

## Designing a Printed Microstrip Filter without a Computer

The hairpin microwave filter shown in photos 1 and 2 has become a poster child for 2D electromagnetic design software packages. Plug in the substrate parameters, desired center frequency, bandwidth, and stopband attenuation, and the computer will spit out camera-ready layouts. A child can do it.

But hairpin filters have been around since before the proliferation of CAD. Designing one without a computer is not only possible, it is a delightful illustration of the use of the most basic math and science to create something new and useful.

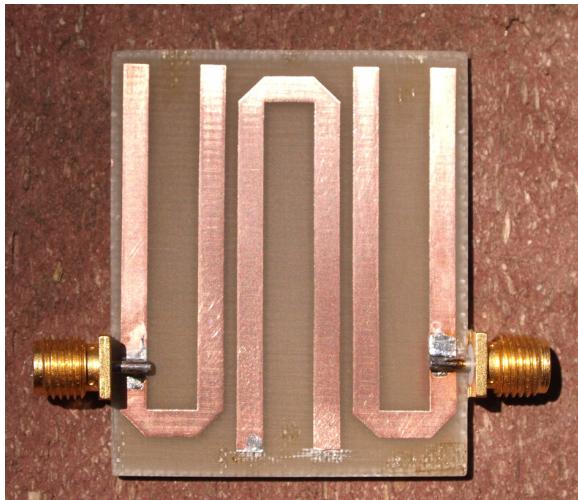


Photo 1

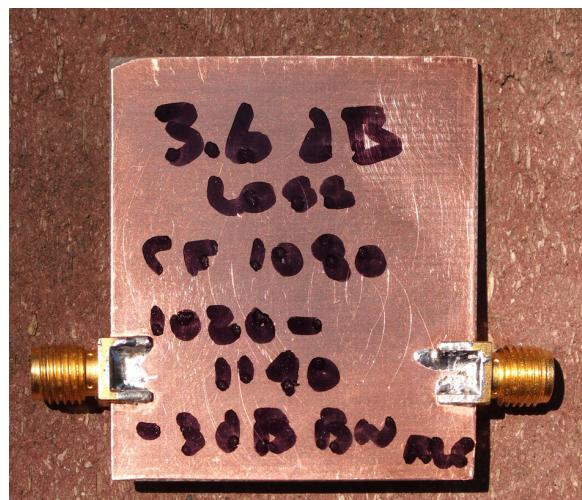


Photo 2

First, a brief review of the scientific method: come up with a theory, design an experiment to test it, examine the results, modify the theory, repeat. The key is to limit the number of unknowns so that a simple experiment can provide enough information to adjust the theory. The method described here is a physical example of a mathematical technique known as separation of variables. If variables can be disconnected from each other, each may be optimized independently of the others. A bandpass filter has a center frequency, bandwidth, passband flatness or ripple, and some characteristics like loss and stopband suppression that are usually constrained by construction materials and filter topology. In the design that follows, the center frequency, passband, and ripple are separately related to physical dimensions. Loss and stopband attenuation are then determined by measurements.

A three section hairpin filter is a special case of the general form of three resonator filter illustrated in figure 1. Symmetry cuts the number of variables in half. Each resonator is tuned to the same center frequency. The bandwidth is determined by coupling between the resonators and to the outside world. Coupling is indicated by the dashed circles. In filter theory, this is referred to as “Q loading” and is a number that represents the amount of energy each resonator shares with its neighbors. Coupling to the input and output is different than to the center resonator.

