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Title: Waveguide Filters You Can Build -- and Tune Part 3 Evanescent Mode Waveguide Filters
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Waveguide Filters You Can Build—*and* Tune Part 3 Evanescent Mode Waveguide Filters

In the last of his three part series, the author introduces us to a filter with which many Amateur Radio operators are not familiar.

The only amateur publication of evanescent mode waveguide filters, to the best of my knowledge, is by Reed Fisher, W2CQH, in 1993.[1] I noticed the paper when it first appeared, but I recall thinking that they couldn't be very good filters, since evanescent modes have high loss.

Evanescent modes occur in waveguides at frequencies below the cutoff frequency, where attenuation is very high. The energy decays exponentially along the guide, so that attenuation is linear with distance (~30 db per waveguide diameter for circular guide. For example, a circular guide with an inner diameter of one inch would have an attenuation of about 30 dB per inch). This phenomenon has been used for precision attenuators.[2]

Recently, I was looking for references on waveguide filters and came across several for evanescent mode filters. Apparently they actually work, and offer good performance in a compact package. What I hadn't realized is that evanescent modes in waveguide are reactive, so that the attenuation is due to reflection, not dissipation, of energy — the energy is not lost.[3] When we make them resonant structures, they behave much differently than non-resonant evanescent mode waveguides. After perusing a few papers, I went back to Reed's paper to look for practical dimensions.

Starting with some of Reed's examples, I did some simulation with Ansoft *HFSS*
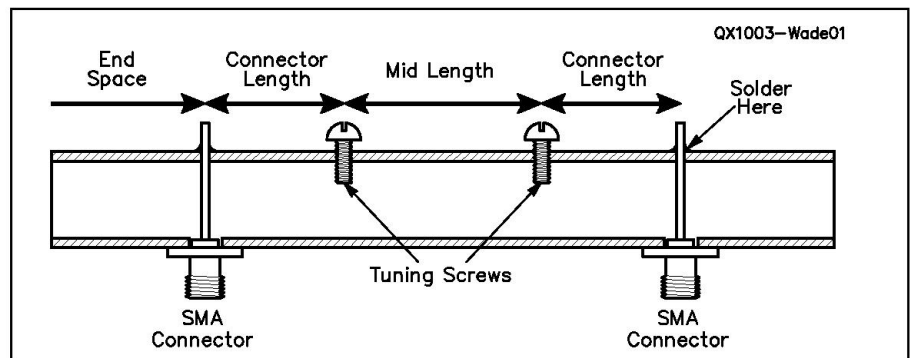
[1]Notes appear on page 29.

Figure 1 — This sketch shows a two section evanescent mode waveguide filter.

electromagnetic software, and fiddled the dimensions until a reasonable filter response appeared.[4] Then it was time to make one. Construction is really simple — two SMA connectors with a tuning screw or two between them, as sketched in Figure 1, all on the centerline of the broad side of the waveguide. The critical dimensions are the distances between the screws — the *Mid Length*, and from the screws to the SMA connectors — the *Connector Length*. The SMA connector center pin connects to the far wall of the waveguide. This is the microwave version of a coupling loop.

The first filter I made was for 3456 MHz in WR-90 (X-band) waveguide. The cutoff frequency for WR-90 is about 6.5 GHz, so this is way below cutoff. Nothing should get through the waveguide at this frequency. However, the filter works pretty well – the

response is plotted in Figure 2. It is a pretty sharp filter, with less than 2 dB of loss. The filter was tuned and measured in my basement with surplus test gear, recording the data by hand, so the range is limited and the curve in Figure 2 has some glitches. Later, I was able to measure the filters on fancy vector network analyzers (VNA) from Agilent and Rhode & Schwarz, who are kind enough to bring these instruments to ham conferences. All the later plots are from these measurements. It is still easier to tune the filters on the old analog readout gear, however, rather than wait for a computerized measurement after each adjustment.

