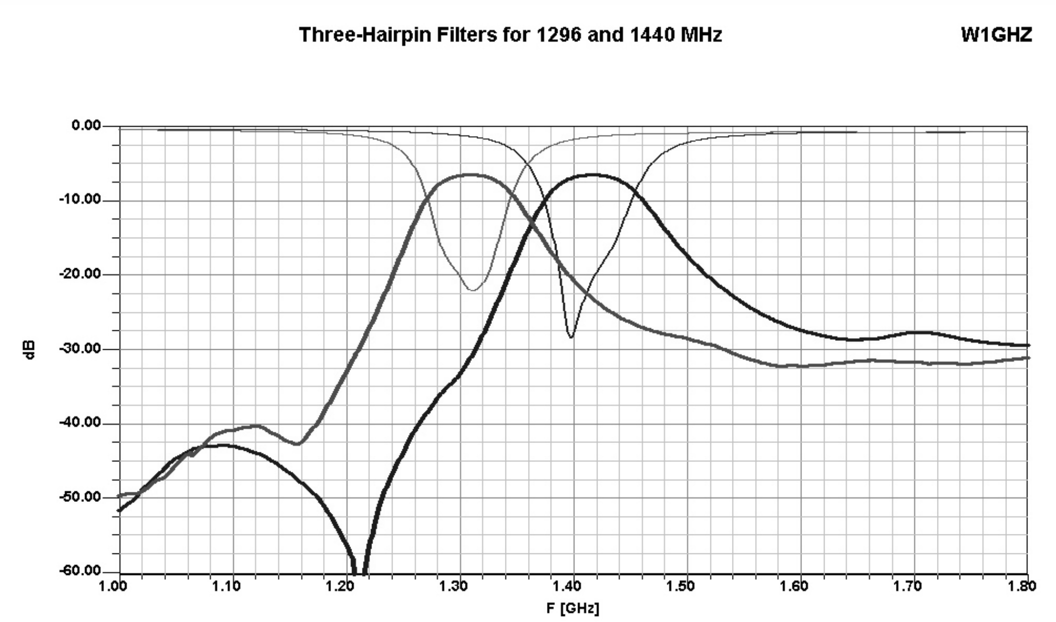

Figure 11 – Frequency response of three-hairpin filters.