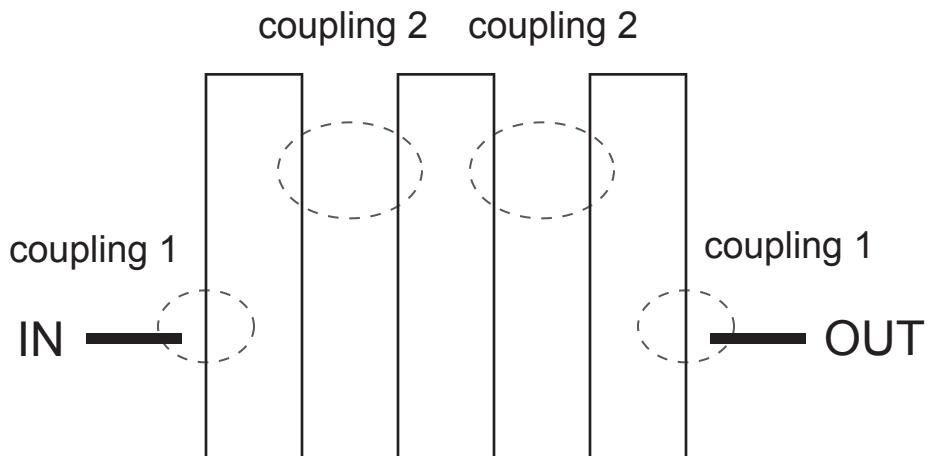


Figure 1

Narrow bandwidth filters share little energy, so the resonators are sharply tuned. Wide bandwidth filters share more energy, broadening the response. The amount of energy converted to heat in the filter--the filter loss--is set by the materials and construction of the filter. For a given set of materials and construction method, it is something we have to live with. The physical quality of each resonator uncoupled from its surroundings is called the Unloaded Q. When we couple the resonator to its neighbors and the outside world, that is the Loaded Q. The higher the ratio of  $Q_u$  to  $Q_L$ , the less energy is lost as heat in the filter. But  $Q_L$  is also inversely related to the bandwidth.  $Q_L = 10$  gives us a filter with a bandwidth one tenth the center frequency. A 1000 MHz filter with  $Q_L$  of 10 has a bandwidth of about 100 MHz. If we build a filter and it is too lossy for our needs, we can decrease the loss by increasing the bandwidth. We increase the bandwidth by tightening the coupling between resonators. In the early days of radio, transmitters achieved narrow radiated bandwidth by “loose coupling” to the antenna. The amount of loss in those early transmitters was directly related to the quality of the materials and construction of the resonators. Q stands for Quality. Coupling has a small effect on tuning and inner resonators are coupled to each other rather than the outside world, so we expect that inner resonators will be slightly longer or shorter than the outer resonators.

One more basic principle needs to be introduced before we proceed to the sketch, prototype construction, and measurements. The relationship between end-loading and resonator coupling, labeled as coupling 1 and coupling 2 in figure 1, determines the flatness of the filter passband response after the center resonator is tuned. A low loss filter may be designed for a specific ripple in the passband. Loss in the resonators tends to round the corners of the passband and wash out the ripple. A fascinating general mathematical treatment for lossless filters is available in any graduate level filter design book, with tabulated results for Chebyshev, Butterworth and Bessel responses. But that is an awful lot of math just to determine two constrained, related variables. Figure 2 illustrates a hairpin filter with fixed coupling between the resonators, and the end-loading varied by changing the tap points on the outer resonators. If the filter has too much ripple, simply move the tap points up. Note that these two simple interconnected variables--center resonator coupling and end coupling--are the only change when moving smoothly from Butterworth through all the different tabulated Chebychev responses. Any choice gives you a textbook filter. It might not be the one you want, but it isn't “wrong.”