Construction is exceedingly simple: drill holes for the connectors and screws, tap the screw holes, solder the connector pins to the far wall, and tune it up. Since energy doesn't travel far in the evanescent guide without
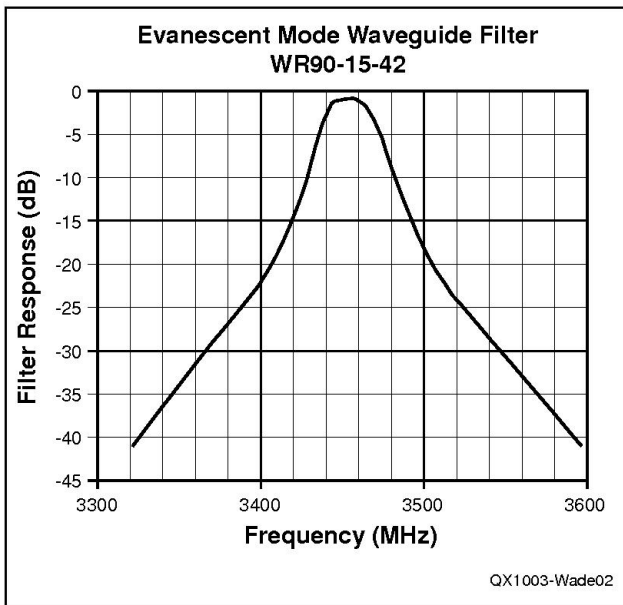
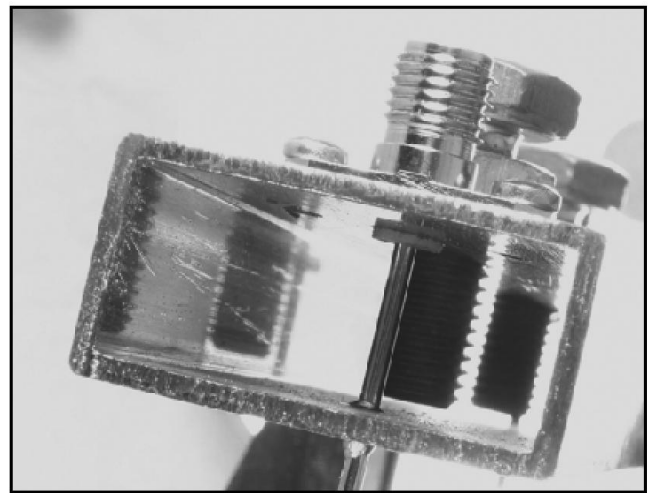Figure 2 — The frequency response of the 3456 MHz filter.

Figure 3 — Here is a view inside an evanescent mode filter.

something resonant, the ends may be left open. I was amazed to stick my finger in the end with no effect! The length of the *End Space* in Figure 1 should be more than half of the waveguide width. I usually leave about 20 mm as a convenient length.

Figure 3 is a photo looking in the end of the finished filter, showing the two screws sticking into the waveguide. These screws are tuning capacitors, so I used a couple of ¼-28 brass screws that I had in my junk box, with the ends faced flat on a lathe. The flat end might make the tuning smoother, but it was still pretty touchy even with the fine-thread screw. I also learned that putting the screw head on the same side as the coax connectors is a bad idea — there isn't much room in which to work. Later versions have the screws on the opposite side, as shown in Figure 1.

Evanescent Mode Filter Theory

So how do these filters work? Basically, a section of evanescent mode waveguide, well below cutoff, acts as an inductor. We add a capacitor to make a resonant circuit.

The simple equivalent circuit of a short length of evanescent mode waveguide is shown in Figure 4, a series inductance with a shunt inductance at each end. If we put connections at each end and a screw in the middle, like Figure 5, it forms the single resonator shown schematically in Figure 6.

The tuning capacitor resonates with the two L_{shunt} inductors, one on each side, and the L_{series} inductor provides coupling to the SMA connectors, to set the loaded Q_L of the resonator. Thus, making L_{series} larger, by increasing the spacing, reduces the coupling and there

fore the loading from the 50 Ω source and load, making the Q_L higher.

The inductances are calculated from the length of waveguide, from the connector to the tuning capacitor (*Connector Length* in Figure 1, center-to-center) and the cutoff wavelength. First, the cutoff frequency of a rectangular waveguide is when the width of the guide equals a half-wavelength. For

Figure 4 — A schematic representation of the equivalent circuit of an evanescent mode filter.

WR-90, the width is 0.9 inch = 22.86 mm, so the cutoff wavelength λ_c= 45.72 mm. Thus, the cutoff frequency is 300/45.72 = 6.56 GHz.

Craven & Mok show a graph of unloaded Q for WR-90 waveguide.[5] The theoretical Q is higher than 10,000 at 10 GHz in a normally propagating TE_{10} mode, but slightly lower for the TE_{10} evanescent mode, perhaps 6,000 just below cutoff, and falling to around 1,000 at 1 GHz. This Q is still high enough to use the lossless transmission line assumption, which simplifies calculations.

For a lossless TE_{10} evanescent mode, the characteristic impedance, X_0, is calculated from the cutoff wavelength, λ_C, the free space wavelength, λ, and the waveguide width a and height b. (See Note 5.)