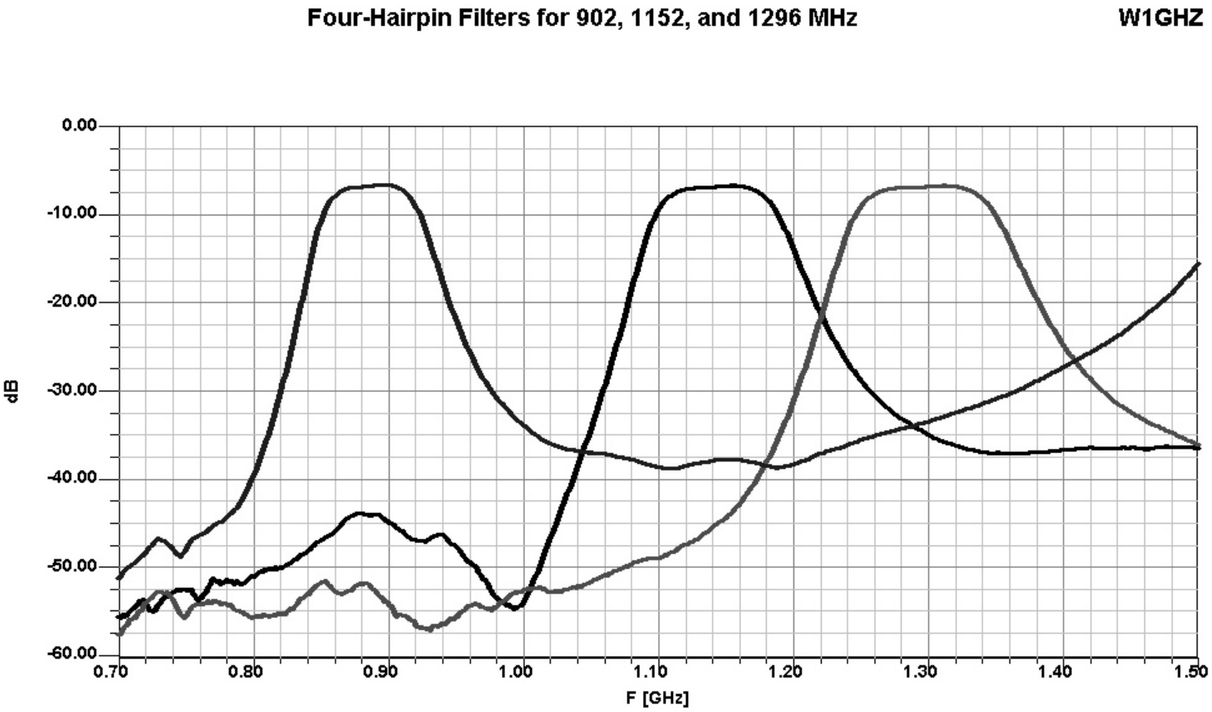

Figure 12 – Frequency response of four-hairpin filters.

Frequency response of the four-hairpin versions is shown in Figure 12. Figure 13 compares the two versions of the filter; loss of the four hairpin vrsion is only slightly greater, but the passband is wider and flatter, making them more tolerant of dielectric constant variation.

Figure 13 – comparison of three-hairpin and four-hairpin filters for 1296 MHz

PCB Layout

ExpressPCB provides free layout software, which is what I use. Since the dimensions are all multiples of 10 mils, the “snap spacing” (under Options) should be set to 10 mils. To draw the legs of a hairpin, use the “Place a rectangle” command, placing it approximately where you want it. Then right-click on the rectangle and select “Set Rectangle Properties” to numerically adjust dimensions and position to exactly what you want. The tricky part is the 45 degree mitered corner – I just fill it in with small overlapping lines. Once you have one hairpin, you can cut-and-paste for the others – they should be identical. Save often, and “Undo” as needed. Mistakes are free until you actually order boards.

The final step is the soldermask. Under Options, select View (top or bottom) Soldermask. Then draw a rectangle where you want to *remove* the solder mask. Note that the Miniboard doesn’t come with soldermask, so you don’t have to worry about it if you kept it within the boundary.

When you are sure it is right, order the boards. If it fits in a Miniboard, you’ll get three boards for $59 – one to experiment with and get it working, one to make a pretty version, and one to get someone else on the air.

Summary

This recipe should enable hams to design with printed hairpin filters without the need for expensive software. Filters for frequencies between 900 and 1400 MHz may be scaled directly from Figure 10 with confidence. Lower frequencies are easy – just make the hairpin legs longer, but you’ll have to extrapolate the length. And the boards get bigger and more expensive. The final frequency can be trimmed with an X-acto knife with little effect on performance; just trim the ends of the straight sections.

Higher frequencies are more difficult. The FR-4 material gets even lossier, so the filters won’t be very good – not only the loss, but the filter response gets more rounded and sloppier. Teflon-based materials work very well, and microwave materials like Rogers Duroid have well-controlled dielectric constants. For these materials, it is possible to design with confidence. However, the cost of having boards made is an order of magnitude higher than ExpressPCB. If you find a reasonable source, please let me know. Otherwise, I’ll stick to pipe-cap filters for the higher frequencies.

References

1. Rick Campbell, KK7B, "A Single-Board, No-Tune 902-MHz Transverter," ***QST***, July 1991, p. 25.
2. Jim Davey, WA8NLC, "A No-Tune Transverter for 2304 MHz," ***QST***, December 1992.
3. Paul Wade, W1GHZ, "Design of Printed Hairpin Filters with Predictable Performance,"
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