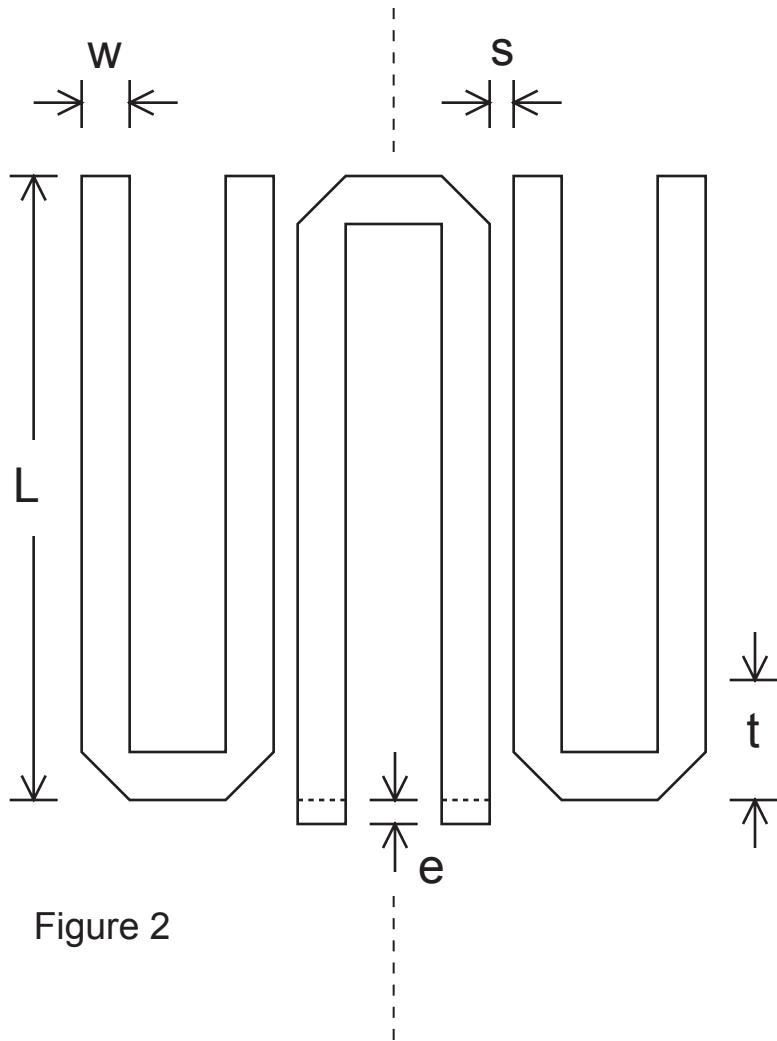


Figure 2

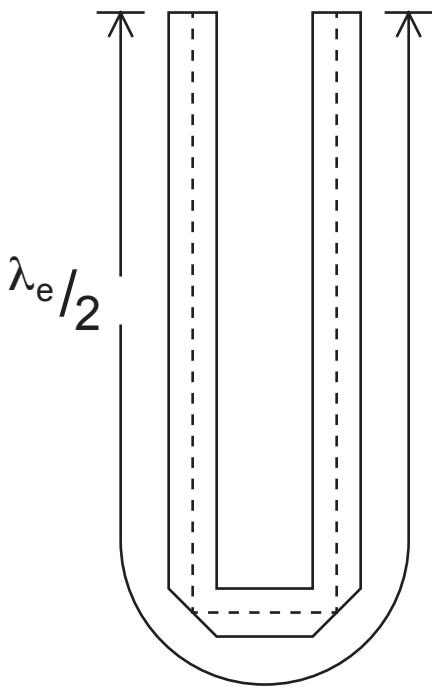


Figure 3

Now let's get practical and treat figure 2 as a sketch of an actual filter. A printed 3 resonator filter only has a few easily modified dimensions, and several unknowns. We don't know the exact effective dielectric constant of the substrate with a microstrip transmission line including bends. We could measure a previous design, but let's assume we don't have one. The resonators need to be about a half wavelength from end to end as illustrated in figure 3. Calculate the wavelength in air at the desired center frequency:

$$\lambda_0 = \text{speed of light} / \text{center frequency}$$

and divide that number by the square root of the approximate effective dielectric constant to obtain an effective wavelength. We don't need an exact number--we'll get that from the measurements. The effective dielectric constant for microstrip on FR-4 substrate is around 4, so the square root is about 2.

To keep losses at a minimum, the transmission line resonators should not be too wide or too thin, relative to the thickness of the circuit board. 0.1" wide on 0.062" thick FR-4 results in a characteristic impedance somewhere around 50 ohms, which is convenient. The width between the legs of the hairpins is twice the transmission line width to reduce coupling between the legs. Note that once the transmission line, coupling  $s$ , and spacing between the hairpin legs is chosen, the same values may be used over a wide frequency range. Only  $L$  and  $t$  change.

We don't yet know the exact center frequency or unloaded Q of the single hairpin in figure 3, but it is a resonator. Any resonator may be used to build a filter. All we need to do is arrange to couple some energy in and out. This is profound. The only reason we can do computer aided design of microstrip filters is that we have reasonably accurate mathematical models of microstrip transmission lines. But we can make a filter out of any three resonators using the experimental methods described here, decades before math addicts have generated and validated new models than can be plugged into a virtual design tool.

Figure 4 is a sketch of our experimental filter. We have three identical resonators, edge coupled, with variable tap points on the outer resonators. The edge coupling to the center resonator was arbitrarily selected by making the spacing between resonators half the width of the resonator transmission lines. If the resulting filter is too narrow (or too lossy), we can reduce the spacing. If it is too wide (and we can tolerate more loss), we can increase that spacing. The key at this point is to recognize that the spacing isn't wrong, it is exactly right for some filter design that we haven't yet specified. After an hour making measurements at the bench we will have a complete design and a good example filter, with all the variables determined so that our next filter may be designed for a specific loss, ripple, bandwidth, and center frequency. This process is sometimes referred to as "First pass functionality, second pass success." It is the direct application of the scientific method to design.

We can build the experimental filter by laying it out and etching in the home lab, using a commercial quick-turn prototype process, or by cutting and peeling the copper from a scrap of FR-4 circuit board using a straight edge, exacto knife, and soldering iron. The author's first filters were fabricated using the last technique.