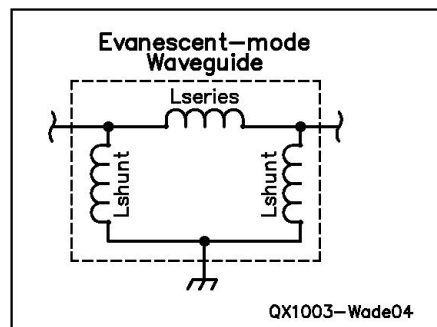$$X_0 = \frac{b}{a} \times \frac{120\pi}{\sqrt{\left(\dfrac{\lambda}{\lambda_c}\right)^2 - 1}}$$ [Eq 1]
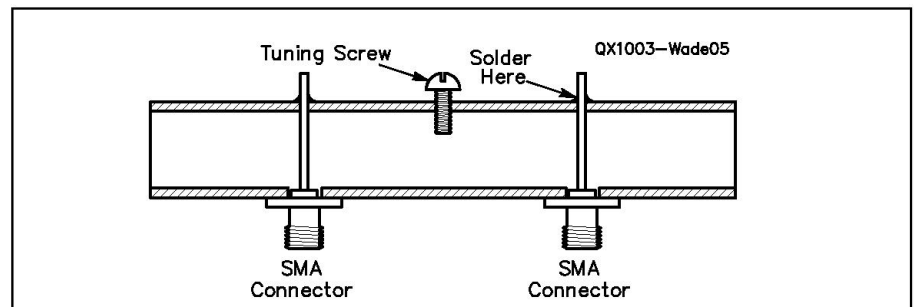

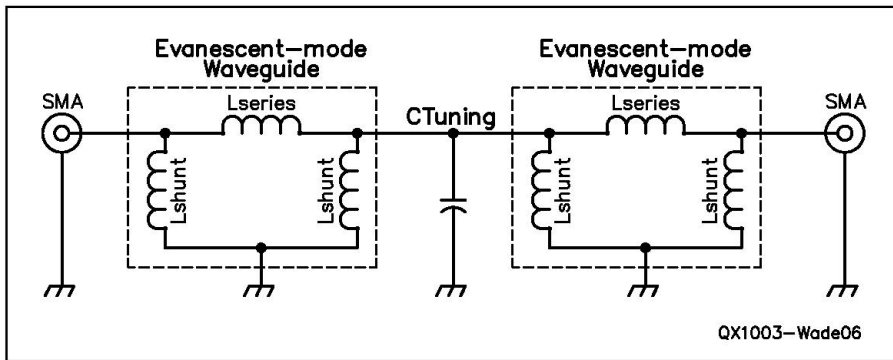Figure 5 — Evanescent mode waveguide single resonator.

Figure 6 — A schematic of the equivalent circuit of an evanescent mode waveguide resonator.

And the propagation constant, γ, is:

$$\gamma = \frac{2\pi}{\lambda}\sqrt{\left(\frac{\lambda}{\lambda_c}\right)^2 - 1}$$ [Eq 2]

For a waveguide length, ℓ, the reactances of the inductors are then calculated:

For L_{series}, $X_L = jX_0 \sinh \gamma \ell \cong \frac{jX_0}{2}e^{\gamma \ell}$ [Eq 3]

And L_{shunt},

$$X_L = jX_0 \coth \frac{\gamma \ell}{2} \cong \frac{jX_0}{2}$$ [Eq 4]

where sinh and coth are the hyperbolic sine and cotangent functions, respectively.

The approximations on the right side are from W2CQH. He uses them for a further approximation to estimate the loaded Q_L:

$$Q_L \approx \frac{R_0}{X_0}e^{\gamma \ell}$$

where $R_0 = 50\ \Omega$ for a coax termination.

All these approximations have some error, and the errors add up, so that the estimated Q_L is lower than the apparent values from simulation and measurement. The discrepancy is as much as a factor of two, which could lead to filters much sharper or lossier than expected. Also, the Johanson trimmer capacitors used to make the lower frequency filters are not nearly as high-Q as the waveguide, so the loss of the lower-frequency filters is higher.

Another factor is the inductance of the SMA connector pin. The inductance creates an additional impedance transformer, further reducing the loading and raising the loaded Q.

With waveguide post filters, we found that a double-tuned filter was adequate for many applications. For a double-tuned filter, we need not only the evanescent mode

waveguide length at each end, but also an additional length in the center, with an L_{series} calculated for the *Mid Length* in Figure 1 that provides the desired coupling between the two resonators tuned by the two capacitors. The double-tuned filter is shown schematically in Figure 7 and sketched in Figure 1. The two *Connector Lengths* should be identi-

cal, but the *Mid Length* is longer — increasing the length decreases the coupling.

The result of all the approximations and errors is that we cannot calculate the parameters accurately enough using these equations to design a filter — even a simple double-tuned filter. Snyder has more equations, but I have not had a chance to evaluate them.[6] Instead, I have resorted to professional 3D electromagnetic software, the Ansoft *HFSS* program, to analyze various trial dimensions, and then to build some of the promising ones. Even then, some of the filters have a measured bandwidth slightly narrower than predicted.