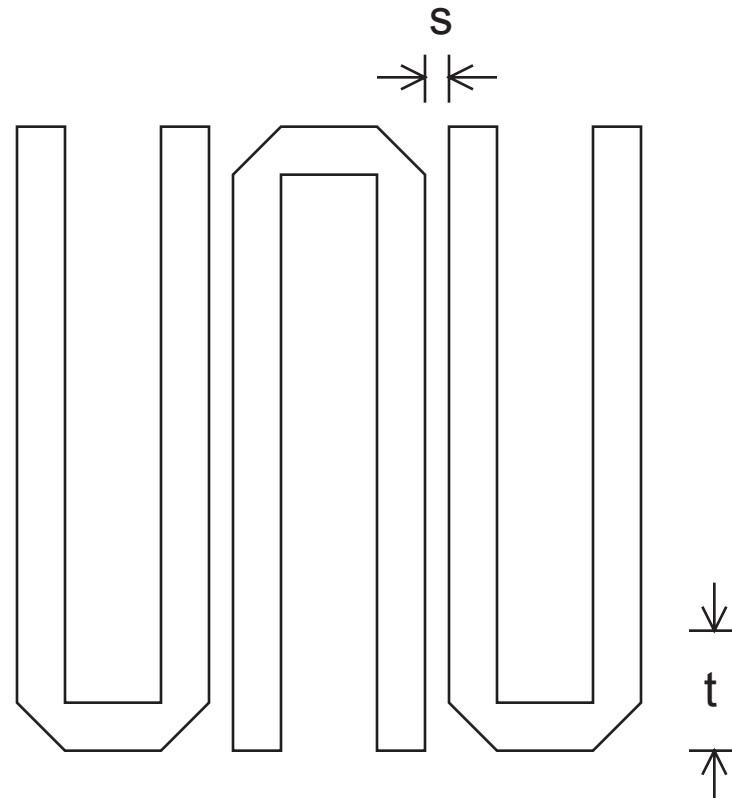


Figure 4



Photo 3

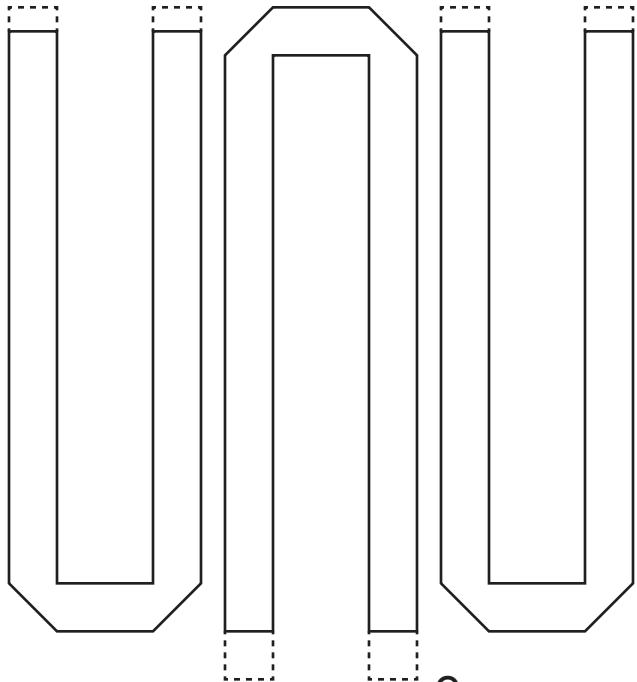


Figure 5

Photo 3 shows the filter connected to a measurement system to determine its passband shape and loss. A home lab spectrum analyzer with built-in tracking generator is available for less than the cost of a laptop computer with 2D design software. In this case it is easier and less expensive to experiment with the real thing than the virtual model. Connect to the tap points at exactly the same place for the input and output, preserving the symmetry. The first measured passband shape looks a little ugly, because the three resonators are all the same length. The center transmission line resonator will need to be a slightly different length than the outer two transmission lines, because it is operating in a different environment. Using the exacto knife and soldering iron, cut and then remove about a mm of transmission line from one end of the center resonator. Note the shape of the passband--maybe it got worse. If so, then that was the wrong way to go, and you can correct it by taking some off each end resonator. Now you should have the same ugly passband shape you had before, but at a slightly higher frequency. Carefully note the change in frequency--that MHz/mm number will be useful when you design the next filter. Now remove another mm from each end resonator. That should change the passband shape, and make it look flatter. If it is almost right, cut a bit more off each end. If it changed shape entirely (it won't if you take small cuts each time) then you might have gone too far, and need to trim a little off the center resonator.

The following photos show progressive trimming of a 1080 MHz center frequency. Only two cuts were needed to achieve a flat response.

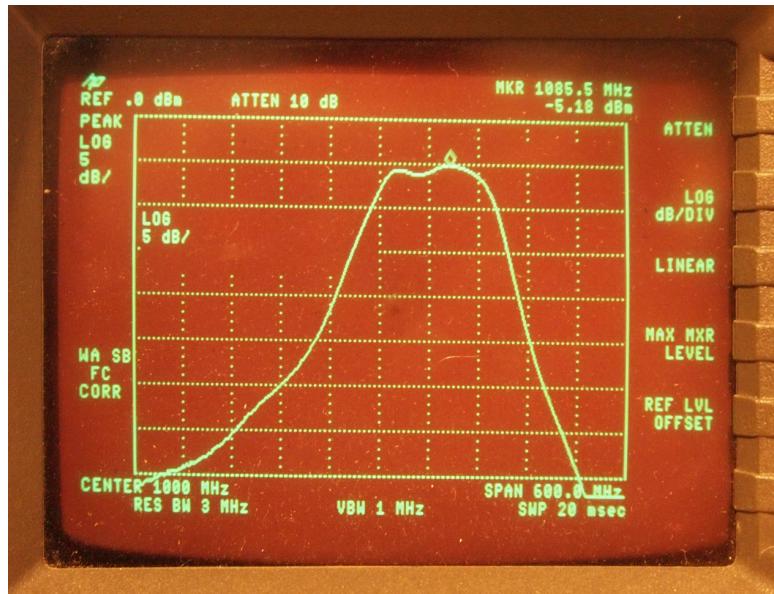


Photo 4

Photo 4 shows the first measurement of the passband and stopband. There is a significant dip below the center frequency of the filter.

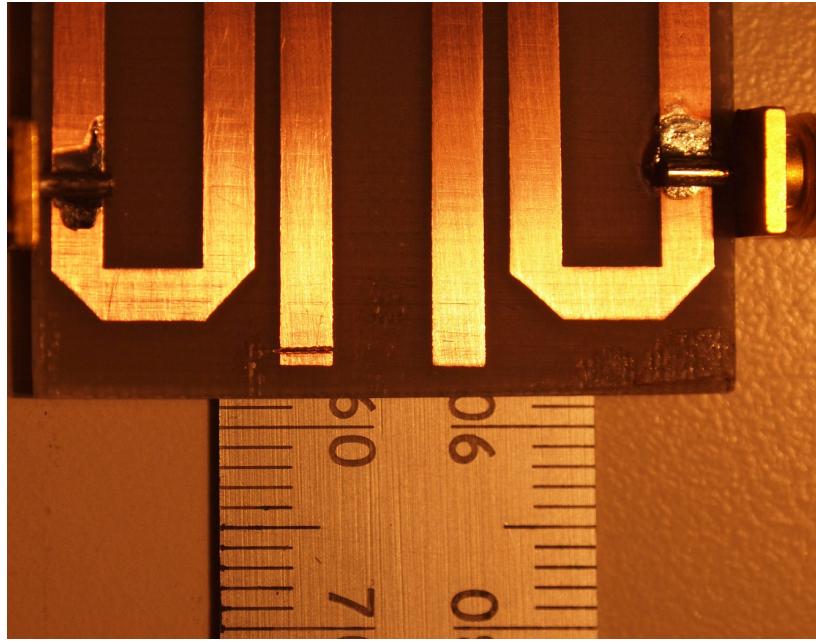


Photo 5

A cut of a little less than 1 mm is made with an Exacto knife across across the end of one of the center hairpin legs. The small piece was then removed by using a hot soldering iron tip to soften the adhesive holding the copper to the board. The next measurement showed a smaller dip, so a second cut was made across the other leg.

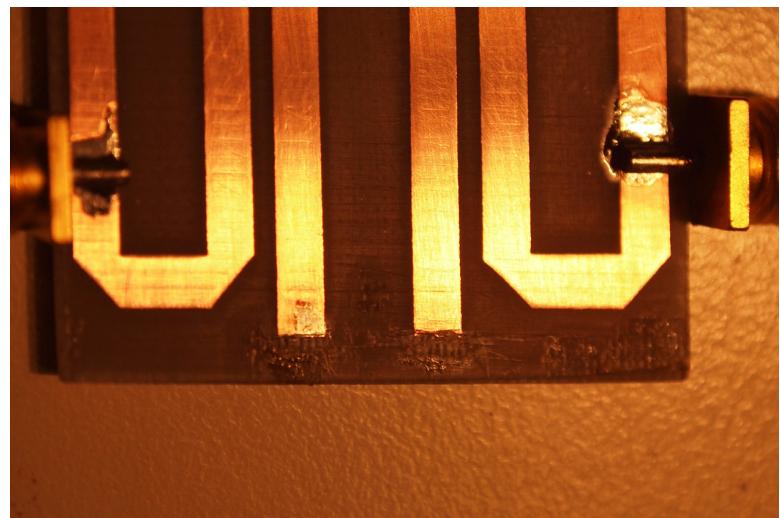


Photo 6

After trimming the second leg, the passband is now flat, with rounded corners to the skirts. Round corners and washed out ripple are characteristic of filters with relatively lossy resonators.