More Examples

I have made a number of successful evanescent mode filters in all sizes of X-band waveguide, WR-90, WR-75, and WR-62, for frequencies from 5.76 GHz down to below 1 GHz. Figure 8 is a photo of several of the filters; the small physical size of these filters should be apparent. The limiting factor for low frequencies is the tuning capacitance – a

Table 1
Evanescent Mode Waveguide Filters

Designation	Band (MHz)	Connector Length (mm)	Mid Length (mm)	Tuning Screw USA	Bandwidth (MHz)	Insertion Loss (dB)
WR-62 Waveguide						
WR62-12-33	5760	12	33	#10	37	1.8
WR62-12-28	3456	12	28	conc #10	31.5	1.64
"	2304	12	28	conc #10	20	2.07
WR62-12-28J	3456	12	28	Johanson	36	3.13
"	2304	12	28	Johanson	18.5	4.5
"	1296	12	28	Johanson	10.5	7.1
"	1152	12	28	Johanson	9	7.9
WR62-10-24J	3456	10	24	Johanson	73	1.69
"	2304	10	24	Johanson	41	2.15
"	1296	10	24	Johanson	21.5	3.37
"	1152	10	24	Johanson	18.5	3.26
WR62-9-22J	3456	9	22	Johanson	109*	1.47
"	2304	9	22	Johanson	63	1.76
"	1296	9	22	Johanson	33	2.75
"	1152	9	22	Johanson	29.5	3.44
WR-75 Waveguide						
WR75-15-45	5760	15	45	$\frac{1}{4}$ - 28	32	1.3
WR75-13-34	3456	13	34	conc #10	37	0.8
WR75-13-32	2304	13	32	conc #10	26	1.08
WR-90 Waveguide						
WR90-12-30J	3300	12	30	Johanson	130*	1.48
"	2304	12	30	Johanson	69*	1.3
"	1296	12	30	Johanson	33	1.8
"	1152	12	30	Johanson	29	1.82
"	903	12	30	Johanson	23	2.36
"	720	12	30	Johanson	18	2.9
"	581	12	30	Johanson	15	3.7
WR90-14-35	2304	14	35	conc #10	(not built)	
WR90-15-42	3456	15	42	$\frac{1}{4}$ - 28	35	1.3

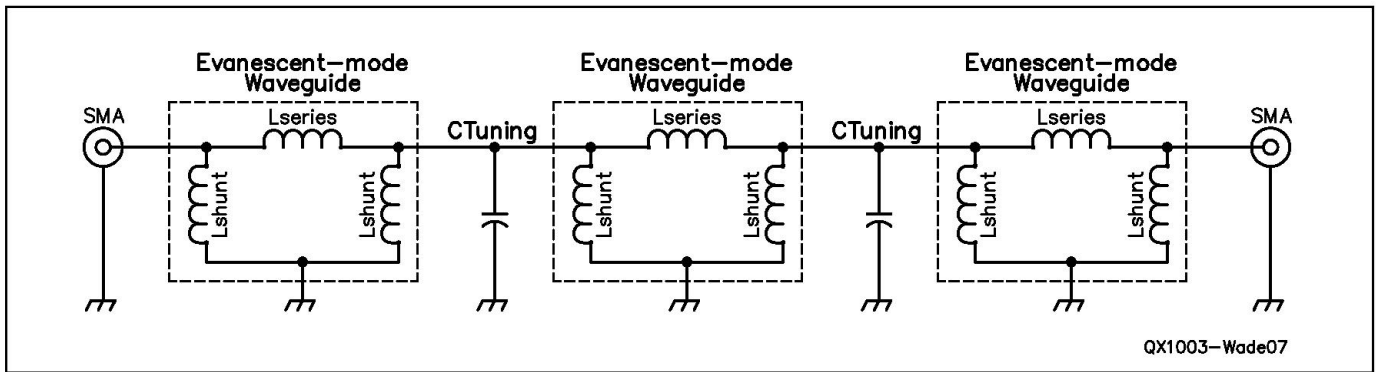**Note**: End Space typically 20 mm   * - Over-coupled response

Figure 7 — This schematic represents a double-tuned (two section) evanescent mode waveguide filter.

simple screw provides only a fraction of a picofarad, and even the Johanson trimmer capacitors are limited to 10 pf or so. For 2.3 and 3.4 GHz, I increased the screw capacitance by soldering a ¼" diameter piece of hobby brass tubing to the opposite wall, so the #10 screw inside the tubing forms a concentric capacitor. This is sketched in Figure 9, and used in the bottom filter in Figure 8.

The performance is shown in Figure 10 of two 5760 MHz filters with plain tuning screws, like the top two filters in Figure 8. These are pretty sharp, good enough for better than 30 dB of LO rejection with a 144 MHz IF, yet the loss is under 2 dB.

These filters have a narrow passband with fairly low loss, and a wide stopband — there are no significant spurious responses below the cutoff frequency for the waveguide. Figure 11 shows the WR-75 filter for 5760 MHz over a very wide band. Above the cutoff frequency, calculated as 7.87 GHz for WR-75, normal propagation can occur in the waveguide and the filter is less effective, with a few spurious responses. Thus, a WR-90 filter for 5760 MHz could have an additional response starting at about 6.5 GHz, so it would be less effective for this band than one with smaller waveguide. On the other hand, a WR-62 filter would not have any significant spurious response below about 10 GHz, so it can be an effective harmonic filter as well as bandpass filter for 2304 or 3456 MHz. Figure 12 shows this for a 3456 MHz filter in WR-62. Any spurious response below 10 GHz is more than 60 dB down. There is plenty of surplus WR-62 waveguide around; it is not as good for 10.368 GHz operation since it is very close to cutoff, but very useful for these filters.