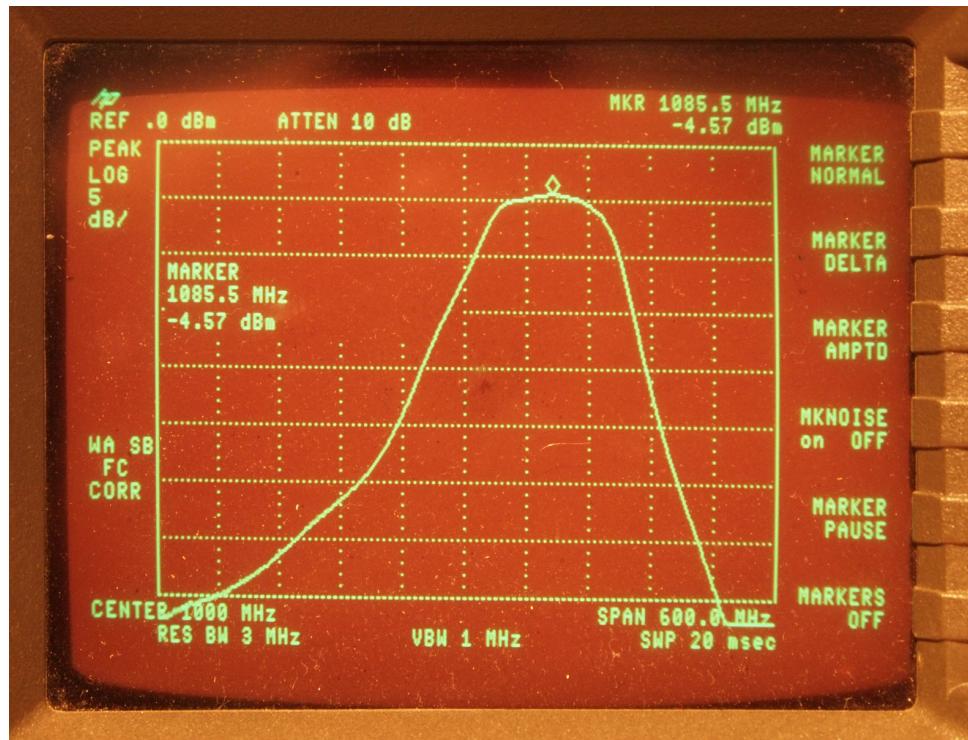


Photo 7

The 1080 MHz center frequency filter response from 700 to 1300 MHz. Vertical divisions are 5 dB and horizontal divisions are 60 MHz.

A word about making those trim cuts to the resonators: Slow down and think about what you are doing. If you make a cut too small to have an effect, then that amount of error in the design or construction of the filter won't have much effect either. You are not just using the scientific method to design the filter, you are using science to explore construction tolerances, manufacturability, the appropriate accuracy needed for your math design models... You are developing intuition that will allow you to quickly design better filters in the future and rapidly figure out why they don't perfectly match the engineering models in the CAD programs. Design intuition isn't some unexplained tendency to make lucky guesses, it is the result of the deepest, most profound understanding of the fundamentals that apply to a particular problem. "Experts" rely on--and are often fooled by--their expensive simulators. Designers, like old jazz musicians, seem to make the right choices without thinking, and then use the simulator and scientific method to confirm their intuitions. To review: the scientific method involves coming up with a theory, testing it, and then making adjustments. Intuition is what generates the initial theory, but without testing, that theory is just a guess. Experienced designers have both good intuition for generating first-pass prototypes and a catalog of validation tools and measurements to test and evolve them.

After achieving a symmetrical passband shape, it's time to experiment with end loading. Move the tap points up and down, observing the effects. Make small modifications, as a large change in end loading will require re-trimming the resonator lengths. After an enjoyable hour of trimming and measuring, you will have a good filter, with some center frequency, moderate loss, and a reasonably flat passband. Now you can fill in all the design specifications, and if an engineering manager happens to wander by, pretend that you intended for it to come out exactly that way.