The filter in Figure 12 looks exceedingly sharp in the wideband plot. Figure 13 zooms in to look at the passband of a half-dozen filters tuned to 3456 MHz. Most of these filters can be tuned over a wide range, so I was able to tune and measure some of them at several different bands. Table 1 lists all the successful filters I made and the different bands at
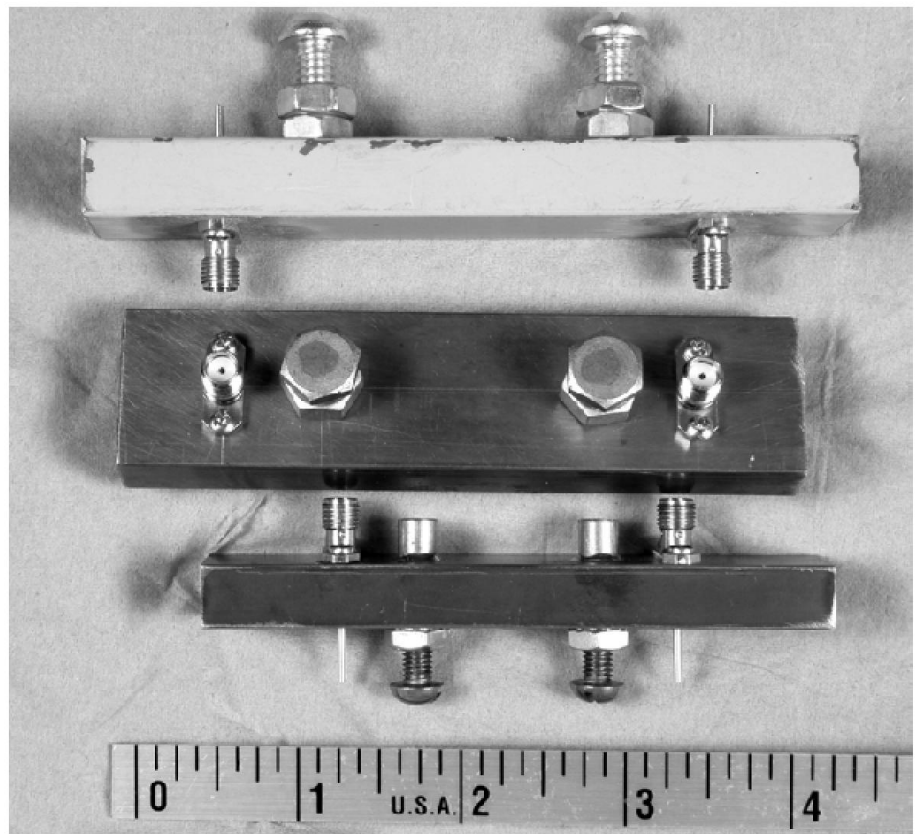

Figure 8 — This photo shows some examples of two section evanescent mode waveguide filters using three sizes of X-band waveguide.
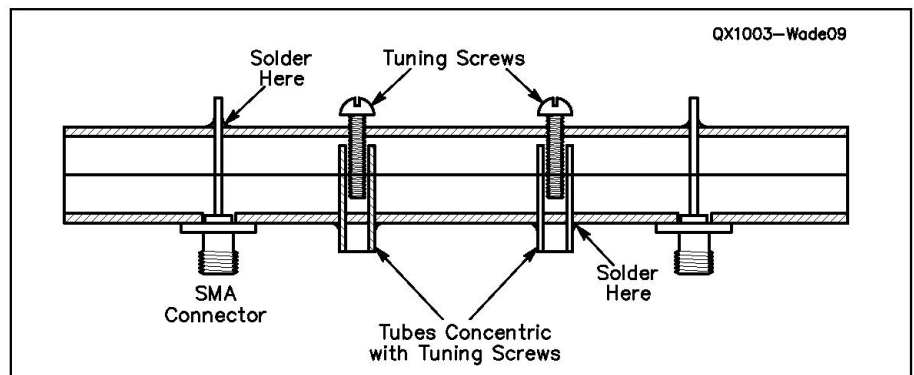