Carefully record the measured performance and the final physical dimensions of the filter. Working backward from the resonator length and measured filter center frequency, calculate an effective dielectric constant to use when scaling the resonators to a new center frequency. Make notes of how much longer (or shorter) the center resonator needed to be trimmed to achieve a symmetrical, flat passband. Check those numbers against your scaling math to get a feel for the errors and approximations involved.

More experiments with narrower or wider spacing between the resonators will gradually fill in your design catalog and understanding of how all the variables interact. Or you can simply take what you have learned from the first pass design and go directly to a final filter with similar performance at your desired center frequency.

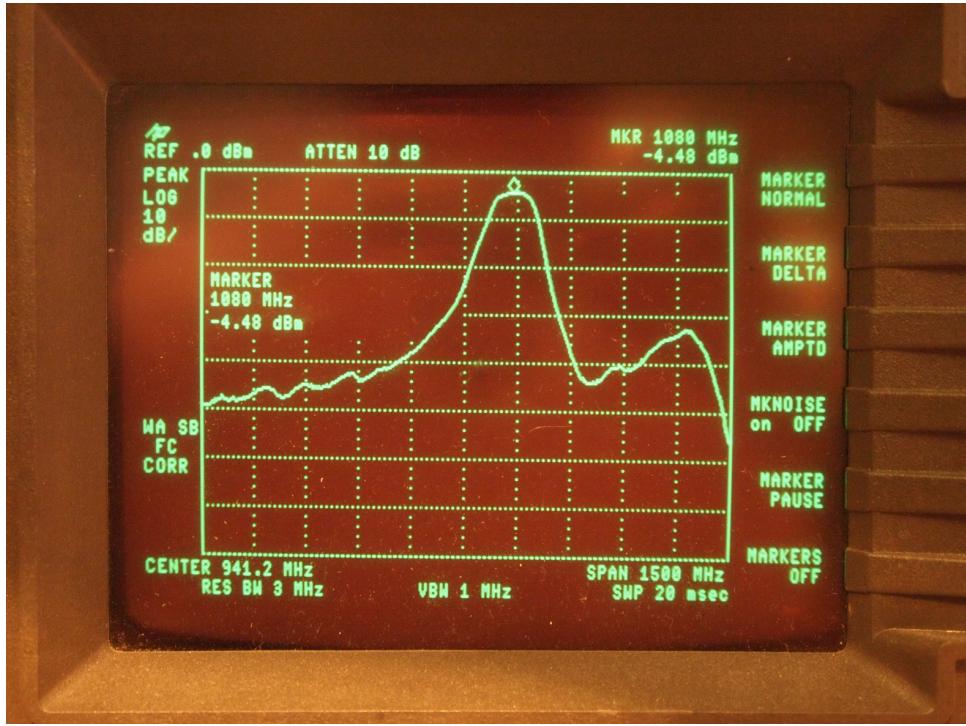


Photo 7

Filter response from 500 to 1500 MHz, on a 10 dB/division vertical scale. Note that the ultimate stopband rejection is only around 40 dB.

The denizens of the virtual design world may point out that computer aided design tools allow filters with more than 3 resonators to be easily handled, in a single pass from design specs to final layout. There are two major flaws in that position: The primary leakage path for printed hairpin filters is coupling across the surface of the board from input to output resonator. A 5 resonator filter may have better stop band performance in the simulator, but in practice on FR-4 substrate, its rejection of out of band signals is no better than the simple 3 resonator filter. Note the response above, from 500 to 1500 MHz. The 3 resonator filter response is symmetrical down to about 40 dB suppression, but above 1200 MHz the response flattens and then comes back up. Coupling through the air over the circuit board limits the ultimate rejection of the filter. The other flaw is that the learning curve for making measurements on the bench is satisfied nicely by working with experimental filters. Skipping that step and going directly from a virtual design environment to a manufactured solution leaves one ignorant of critical practical details. You shouldn't call yourself a violin player if you've only synthesized a perfect track in the studio, and you probably should be careful referring to yourself as a filter designer until you've tuned your own designs up in the lab. That will change as the previous great generation of filter designers retires and fades into legend and myth. We live in an era when tasks that may be done on a computer are defined as "work" and everything else is "not work." Management often requires every design decision to be backed up by simulations presented in Power Point--no matter how inappropriate that is to the task at hand. In the real world, measured data still carry some weight.