Figure 9 — This filter uses a concentric screw-inside-tubing capacitor.
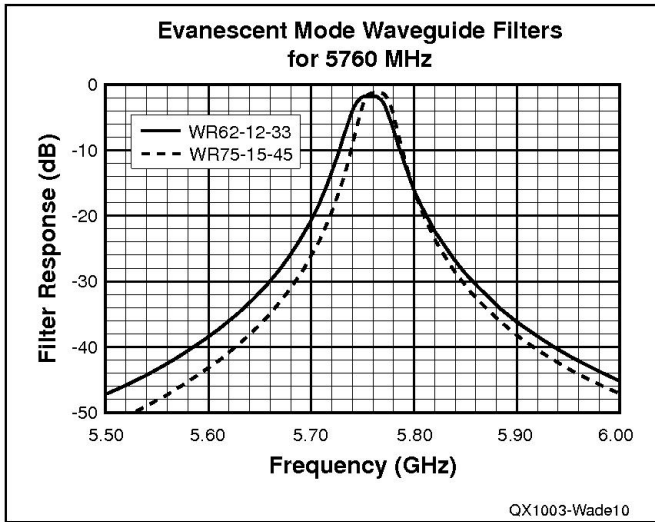
Evanescent Mode Waveguide Filters for 5760 MHz

WR62-12-33
WR75-15-45

QX1003-Wade10

Figure 10 —This graph shows the response of a two section 5760 MHz filter, using two different types of waveguide.

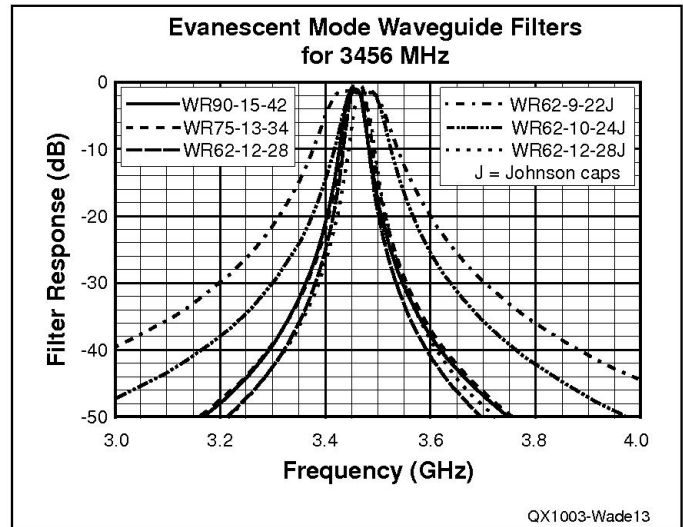**Evanescent Mode Waveguide Filter for 5760 MHz WR75-15-45 Wideband Response**

QX1003-Wade11

Figure 11 —This plot gives the wideband response for a 5760 MHz filter built with WR75-15-45 waveguide.

Evanescent Mode Waveguide Filter for 3456 MHz WR62-12-28 Wideband Response

QX1003-Wade12

Figure 12 — Here is the frequency response of a 3456 MHz filter built with WR62-12-28 waveguide.

Evanescent Mode Waveguide Filters for 3456 MHz

WR90-15-42
WR75-13-34
WR62-12-28
WR62-9-22J
WR62-10-24J
WR62-12-28J
J = Johnson caps

QX1003-Wade13

Figure 13 —This graph shows the frequency response of several two section 3456 MHz filters.

Evanescent Mode Waveguide Filters for 2304 MHz

WR62-9-22J
WR62-10-24J
WR62-12-28J
WR90-12-30J
J = Johnson caps
WR75-13-32
WR62-12-28

QX1003-Wade14

Figure 14 — Here is the frequency response of several two section 2304 MHz filters.
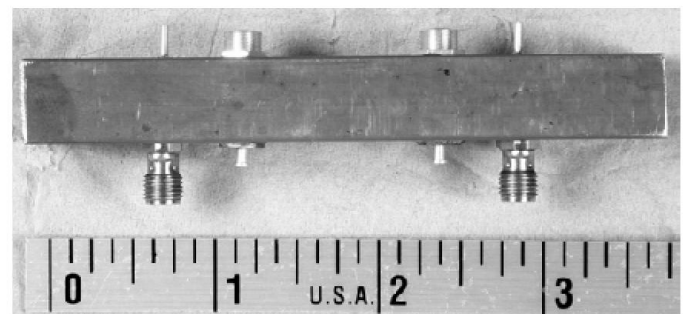
Figure 15 —This photo shows an evanescent mode filter tuned with Johanson capacitors.

which they were tested. For one set of dimensions, the WR62-12-28, I made one with concentric tuning screws and another with Johanson capacitors — the difference in loss is clear at 3456 MHz, as shown in Figure 13 and at 2304 MHz, as shown in Figure 14.

The filters plotted with solid lines in Figure 13 have tuning screws, either plain or concentric. All have loss under 2 dB and would provide more than 30 dB of LO rejection for a 2 meter IF. The dashed lines are for filters using Johanson piston-trimmer capacitors. These were intended for lower frequencies, but I wanted to see how high they would tune. The wider ones still have low loss, while the narrowest one has more

loss, about 3 dB. We expect narrower filters to have more loss, since the loaded Q_L is higher, and the Johanson capacitors probably have a lower Q than a tuning screw.

The filters for 2304 MHz are small, the same size as 3456 MHz. Many of them are the same filters with the screws farther in, but they still have good performance, as shown in Figure 14. The filters with concentric screws have loss under 2 dB, while the narrow WR-62 filter with Johanson trimmers has more loss at 2304 MHz.

With the higher capacitance of the Johanson trimmers, the lower end of the tuning range is extended. A WR-90 filter with large Johanson trimmers, model 5502, tunes

from about 3.3 GHz down to 580 MHz. Figure 15 is a photo of the filter, and Figure 16 shows the tuning range, retuning the filter and measuring at several frequencies across the range. The loss increases as we go down in frequency. I don't know whether this is due to lower Q of the evanescent mode waveguide, the trimmer capacitors, or both. At the upper end of the tuning range, the filter starts to become over-coupled, with a double-hump response.

WR-62 filters with the more common Johanson capacitors, models 2954 and 5202, tune from 3456 MHz down to about 980 MHz. I tuned several of them, as well as the WR-90 filter from Figure 15, to
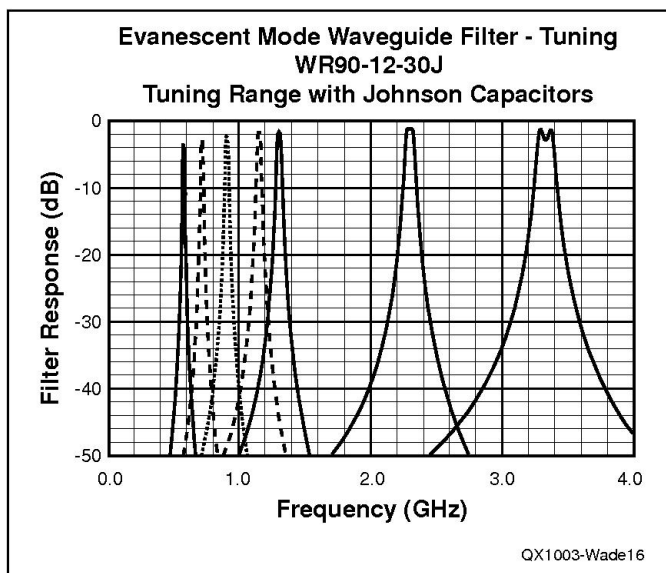

Figure 16 — A graph of the frequency response of the filter shown in Figure 15. The filter was retuned for several frequencies across its range, from about 580 MHz to about 3.3 GHz.
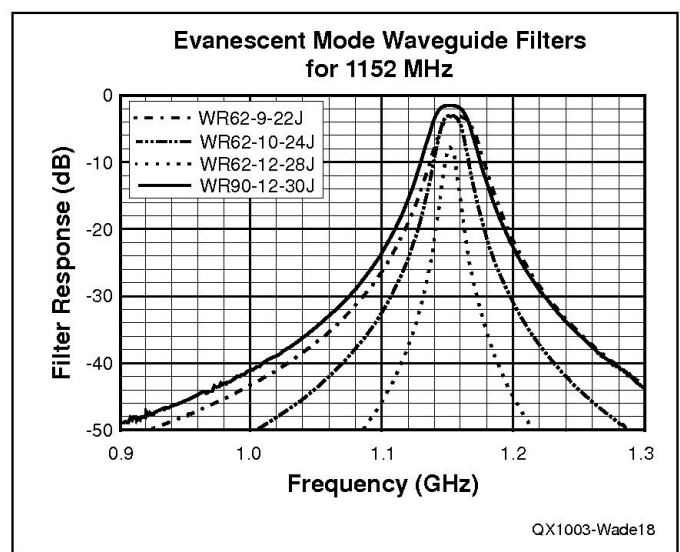

Figure 18 — Here is the frequency response of various two section filters tuned to 1152 MHz.
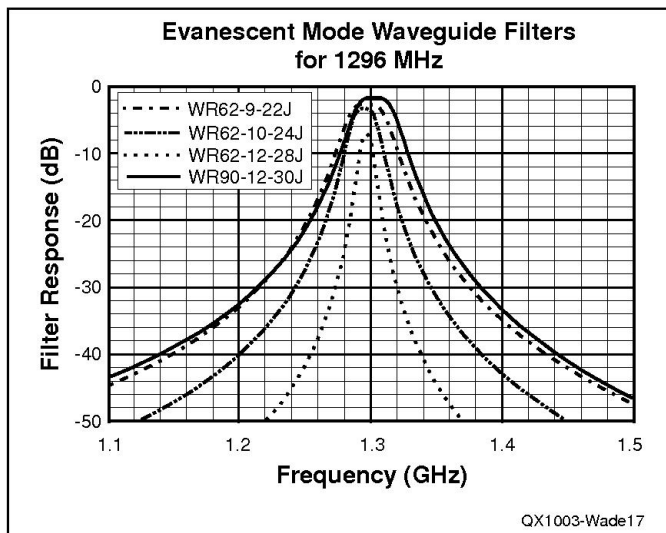

Figure 17 — This graph shows the frequency response of several two section filters for 1296 MHz.
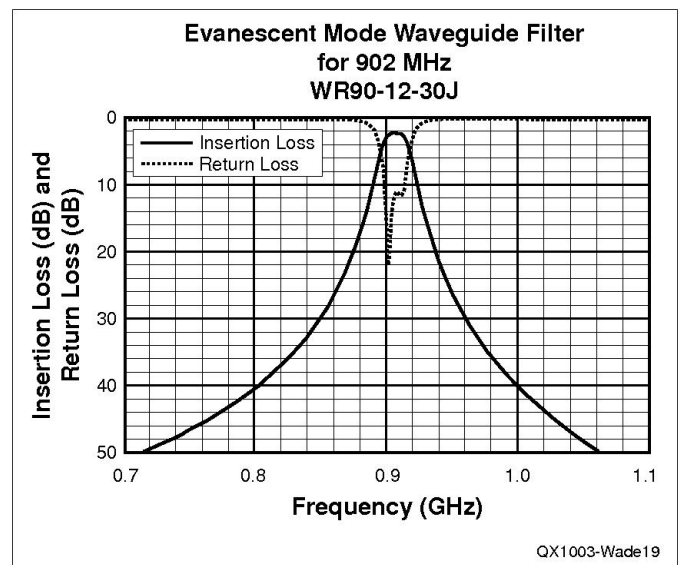

Figure 19 — This graph shows the insertion loss and the return loss for a two section filter built from WR90 waveguide and tuned to 902 MHz.

1296 MHz. Results are shown in Figure 17. The WR-90 filter has less than 2 dB loss, while the WR-62 filters have slightly more loss. As expected, the narrower filters have higher loss.

The same four filters have similar performance when retuned to 1152 MHz, a common LO frequency for 1296 MHz, as shown in Figure 18.

The WR-62 filters will not tune as low as 902 MHz, but the WR-90 filter from Figure 15, with the larger Johanson capacitors, will tune much lower in frequency, as we saw in Figure 16. Performance of this filter tuned for 902 MHz is shown in Figure 19. Loss has increased to around 2.5 dB, but the filter might be sharp enough for a 28 MHz IF at 902 MHz. The upper trace shows that the input return loss is much narrower than the bandpass, but it is still fine for our use.

A summary of dimensions for all the successful filters is shown in Table 1, along with frequencies at which each was tested — some of them work at 3 or 4 different bands.

Tuning these filters can be tricky, unless a swept-frequency test is available, since the filters tune over a wide range. If only fixed frequency testing is possible, it is necessary to slowly tune both screws together until some output is noted. Then it is simply a matter of tuning for maximum output and minimum SWR. Most of them tune with the screws inserted quite far into the guide, so it might be easier to start with the screws nearly shorting and back them out slowly.

The performance shown is tuned to ham bands, but several of the filters can be tuned to more than one band. Obviously, they can be tuned to any frequency in between, and more. Thus, the examples shown above and in Table 1 should fulfill most requirements.

Summary

Evanescent mode waveguide filters offer very good performance in a compact package, and are easy to build for several of the lower microwave bands. While we have not worked out design formulas, a table of dimensions for a number of working filters is included. These examples utilize small lengths of any of the common X-band waveguides, including WR-62, which is of other-wise limited usefulness.
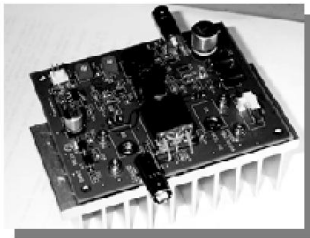
Notes

[1]Reed Fisher, W2CQH, "Evanescent Mode Waveguide Filters," *Proceedings of Microwave Update '93*, ARRL, 1993, pp. 10-16.
[2]David H. Russell, "The Waveguide Below-Cutoff Attenuation Standard," *IEEE Transactions on Microwave Theory and Techniques*, December 1997, pp. 2408-2413.
[3]George F. Craven & Richard F. Skedd, *Evanescent Mode Microwave Components*, Artech, 1987.
[4]*HFSS* is a simulation tool for 3D full-wave electromagnetic field simulation: **www.ansoft.com**
[5]G. F. Craven & C. K. Mok, "The Design of Evanescent Mode Waveguide Bandpass Filters for a Prescribed Insertion Loss Characteristic," *IEEE Transactions on Microwave Theory and Techniques*, March 1971, pp. 295-308.
[6]Richard Snyder, "New Application of Evanescent Mode Waveguide to Filter Design," *IEEE Transactions on Microwave Theory and Techniques*, December 1977, pp. 1013-1021.

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