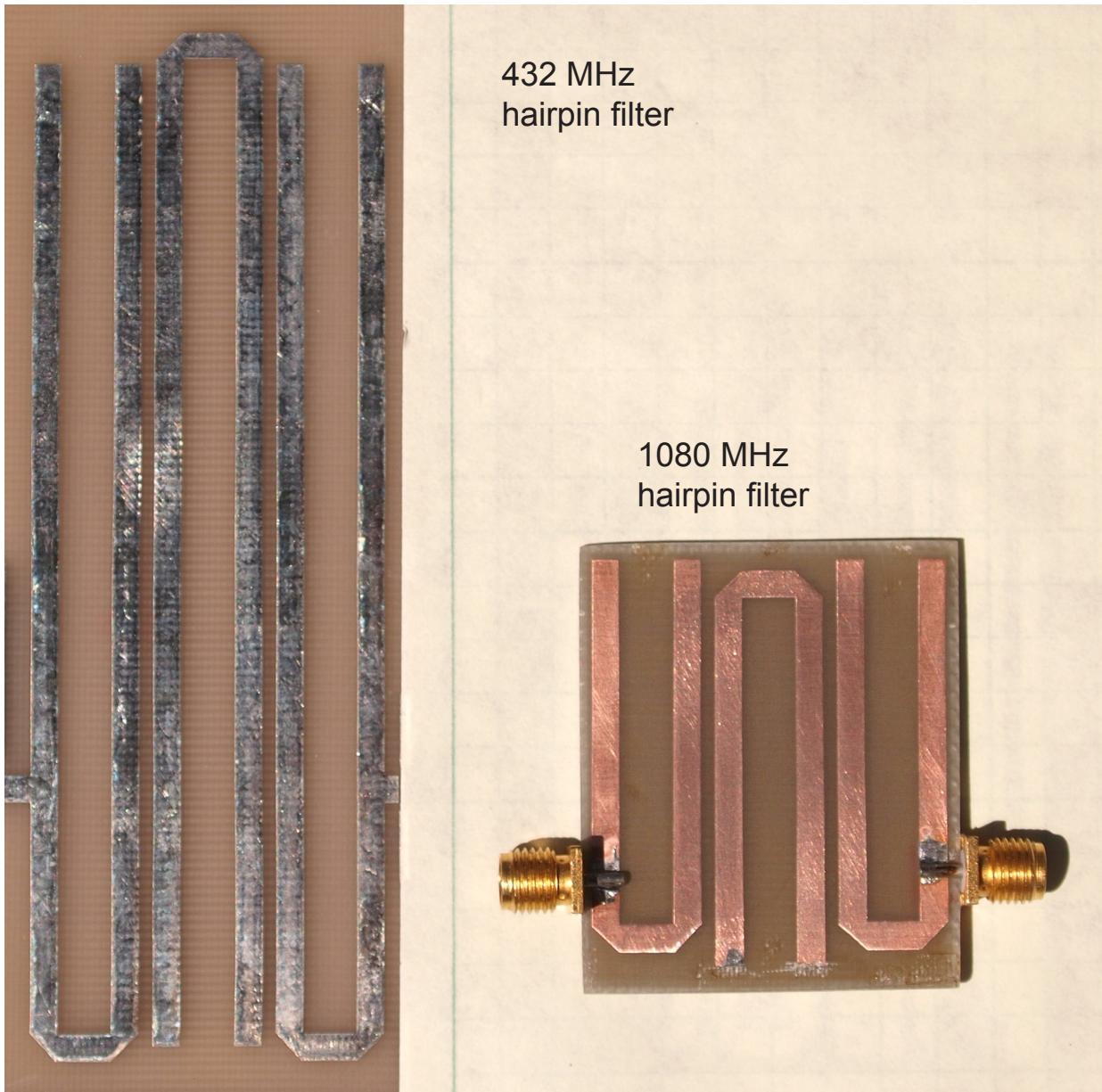


Photo 8

A filter from a commercial product, centered on 432 MHz is on the left. On the right is the 1080 MHz filter described here. Note that the only change is the length of the hairpins and position of the input and output taps.

The 3 resonator coupled hairpin filter is a good choice in certain applications, but much of what makes it easy to design is the constrained space in which it performs well. Hairpin resonators work well when made from lengths of microstrip transmission line a little wider than the thickness of the printed board substrate. FR-4 Filters with edge coupling to the center conductor a little less than the substrate thickness and symmetrical input-output taps near the bottom of the hairpins will have a few dB loss and a passband around 10% of the center frequency. For narrower filters and/or lower loss, use different resonators. For wider bandwidth filters in the UHF range, lumped passive components have sufficient Q and result in a more compact layout.

A plethora of references: