THE CAVITY DUPLEXER

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NOTE FROM AUTHOR

This book was written several years ago and based on hardware-store copper water pipe as the source of home-brew duplexer construction materials. Later I began making from spun-aluminum commercial cake pans. Both require no welding. Unfortunately the price of copper is today much higher.

Cake pans, however, are still reasonably priced, readily available and very acceptable as the basis especially for VHF cavities. Because of maximum cavity size limit, copper water pipe may still be indicated for UHF and above.

In any case, how a duplexer operates is basic physics. No matter what the material, or whether the duplexer is commercial or home brew, the principles herein are universal to duplexer construction, modification and tuning.

This book, however, is not finished. Repeater building is no longer my primary interest in ham radio. Some subjects could be added. But as it contains the essentials, I have placed on the internet incomplete. If you reproduce it, be so kind as to give proper author's credits.

W6NBC January 2019

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Chapter 1 – The Mysterious Duplexer

The cavity duplexer is a very familiar part of both amateur and commercial two-way radio. On a typical two-way hilltop, cavity duplexers are as common as the forest of antennas that bristle from the towers. Most repeaters have one. They're well known to repeater owners and builders. Or are they? Don't be so sure.

If you are like many hams and two-way radio professionals, you likely have more questions about duplexers then answers. More than the other parts of a modern repeater, an aura of "black magic" and many "old-wives tales" shroud the cavity duplexer. It might be better to call it the familiar "black box" that everybody uses, but nobody really understands.

What are the keys concepts? Why are there different type? What is the right way to tune one? How can you minimize duplexer losses? And for the aspiring ham repeater builder, "How do I modify a commercial duplexer for an amateur band, and can I possibly build one for myself using hardware-store materials and ordinary home workshop techniques?"

These same questions were running through my head when I first decided to enter the world of repeater ownership. By then I'd already successfully installed and maintained several duplexers. I'd even retuned commercial units to the ham bands. But did I really understood them? Did this kind of ham experience really qualify me as a knowledgeable duplexer user? Definitely not, and frankly I knew it didn't.

Like so many hams, especially those who want to put up their first repeater, my experience had only given me a piece of the picture. It was also the dangerous part – bits and pieces, acquired from other ill-informed hams and several old wives tales. Cavity duplexer duplexers were truthfully then still a very big mystery to me, as they currenly still are for many.

Purpose of This Book

My objective is to cut through the common "clouds of fog" that surround the cavity duplexer, and to do so as simply and as non-technically as possible. Duplexers aren't "black magic" You really need only a handful of basic principles to build, modify and tune one from a base of sound knowledge. So I have no intention to write a definitive treatise on duplexers here. We won't be able to avoid some simple mathematics. I will leave out any that is of little value in the practical world, however. Basic principles are the objective. That's what most repeater owner/builders need and normally lack.

Also this book is not a cookbook. There are no cut-and-paste duplexer building plans here. It it your responsibility to translate these concepts into actually constructional designs. But don't be discouraged, there's precisely what you need here to "roll your own," to modify an existing commercial duplexer for an adjacent ham band, or to knowledgably purchase a new unit. For perhaps more than for any other aspect of the modern repeater, working with a duplexer from sound basic principles and not blueprints is very important.

We will, though, build an 2M cavity. The idea is to illustrate the basic principles of cavities in a practical way and to show that they can be built in a home workshop. We'll also look at a few examples from the 440 MHz band. 70 cm was my specific interest when I began this book.

Lastly, there are many related topics of major importance to repeater builder and owners other than duplexers – feed lines, antennas, isolators, to name just a few. Some of these may get mentioned, but my objective is to limit this discussion, as much as possible, to the common type of duplexer used in most modern repeaters. The early chapters apply to all readers, the latter to home builders. All are useful in concept, however.

Origin of The Book

In my original quest to understand duplexers I begin my search for an understanding of the basic principles of duplexers in the highly-technical engineering textbooks. My own engineering background suggested that for me this was a resonable place to start. And this did yield a degree of useful principle. I also did of course review the available popular amateur sources. There have been a number of moderately-informative duplexer/cavity articles published in the ham literature over the years. But to my general disappointment, from both sources, I discovered quite quickly that the duplexer in the modern repeater really remains somewhat of a "mystery" topic.

So I turned to a practical approach to close my understanding gap. I would jump straight in and try to actually build a practical working duplexer for myself. Maybe that was foolish. I'd probably make all sorts of mistakes, but I also sensed that I'd probably learn a lot too. I've always been one who believes that trying to "roll your own" is a good way to acquire practical understanding.

Immediately though, as you might guess, my ham friends loundly proclaimed that I couldn't do it. "Only professionals can build duplexers, not amateurs. Duplexers are beyond the weekend radio warrior. You don't have the proper tools and test equipment." And yes, I will admit that at times it did seem that I'd bitten off more than I could chew. Consequently, by the time I completed my first successful duplexer, I'd gathered an impressive collection hardware-store leftovers.

Today, thought, I can say that the struggle was worth the effort and I did save "some" money. Though with the cost of metals these days, the savings in a home-brew duplexer is less than one would like. The valuable part is what I learned. That should be your primary objective in reading this book as well, not saving money or finding cookbook-style plans for a duplexer. Learn the concepts first. For despite how much mystery there seems to be surrounding duplexers in the ham and commercial two-way radio world, they are not as difficult as they seem.

Using the Ham Bands

For my first duplexer in the 1990's, my interest was the 420-450 MHz amateur UHF band, 70cm. At that time, common hardware store copper water pipe and fittings were reasonably priced and were very suitable for building UHF cavities. Today, aluminum is generally my preference, as we will see in the next chapter. That why this book shows an aluminum 2M cavity built using home-workshop tools and techniques. Again, the object is not to save money, but to give an example fundamental duplexer principles and construction concepts.

If your interest lies on another band – no problem. Simply re-scale this 2M cavity in direct proportion to wavelength. An important word of caution here. Do not attempt to re-just simply re-scale the coaxial lines between the cavities. It is much more complex than that. I will, though, show you how to easily deal with the inter-cavity lines in a later chapter. It isn't difficult either.

The home-brew 2M cavity in this book demonstrates one of the easiest way to construct very-workable cavities in the home workshop. They are large in size, but perform very well. I have actually used the technique for successful duplexers on 2M, 70cm and 6M. I will even suggest a possible way to use the design on 10M.

Vital Opening Concepts

We really do need to begin with two very basic principles. Don't mistake these for "fluff," however. In my view they are vital to one's broad working knowledge of duplexers. They have to do with, "Why do we need a duplexer in a repeater in the first place?" Simple, you say? Yes it is, but many mistakes begin here.

At the most basic level, a repeater requires a duplexer for two reasons: (1) to allow a very sensitive receiver, and a transmitter making power, to operate at the very same time on the very same antenna. Also it must (2) isolate a repeater from other radios I paid way too much attention to old wives tales in both these areas in my early. So let's very quickly get the essentials here. Every repeater owner or builder must be "easy" with both.

DUPLEXER JOB ONE: The Same Antenna

Consider, if you will, a typical repeater. How do we state its output? In Watts, of course. Similarly, how do we specify its receiver sensitivity? This time in microvolts. Simple, you say, but don't pass too quickly over the difference.

Let's take a real example by creating a theoretically repeater here in this opening chapter. It will serve as an example throughout the entire book; we'll return to it often. So first let's assume that the receiver can just hear a 0.22 microvolts from a weak distant user station. I chose this specific value, as we'll see in a moment, to simplify the easy math tht follows. I think, though, that you will agree that 0.22 microvolts is a reasonable as a minimum receive sensitivity for a modern 2M repeater.

The important issue now is this. As different as Watts and microvolts might seem, they tare the same entity. Merely the size is different. We know this because we can convert one into the other. It's much like saying that a temperature of 23 C is also 68 F. We can quite literally also state the Watts from a repeater's transmitter stated in microvolts, even though we normally don't do so. So indulge me. This conversion will emphasize a very important point about all repeaters.

To convert Watts in a repeater's antenna system to microvolts we use Watt's law:

$$\text{Watts} = \text{Volts}^2/\text{Ohms}$$

For our sample repeater, we'll assume 100 Watts. But as you can see, we need a resistance in Ohms to solve the equation. No problem. It is automatically specified by the impedance of the antenna system. The 50 Ohm feedline impedance gives us this value. Computing the equation we get:

$$100\ \text{Watts} = 71\ \text{Volts}^2\ /\ 50\ \text{Ohms}$$

Work through the math yourself if you like, but notice that a 100 Watt transmitter produces a 71 Volts in a 50 Ohm antenna system. That's 71 million microvolts compared to the receiver's sensitivity of 0.22 microvolts Clearly, the transmitter is making a signal very much too large for the receiver to handle. To illustrate this point, which will become very fundamental to an understanding of duplexers, is the reason we made this comparison.

Just to drive home the massive difference between the working signals associated with both the transmitter and the receiver on the very same antenna, consider Table 1-1. It lists the entire possible range, in power steps of 10, of the signal levels possible between the two. It should make the equivalence of Watts, microvolts and dBm as used in repeater discussions even clearer.

Watts	Volts	dBm	
10^{-15} Watts	**0.22 microvolts**	-120 dBm	Our receiver
10^{-14} Watts	0.71 microvolts	-110 dBm	
10^{-13} Watts	2.2 microvolts	-100 dBm	
10^{-12} Watts	7.1 microvolts	-90 dBm	
10^{-11} Watts	22 microvolts	-80 dBm	
10^{-10} Watts	71 microvolts	-70 dBm	
10^{-9} Watts	220 microvolts	-60 dBm	
10^{-8} Watts	710 microvolts	-50 dBm	
10^{-7} Watts	2.2 millivolts	-40 dBm	
1 microwatt	7.1 millivolts	-30 dBm	
10 microwatts	22 millivolts	-20 dBm	
100 microwatts	71 millivolts	-10 dBm	
1 milliwatt	0.22 volts	0 dBm	dBm reference
10 milliwatts	0.71 volts	+10 dBm	
100 milliwatts	2.2 volts	+20 dBm	
1 watt	7.1 volts	+30 dBm	
10 watts	22 volts	+20 dBm	
100 watts	**71 volts**	+30 dBm	Our transmitter

Table 1-1: Watts, Volts and dBm is a 50 Ohm antenna system

Remember from electrical theory that Volts are proportional to the square root of the power. In any case, you should now be able to see why I chose 0.22 microvolts above.

Now notice the additional column on the chart, dBm. This is only another way to specify signal strength. All three are exact equivalents. Which term we choose to use in a repeater discussion depends mostly on which aspect of a repeater we are discussing. For receiver sensitivity, microvolts is more convenient for output power, Watts is best. dBm, being a logarithmic scale is good for both. Hams are often intimidated by dBm so may avoid the term. But as Table 1-1 clearly shows, one can state the sensitivity of a receiver, or specify how much power a transmitter is making in dBm just as easily. I'll therefore use all three terms throughout this book. Just keep in mind that all are the same entity, though. Use Table 1-1 for easy conversion.

A Little More on Signal Strength in dBm

"Plain" dB are not absolute. dB compare only the relative strengths of two signals. dB say nothing about how many Watts or microvolts, for example, a signal actually is. dBm do, however, specify the actual power or voltage of a signal.

To change dB into dBm we must give an actual value to one of the two signals being compared (1 milliwatt is the usual practice for dBm). We must also specify a system impedance, (typically 50 Ohms for radio antenna systems).

Therefore, in a typical repeater system,

$E^2 = W \times R$ (Watt's Law)
$E^2 = 1 \text{ milliwatt} \times 50 \text{ Ohms}$

You should now grasp the right column of Table 1-1. Our receiver has a sensitivity of -120 dBm and our transmitter an output of +30 dBm. Again this is saying exactly the same thing as 0.22 microvolts and 100 Watts.

Don't, however, let all of this math confuse you. The issue here is not the technical terms or the math. Though as a repeater owner/builder it is usually worthwhile to master the math of dBm, if for no other reason than to not be intimidated when the term comes up in repeater discussions.

What matters is that 100 Watts from our sample transmitter is equivalent to a colossal 71 million microvolt signal (+30 dBm) on the very same antenna as our receiver. Such an immense signal can never be feed directly into the input of our sensitive receiver. So as you have already likely guessed, preventing the majority of our transmitter's +30 dBm signal getting directly to our -120 dBm receiver's input on the same antenna system is the duplexer's number one job.

To make this point more evident, think about your car or home transceiver. Here the transmitter is NEVER connected to the same antenna at the same time as the receiver. That's the reason for the T-R switch in a transceiver. Never do receiver and transmitter operate at the same time. Therefore, the receiver never has to look at the transmitter's signal even though it is connected to the same antenna, at least some of the time.

Again, this isn't true for a repeater. Here it is necessary for the repeater's receiver and its transmitter to operate on the same antenna simultaneously, in real time. Otherwise the repeater could not "repeat" the signal it hears from a user, also in real time. Saying this one more time, but this time in actual numbers, the receiver must efficiently be able to detect a tiny 0.22 microvolt signal on the very same antenna that is simultaneously carrying a bone-crushing 71 million microvolt transmitter signal.

In relative dB this is a 150 dB difference. So to say one more time, solving much of this difference IS the number one responsibility of a duplexer. In other words, the duplexer provides a major part of a real-time isolation of roughly 150 dB between the -120 dBm receiver and the +30 dBm transmitter. This amount of total isolation is very typical of a modern repeater, and the duplexer provides a major portion of it.

DUPLEXER JOB TWO: The Neighbors

Unfortunately, most mountain-top repeaters live on the “shady” side of town. The RF occupants of a typical repeater site, the other radios in the same building, are very often “bad” characters. The rogue’s gallery includes:

- Other amateur repeaters
- Commercial repeaters
- Remote base radios
- Broadcast radio and TV transmitters
- Paging and telemetry radios
- Link radios
- Data radios

Often overlooked by repeater builders, the secondary job of a duplexer is to keep all these potentially bad customers from disturbing your repeater, and like a good neighbor to keep your transmitter from bothering them. This isn’t frankly always a cut-and-dried matter. Too often repeater builder/owners pay little attention to this. They thoughtlessly assume that if the duplexer worked well on the test bench it will work the same on the hilltop. In this they forget that the other hilltop transmitters are also making millions of microvolts for your antenna to pick up. The potential intermix problems can be severe and also be quite a surprise at a new repeater installation. This is the main reason low-cost duplexers won’t work on all hilltops.

There’s also the real possibility that hilltop repeaters, including yours, may be “out of adjustment.” These two ever-present factors regularly cause every repeater owner and its users, to be very familiar with “intermod.” Keeping “grunge” minimized therefore is the second main responsibility or a duplexer. And it is here that correctly determining how good a duplexer to use is vital.

Therefore, frankly, never can a repeater owner/builder ignore the other radios on a hilltop. As you master the principles of this book, you will gain the tools to correctly deal with these challenges. Many factors make up our arsenal of defense. What’s more, you will also learn the practical lesson that sometimes small compromises in transmitter output power and receiver sensitivity are much better than living with grunge or being a bad neighbor on your hilltop.

So these are the two responsibilities of a duplexer:

(1) To keep your transmitter (and your neighbor’s transmitters) out of your receiver.
(2) To keep your transmitter out of your neighbor’s receivers.

Neither is a simple, but is a challenge a repeater builder/owner MUST face. The following chapters will give you the keys.

Chapter 2 – Let’s Make a Cavity

We’ll step aside in this early chapter for a do-it-yourself project and build an actual working 2M cavity. It’s practical for two reasons. It will make the remaining chapters easier to illustrate. If you will build one and experiment with it, you will gain the kind of practical knowledge most repeater owners' lack. This is how I acquired mine. I highly recommend the process.

You can also, if you wish, use several of them to build an actual working 2M duplexer. This cavity is a bandpass (Bp) cavity. We’ll learn about cavity types and how to change this cavity into a notch (Br) cavity later. You can also scale these cavities up or down for another band.

Construction Objectives

When I built my first duplexer I had two objectives. They’re still the same today. First I wanted to use only hardware-store materials and home-workshop techniques. Published home-brew designs often discourage would-be builders with hard-to-get or expensive materials, and often the need for machine-shop facilities. This design uses neither.

Second, the cavity(s) had to be easy to tune. Here you’ll only need a thru-line wattmeter, a couple of dummy loads suitable for the frequency, and an ordinary synthesized HT or mobile transceiver on the band. Any of the common ham antenna analyzers is also useful handy. If you just happen to have access to a spectrum analyzer or a vector network analyzer with a tracking generator, all the better, but it isn’t necessary. These just makes things easier.

Materials and Special Tools

The first decision in building a cavity is the type of metal to use. As any home craftsman knows that there are not many choices, steel, stainless steel, brass, aluminum and copper. For low insertion losses, copper is by far the best. What’s more, it solders easily. But copper is expensive. In recent years it has become almost prohibitive. That’s why commercial duplexer manufacturers often use aluminum. The losses are just a little higher and aluminum does present fabrication problems for the home builder, but these are manageable in the home workshop.

In case you are wondering, steel is unsatisfactory. Number one, it rusts. More importantly, it has very poor conductivity compared to copper or aluminum. See Table 2-1. A steel duplexer would have very high insertion loss. Stainless steel is also of no interest either. It too has low conductivity.

Some commercial manufacturers use silver-plated steel, but electroplating is generally impractical for home builders. Common yellow brass, as Table 2-1 illustrates, is also not a good choice, again because of relatively low conductivity. Red brass, which has much a higher percentage of copper, can be used.

Silver	1
Copper	1.1
Gold	1.4
Aluminum	1.6
Nickel	4.3
Brass	5
Iron	6.3
Tin	6.9
Lead	14

Table 2-1: Relative resistivity of common

A curious point here is that gold is a poorer conductor than copper. Gold is used on electronic connectors because of corrosion resistance, not high conductivity.

Copper is the most workable choice for home-brew cavities, particularly common hard-drawn household copper water pipe. It solders easily and excellent ends caps are readily available in all pipe sizes. These eliminate the need for machining. That's why I chose common copper water pipe for my early duplexers. Today, however, copper has become almost prohibitive for the home duplexer builder at all but UHF.

Aluminum is to me the best choice for home brew 2M and 220 MHz cavities and duplexers. True, aluminum cannot be soldered and there are no available end caps as with common copper water pipe. But as you will see, there are easy ways around these.

Also, is slightly lower conductivity than copper is not enough to make aluminum unsatisfactory. One just needs to make the cavities slightly. Aluminum is, therefore, the material we'll use for an example cavity.

Connectors

The second decision is the connectors used to connect the cavities to a repeater or between cavities in the duplexer. I universally recommend BNC connectors. N-type are also excellent, but are more expensive and not really necessary for most repeaters, which are generally under roughly 100 Watts. Common PL/SO-239 connectors are just barely okay for 2M and below but are quite poor at UHF.

Commercial Cake Baking Pans

Now for my "big trick." This is how I easily tamed aluminum for home brew. I was looking around a restaurant-supply store one day and noticed some heavy-duty round commercial aluminum cake-baking pans. They have nearly vertical sides, are about 2 inches high and come in diameters from seven to twelve inches. And, they are reasonably priced. "Here are the end caps I have been looking for to make aluminum cavities."

I then remembered that hardware stores sell flexible 10 mil (thin) hard-alloy aluminum sheet in rolls. It was obvious that a sheet of this could easily be wrapped around two commercial aluminum baking pans (bottoms facing) and held in place with stainless steel hose clamps. The end result would be an excellent aluminum cavity, easily made in a home workshop. If you can't find stainless hose clamps long enough, simply use several to form one longer clamp.

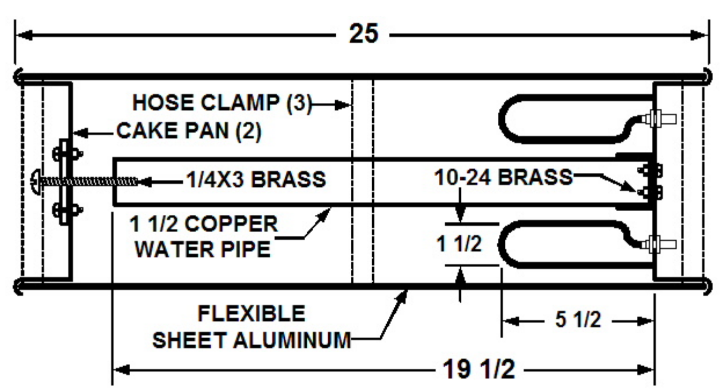

Figure 2-1: Cross section of 2M sample cavity

The example cavity here is made from the smallest commonly-available cake pan size (7 in.), Figure 2-1.

If you are contemplating 6M or 10M cavities, larger cake pans are ideal. I have used 11 in. cake pans on these lower-frequency bands. Frankly, even at 2M, larger diameter cavities perform better. Use them if you have the room. There is, however, a size limit which we will see later.

Figure 2-2: Example 2M cavity and loop detail

The center conductor here is a ¼ wavelength legth of 1 ½ inch common copper water pipe with an end-cap to make attachment to the end of the cavity easy. We'll learn later how to select the diameter of the center conductor for other bands or larger cavities.

Here the coupling loops are made from ordinary 3/16 in. soft-drawn copper tubing. The connectors are chassis-mount BNC jacks, fitted with long ring-type grouning lugs.

Tuning the Cavity

To tune the cavity and its loops, only a simple setup is needed.

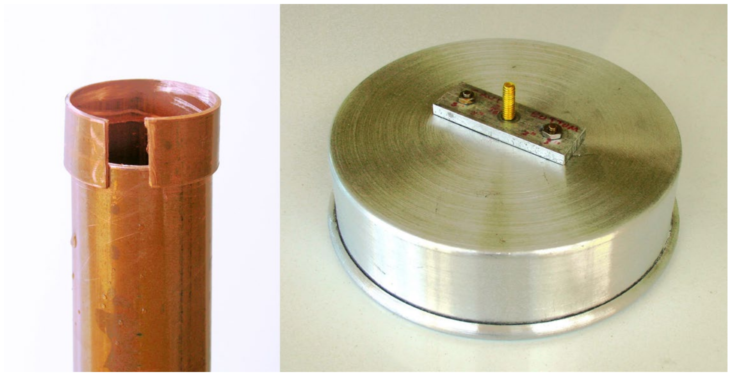

Figure 2-3: Center conductor extension and tuning screw

The transceiver needs to be modified to transmit outside of the ham bands so that you can cover more than the ham band during the initial design phase.

Tune-Up Procedure

Here's the basic cavity-tuning process. It is much the same as we'll also use to tune up a complete duplex later.

First connect one port of the cavity (either connector) to your transceiver and on the other side a through-line Wattmeter and a dummy load. The dummy load MUST be specified for at least the frequency on which you are working. If you happen to have a spectrum analyzer with a tracking generator, connect the tracking generator to one connector and the analyzer to the other. Figure 2-4 shows both setups.

For the basic setup, in small frequency steps, apply power briefly and record the Wattmeter reading. Power throughput will peak at the cavity's resonant frequency. Plot the data on a graph. The graph wizard in Microsoft Excel is an excellent tool for this, though a paper graph is completely satisfactory. It will immediately show you the frequency to which the cavity is tuned, as well as its overall frequency response, and the insertion loss (space above the curve). See Figure 2-5. This is the basic tuning procedure used for design and in the field, for individual cavities and complete duplexers. No other tools are needed.

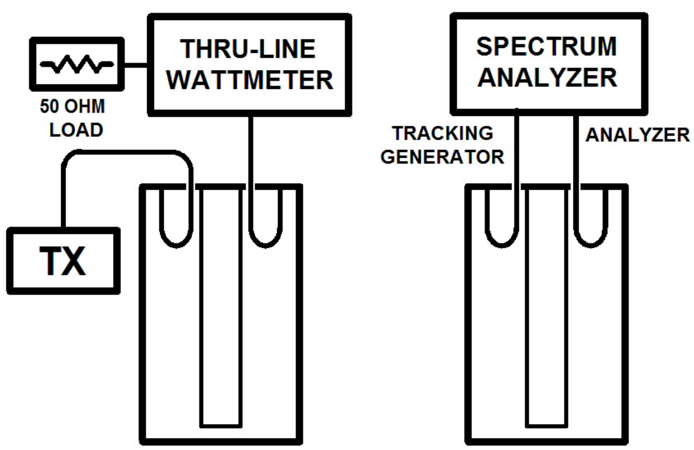

Figure 2-4: Cavity tune-up setups

If the graph shows that the cavity is quite a bit off frequency, you will now need to lengthen or shorten the center conductor. The tuning screw shown in Figure 3 is only for fine tuning.

To raise the resonant frequency, shorten the center conductor in this cavity by roughly ¼ in. per Megahertz. To lower it, lengthen the center conductor. An easy way to do this without installing a new center conductor each time is to fabricate a slip-on extension from a short piece of the same-sized pipe, slit lengthwise down one side. I cut the slit with a hand-held hobby grinding tool and a cutoff disk. Pry the slit open with a large screwdriver until the extension fits snugly over the end of the center conductor. You can solder the extension in place if you wish after tuning, or replace the entire center conductor.

Figure 2-5: Frequency response (Bp) of sample cavity

This configuration naturally creates a bandpass (Bp) cavity. Bp cavities have the response shown in Figure 2-5. Our sample cavity here has a power bandwidth of roughly 2.5 MHz and an acceptable small amount of insertion loss. Later we'll modify it to form a band-reject (Br) or notch cavity. By building several cavities and following the guidelines given in the remainder of this book, you will be able to assemble a complete 2M duplexer.

Actually building and then experimenting with a cavity like this was the most instructive part of the entire duplexer adventure. Hilltop experience does not even come close. Try it. You will not regret it. If nothing else, you will at least find out that duplexers are not black magic.

Chapter 3 – Cavities

A duplexer is normally made up of four to six ¼ wavelength coaxial cavities. Figure 3-1 shows the common configuration. We'll have more to say about the overall structure of a complete duplexer later. First, though, we need to take a look at the important mechanical and electrical properties of the individual cavities.

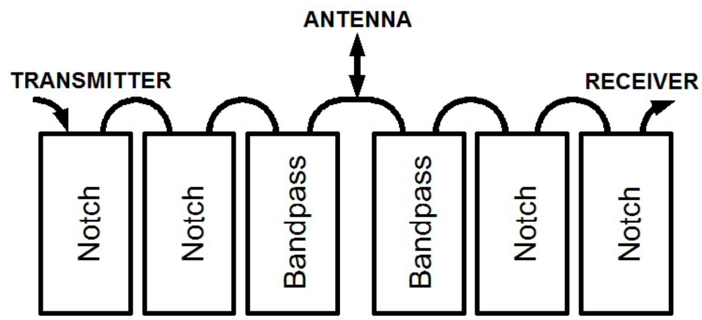

Figure 3-1: Most common duplexer configuration

We'll discuss three vital issues: (1) why we use resonant cavities (2) how RF energy gets in and out of a cavity, and (3) the three basic cavity types: bandpass (Bp), band reject (Br) and bandpass-band reject (Bp-Br).

As a final footnote to this chapter, we'll take a very quick look at a cousin of the ¼ wavelength coaxial cavity, the helical resonator. Especially to hams interested in 6M or 10M repeaters, helical resonators have much practical application.

(1) Why Resonant Cavities

Here is a very basic question. Why are quarter-wavelength coaxial cavities the only real choice for duplexer filters? It's because there actually isn't much choice. The still continues, even in today's world of miniaturized solid-state electronics, to be the only practical filter type for a duplexer.

The ¼ wavelength cavity has three essential properties for a duplexer all present in one filter type. The other main types, namely discrete coil-capacitors filters and active filters, lack one or more of the three essentials: (1) the ability to handle power, (2) high Q, and (3) low loss. It is this unique combination of all three in one filter type, that has long made the resonant cavity the only real choice as a duplexer filter. The cavities are not about to disappear from repeater hilltops.

Of these three properties, perhaps the most significant is the first. For only a passive filter, that is, one without active electronic components, can handle the power of the repeater's transmitter. Remember, our sample duplexer must deal with 71 million microvolts (+30 dBm). Active electronic filters can't.

Yes, it is true that filters made from discrete coils and capacitors also can handle power, such as in an antenna tuner. But at higher HF and VHF frequencies, and especially at UHF, discrete coil-capacitor filters have poor Q and exhibit high losses. So it is the combination of all the three properties, as found in the resonant cavity, that has caused resonant cavities to be the filer of duplexers for the last fifty years. The principles of this book were just as valid in the 1930's as today.

As an aside, but still on the basic concept of cavities, it's conceptually useful to point out that resonant cavities actually do behave as if they were made up of discrete coils and capacitors even though they aren't. That is, they exhibit real inductance and real capacitance. Hence it is not surprising that the equivalent circuit of the ¼ wavelength coaxial cavity is a parallel-tuned L-C "tank" circuit. Notice Figure 3-2. Noting this simple fact might make the basic concept of the resonant cavity a little easier to visualize.

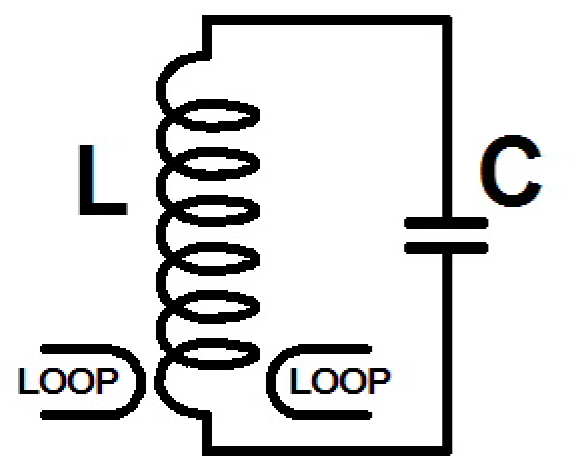

Figure 3-2: Equivalent circuit of a cavity -- parallel L-C tank circuit

Physically though, as opposed to electrically, a cavity resonator is just an open volume of space enclosed by highly-conductive walls. It's metal container "rings" or resonates very readily in the presence of RF energy, very much like a soft drink bottle makes a tone when air is blown across its top. In the cavity, the vibrations aren't in air in thee electro-magnetic field. You can liken a cavity resonator to an organ pipe, a penny whistle or a flute. The math formulas describing both are almost identical.

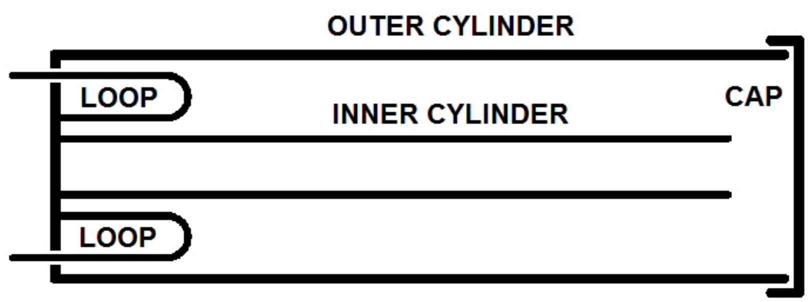

Figure 3-3: Components of a 1/4 wavelength coaxial cavity

A hollow metal sphere is technically the best shape for a cavity resonator, at least in terms of electrical efficiency, but it isn't a very practical shape physically. A metal cylinder is much easier. We also add inside In a duplexer cavity there is also a smaller metal cylinder about 1/3 the diameter of the outer cylinder. This is the center conductor. See Figure 3-3. The center conductor is connected to the outer cylinder at one end of the cavity but not at the other.

You may recognize this configuration as a short length of large-diameter air-insulated coaxial transmission line, shorted at one end. The common duplexer cavity is a simply a ¼ wavelength shorted coaxial stub. And simply by making it large we easily achieve the three basic desired filter characteristics. In a duplexer, we also cover the open end with a conductive cap placed just a small distance away from the open end of the center conductor. The cover has little effect on the action of the filter. It would work perfectly well as a duplexer filter without the cover, though undesired outside signals could enter.

Field Strength and Orientation

As we said above, our signal in the cavity is in the form of induce an electro-magnetic (E-H) field. The electric lines of force (E) lie parallel to the length of the cavity, as shown in Figure 3-4. The magnetic force lines lie at right angles, in concentric circles around the center conductor.

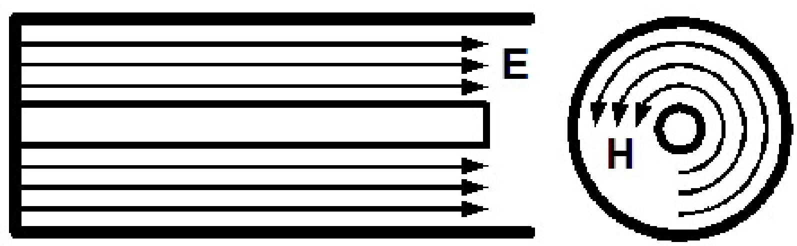

Figure 3-4: Electric and magnetic field orientations

The magnetic field and the associated currents in the cavity walls are strongest at the shorted end of the cavity and weaker at the open end. The electric field and its associated voltages on the cavity walls are just the opposite. They are strongest at the open end and weakest at the shorted end. Both, however, are stronger near the center conductor and weaker near the outer conductor.

These orientation are important when we look at loops and probes for coupling later. It is helpful, therefore, in a solid understanding of duplexers to have a strong mental picture of the E and H fields inside the quarter-wavelength coaxial filters.

Resonant Frequency

Returning now to the soft drink bottle analogy, if we gently blow across the open end, we produce the bottle's fundamental “note” or frequency. Like our cavity, the soft drink bottle will now be oscillating in ¼ wavelength mode. If, however, we blow harder, the bottle will break into an overtone mode. The note will now be one or more octaves higher.

These overtone or harmonic modes are why a trumpet, for example, can make many notes with just three valves. For specific notes the musician excites an overtone mode merely by blowing harder. Cavity resonators can also be driven into overtone modes. But here it's a "hazard" not an asset as it is in a trumpet. In duplexer cavities we must avoid overtone modes. They exhibit high losses.

To establish the operating frequency of a coaxial cavity, we merely make the length of the center conductor roughly ¼ wavelength. At 450 MHz, for example, that's about 6 inches. For other bands, the length is directly proportional to wavelength. Hence a 2M cavity's center conductor it is roughly 19-20 inches long, again ¼ wavelength. On 6M and especially on 10M the cavities become very large. This is where helical resonators, which we'll look at very briefly at the end of this chapter, can be useful.

Perhaps surprising to some, the outer shell of a cavity has virtually no effect on the tuning of a cavity. So we simply make it a little longer than the center conductor. Also, neither does the outer diameter of a cavity alter the frequency. These two facts constitute a key concept. The resonant frequency is determined almost exclusively by the length of the center conductor. This is not however true for all possible resonant-cavity shapes where the resonant frequency is more complex. This is another reason why duplexer cavities are generally ¼ wavelength coaxial cavities. For other electronic applications the harmonic modes in other cavity shapes are useful.

Outer Cavity Diameter

Never the less, even though outer conductor diameter has little effect on the resonant frequency, diameter is very important in a cavity. We'll say more about that later. For the moment, merely note that it should not be made larger than roughly 1/3 wavelength. If we do, the cavity will break into a high-loss overtone mode. This means that the diameter limit for 450 MHz cavities is roughly 8 in. A 2M cavity should not be larger than roughly 25 inches. But up to that limit there is considerable benefit in a big diameter. Larger cavities filter better and with less loss. For the home builder, a single large-diameter cavity could work better than two smaller ones. With the construction techniques shown in the previous chapter, large diameters are relatively easy to achieve. So this is an option worth considering for home-brew duplexers.

(2) Coupling Energy in and out

The next main concept of this chapter has to do with how best to couple RF energy in and out of a cavity. The most common method is a single-turn coupling loop. This isn't the only choice, it is just the most-frequently used method. Actually, there are four practical ways to couple to a cavity: loops, probes, ports and taps. In my investigations I examined each, and the results surprised me somewhat. Let's look quickly at each.

Loop Coupling

A loop is a simple single-turn coil excited from a connector mounted through the cavity wall. It is most often placed in the shorted end, but may also be put in the side. The far end of the loop is grounded to the cavity. Notice Figure 3-3 again. You may recognize that loops are analogous to the link windings shown in the equivalent circuit, Figure 3-2.

A loop couples to the magnetic field and does this best when it is perpendicular to the H field. Since the H field, as we learned, lies in concentric circles around the center conductor, the loop is normally placed parallel to the length of the cavity and on the cavity's radius. It also couples best where the field is strongest. This, as we also learned, is near the shorted end and near the center conductor. Figure 3-3 shows loops in the maximum coupling position.

In my experimentation I was surprised to discover that the placement of the loops isn't actually critical. Despite what cavity design texts often imply, I have made successful low-loss cavities with loops in the end, on the side and even near the center of the cavity's length. The loop size does change with these position changes, in order to achieve equal performance, but the action of the cavity is much the same no matter where one puts the loops. I will have much more to say about loop placement in a later chapter.

A simple but meaningful analogy to the placement of a loop is pushing a child on a swing. You may push anywhere you like up and down the ropes. If you push at the bottom, you push gently with a long arc. If you push higher up the ropes, you push harder but with a shorter arc. These are equivalent to larger and smaller loops closer or farther from the shorted end of the cavity.

Probe Coupling

The second, though less frequently used coupling method, is a probe, Figure 3-5. The probe is just one plate of a capacitor used to couple energy in or out. The center conductor of the cavity acts as other half of the coupling capacitor. As opposed to a grounded loop, a probe is open at the end. And as you may have surmised, a probe couples to the electric field (E) instead of the magnetic field (H). But like a loop, a probe couples best when it is perpendicular to the field, in this case the E field, and is placed where the E field is strongest. This, as we've learned, this is at the open end of the center conductor, near to it, as shown.

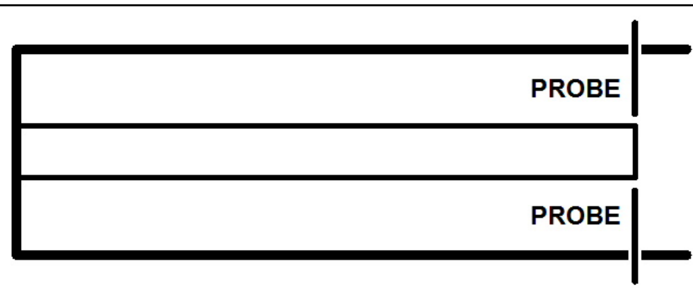

Figure 3-5: Maximum coupling position for probes

In my experiments, I discovered that probes function just as well as loops, and this too surprised me. For it made me wonder why commercial duplexer manufacturers don't commonly use probes. I soon discovered that there is a good reason. In that probes must utilize the E field, they must be placed at the high voltage end of a cavity. A loop, on the other hand, which utilizes the H field is placed at the low voltage end. With probes, therefore, arcing is a potential problem, even at moderate power levels.

Recall as we saw, that a 100 watt transmitter places a 71 volt signal on a 50 ohm transmission line. But in a good quality cavity Q can easily reach 1000. We therefore multiply the 71 volts by 1000. This makes is clear that very high voltages can exist at the probe end of a cavity.

Port Coupling

A third way to couple energy, this time normally between adjacent cavities, is to cut a hole in outer walls of both to let some of the field leak through into the adjacent cavity. This is called port coupling. A number of duplexer designs do successfully implement this method. Also the helical resonators, often found in receiver front-ends, commonly use port coupling. It is economical and a space saver. Loops or probes usually need more room.

The main difficulty with port coupling for the home repeater builder is purely mechanical. Varying position and coupling of loops and probes is easy. To change the amount of port coupling one must physically change rhe size of the port. This precludes easy experimentation. Also, since duplexer filters are often made of cylindrical tubing, a port between cavities is also not easy to fabricate. Small mobile duplexers of rectangular cross section often use port coupling. Therefore, I only mention port coupling in passing. I did not extensively investigate it, though I am confident that the end result would have been the same as for loops or probes.

Tap Coupling

The final method, illustrated in Figure 3-6, is tap coupling. On the left is an actual cavity with taps.

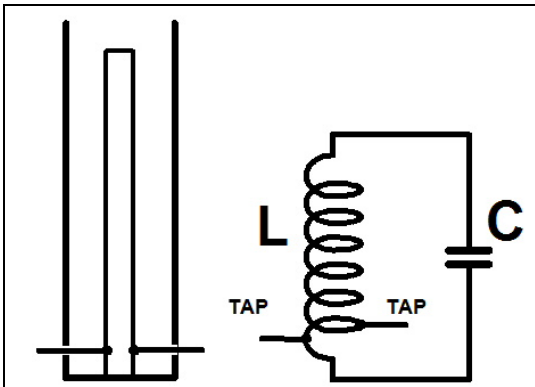

Figure 3-6: Tap coupling and equivalent circuit

On the right is the equivalent LC circuit again with taps. By adjusting the position of the taps, one can achieve a good impedance match as well as efficient coupling. In small cavities, where loops could be too large for the space available, a tap is an easy way to obtain tight coupling.

The disadvantage of tap coupling, however, is isolation. If the type of cavity you wish to use requires two ports, an input and an output tap, isolation between ports is difficult to achieve. Tap coupling finds its best application in single port cavities, such as notch cavities. It is seldom used in band-pass cavities. We will discuss cavity types in a moment.

Which Coupling Type is Best?

Getting practical now, one might ask which coupling method is best? Does one type make a better duplexer? By actual experimentation I found that the answer is no. Surprising as it was for me, all four coupling methods ultimately perform more or less the same after critical adjustment.

Experience, however, did lead me to the practical conclusion that loops are the easiest choice for the home builder. They are also the most common choice for the commercial manufacturers. If a loop will physically fit inside the cavity, you can get it to perform just as well as any other method. It is much easier, however, to mechanically implement and adjust. For this reason, I will stick to loop coupling in the rest of this book.

(3) Cavity Types

Here is the final main concept of this chapter. It was another surprise to me to discover that all one must do to change the same basic ¼ wavelength cavity into any of the three basic types commonly found in duplexers: bandpass (Bp), band reject (Br) and bandpass-band reject (Bp-Br) is to reconfigure the loops. Each cavity type has a unique role to play in a duplexer, but the overall physical cavity configuration is very much the same for all.

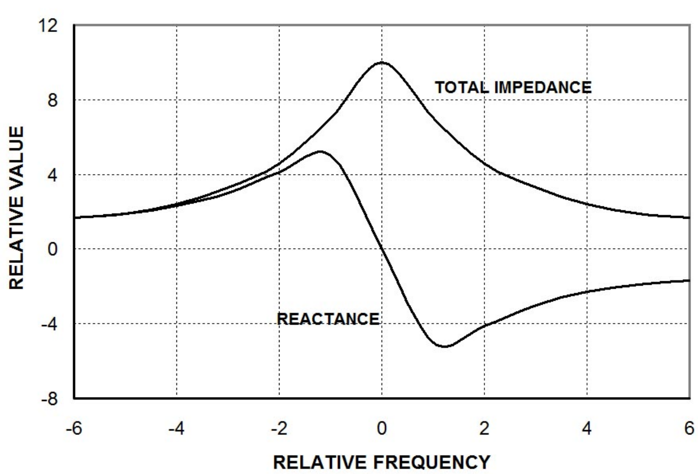

Figure 3-7: Impedance and reactance of an L-C circuit

The best way to grasp how the conversion from one type to another is achieved, is to examine Figure 3-7. It is a classic diagram found in many electronic textbooks. We won't labor over it here, but only point out a couple of important points.

Bandpass Cavities

The behavior of a Bp cavity follows the total impedance curve of a parallel L-C circuit, Figure 3-7. The response of a notch cavity follows the reactance curve. To obtain a Bp response we must place the cavity in series with the transmission line. Notice Figure 3-8.

First let's look at a bandpass cavity. When a Bp cavity is off resonance, like a parallel L-C circuit, its total impedance is low. At resonance, impedance reaches a maximum. The absolute value depend on the Q of the cavity.

In a series configuration, all of the energy passes through the cavity. It is coupled into the cavity by one loop and out by the other.

At the center frequency, the high Q cavity readily absorbs the energy supplied to it by the input loop. Then at the output loop the H field couples back into the transmission line. At resonance very little signal is lost. To the energy on the transmission line, the cavity is invisible .

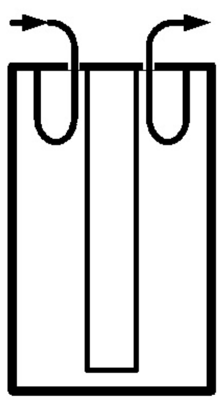

Figure 3-8: Bp cavity, in series with transmission line

But transparency ONLY happens at the cavity's resonant frequency. Off resonance, that is, at a higher or lower frequency, the cavity's impedance rises very rapidly. This greatly suppresses off-frequency signals. Again, in a Bp cavity, non-resonant energy is attenuated in response to the impedance curve of Figure 3-7.

On the other hand, if we place the cavity in parallel with the line, we create a band-reject (Br) or notch cavity or shunt configuration. Figure 3-9 shows the common ways to do this. Parallel or shunt-connected cavities are sometimes called or "suck out" cavities. The difference, therefore, between a Bp and a Br cavity is merely the way the cavity is connected to the transmission line, series or shunt. This alone determines whether it is a bandpass or a notch cavity. Both types still employ ¼ wavelength shorted transmission line stubs.

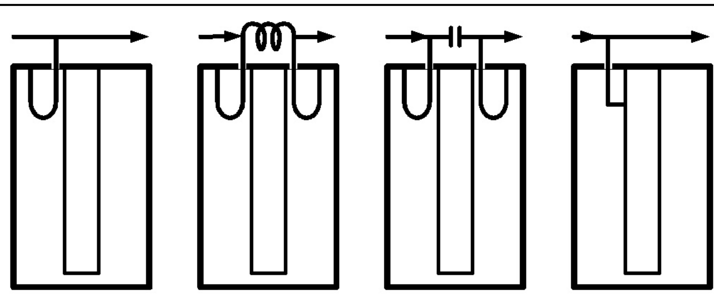

Figure 3-9: Br (notch) cavities, in parallel with transmission line

In (a) a single-loop shunts the cavity

across the line. In (b) and (c) the cavity shunts across a coil or capacitor. In (d) a single-tap cavity shunts the transmission line. As we saw earlier, this is generally how tap-coupling is implemented.

Here, however, is the key issue with Bp and Br cavities. A Bp cavity PASSES a small band of frequencies. ALL others are rejected. A Br cavity REJECTS only a small band of frequencies. ALL other pass on through. Said another way, a Br cavity “sucks out" only a small band of frequencies.

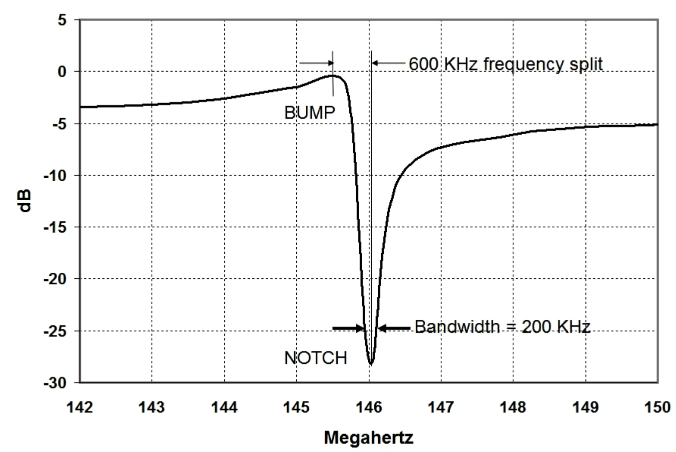

Figure 3-10: Br (notch) cavity response

In the Br or notch cavity, behavior tracks the reactance curve of Figure 3-7. As you can see, a long way off frequency the cavity reactance is moderate.

As we approach resonance, reactance rises a little but then rapidly becomes a deep notch. By maximizing this response, with either parallel inductance or capacitance, we achieve the familiar response curve of Figure 3-10. Notice that the notch of a Br cavity is very sharp compared to response of a Bp cavity..

Bp-Br Cavities

It is sometimes said that there is a third class of cavities, which supposedly has both Bp and Br characteristics. How is it different? Actually it isn't. All Br cavities have both a reject “notch” and a pass “bump.” When the frequency is significantly off resonance the filtering action is only moderate, a few dB. Near resonance one of the reactance excursions produces a small bandpass "bump" which is also only moderate. But the opposite reactance excursion, creates a deep notch. This is the action we are looking for in a Br cavity, capable of many dB of filtering, far more than a Bp cavity. The deep narrow notch is why Br cavities are the real work horses of cavity duplexers.

In a few designs the bandpass bump is intentionally minimized and the cavity called a pure notch cavity. In theory though, all Br cavities are Bp-Br reject cavities. There is always both a notch and a bump. Hence there really are only two basic cavity configurations, bandpass Bp and band-reject Br.

Bump Up or Down?

Of great importance, however, to duplexer design is whether the bump is configured to be above the notch or below it in frequency. Both are easy to arrange. If the line bypassing the cavity has a shunt inductor, as in b, the notch will be on the high frequency side of resonance. If the line has a shunt capacitor, the notch will be on the low frequency side.

But as I just said, the relationship of the notch to the bump, as compared to the cavity's resonant frequency is very important. And again, that's because the transmit filters must always be one way and the receive filters the other. Which one you will need for your repeater is dictated by the frequency split of your repeater, that is, whether the transmitter is higher or lower in frequency than the receiver. In Figure 3-10, a 2M cavity, the notch is high of the bump. This would be for a repeater with a positive offset of 600 KHz. We'll get to the specifics in a moment.

The Merits of Bp (Bandpass) vs. Br (Notch)

The final piece of basic theory of this chapter will be to compare the basic way we use both types of cavities. For they fulfill different roles in a duplexer.

As far as the bandpass bump part of the response curve of either, both work the same basic way. We want the bump to be centered on the frequency we want to pass on either side of the duplexer. And at that frequency only a fraction of a dB will be lost. The deep notch of the Br cavity(s) is another story as we shall see.

If bandpass cavities were good enough, that is, if its bandwidth were small enough, then an all-Bp cavity duplexer would be ideal. Unfortunately Bp bandwidth of a Bp cavity is not sufficiently narrow to be the only type of filter used in a practical duplexer. Referring to our sample cavity, its bandwidth is only 3.6 MHz. At the normal frequency offset of a 2M repeater, 600 KHz, it can provide only 3dB of filtering. This is why we must also use notch (Br) cavity cavities in a duplexer. The notches provide many more dB of filtering than the off center rejection of a bandpass cavity.

The notch cavity, however is incapable of rejecting anything but the small band of frequencies on which its notch is centered. But in a duplexer that's precisely what we need. We primarily only need to keep the transmitter frequency out of the receiver. Notch cavities are ideal for this.

On hill tops, however, and to a smaller degree in our own repeater, a combination of both notch and bandpass cavities is necessary. The notch cavities fulfill the duplexer's primary job of isolating a repeater's receiver from its transmitter. The bandpass filters fulfill the secondary responsibility of providing general isolation from the outside world.

Duplexers, therefore, that are used on radios where there are no neighbors, such as in mobile installations if both transmitter need to operate at the same time, a notch-only duplexer can be used. Unwittingly, however, many radio amateurs make the mistake of trying to use this type of duplexer on a hill top. They are attracted to the small size and low cost of mobile notch-only duplexers. But when they do, they forget that their repeater is wide open to interference from the mixes and intermod that is common at such a site. Small mobile duplexer by themselves are not a good idea on mountain tops.

If economy is imperative, you can us a notch-only mobile duplexer on a hill top. But you will need to add some outboard bandpass cavities to take care of the neighbors. I have personally built good-performing hill-top duplexers from a low cost mobile duplexer and outboard bandpass "bottles."

Fix in your mind then, that series-connected bandpass cavities are to keep the neighbors out. Shunt connected band-reject cavities are to keep your transmitter out of your receiver. This is a bit of a simplification, for both cavity types do also provide other protections. But in tuning a duplexer to fulfill its main responsibilities you will naturally cover all the bases at the same time.

Helical Resonators

As we promised, let’s take a very quick look at a close relative to the cavity resonator, the helical resonator. You most commonly find them in the front end of narrow-banded receivers. I have experimented with a hybrid form of the helical resonator for ham 6M and 10M repeater application. I personally call a duplexer built from helical resonators a heli-plexer. Here I will only very quickly overview the concept of helical resonators in duplexer service. They do work, though, as my limited experiments have verified.

As we can do with a full-sized antenna, we can also shorten the length of a resonant cavity by inserting a discrete coil into its center conductor or by completely replacing it The quarter wavelength cavity now becomes a semi-helical resonator or full helical resonator. See Figure 3-11. To implement this concept in a duplexer filter one only needs to exert knowledgeable caution. The advantage of semi-helical filters can easily

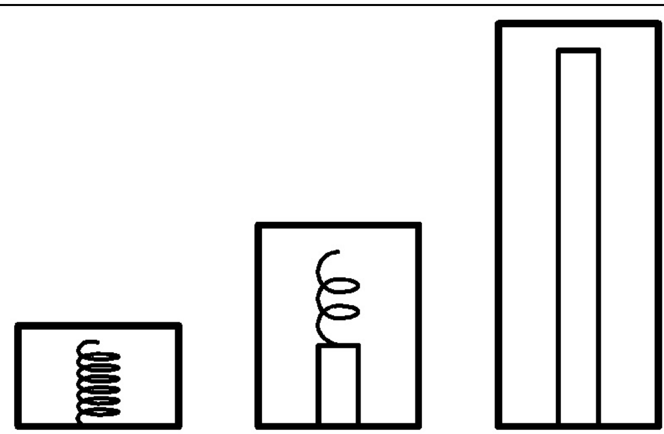

Figure 3-11: Helical resonator, semi-helical resonator, cavity

outweigh their small disadvantages. But what are the advantages and disadvantages?

The main advantage is the large reduction in the length, which on 6M or 10M is highly desirable. However, for exactly the same reasons an antenna shortened with a loading coil has disadvantages over its full-length cousin, so does a semi-helical resonator. Still for 6M and 10M, a shorter filter may well be worth the disadvantages.

Personally I have only just scratched the surface of substituting semi-helical resonators for full-size cavities in repeater duplexers for one working 6M heli-plexer. I have yet to try the technique on 10M. The 6M duplexer was, however, a reasonably good performer. I used 10 in. baking pans for it. So I only offer the following as grounds for experimentation. The 2M cavity in this book should be easy to use as a test bed.

First of all I personally think that one should not reduce the length of the center conductor of a semi-helical filter to more than roughly ½ the full-sized length. On 6M that would be just over two feet. Too much coil would be required. And as we have seen, discrete coils exhibit too much loss at VHF and above to be satisfactory as the center conductor. This is why a recommend the semi-helical design, which retains a significant portion of the normal center conductor.

RF skin effect is the major enemy. So make the coil from copper tubing as large as possible and use only a turn or two. This is also a good idea for rigidity. Likewise keep the space between turns wide. To do both of these you will have to retain as much of the normal center conductor as is required to bring the filter to resonance.

I do not know if semi-helical cavities are more or less temperature sensitive than full-sized cavities. I suspect more. So you will need to implement the brass tuning screw technique we saw earlier. It will work much the same. Coupling loops and shunts to create notch cavites should also be similar to full-sized cavities.

I have not seen the semi-helical resonator employed in the commercial two-way radio world. There are two significant reason why. Low-band 30-50 MHz VHF commercial repeaters have not ever been common in the two-radio world. Simplex and remote base radios have rather generally been the rule. Duplexers are not needed for either. Also the widespread use of commercial low-band for land-mobile services is generally fading. Hams are generally the only current uses of repeaters in this spectrum.

One final thought on the practicability of the heli-plexer on 6M and 10M is our old friend band noise. It is three times higher on 6M, and five times higher on 10M, than on 2M. We can live with the lower efficiency of a heliplexer. The 0.22

microvolt sensitivity of our sample 2M is far more than the noise on the lower bands will ever allow. Less duplexer is needed.

Chapter 4 – Temperature Drift

This chapter is a side issue, but one of considerable importance. How does temperature affect a duplexer? With a commercially-built unit, a repeater owner does not need to pay much attention to this; it has been dealt with by the manufacturer. For the home builder, it is of major concern, however. The do-it-yourself builder must make provision during the design phase to keep home-brew cavities "on tune" as the weather changes.

We likely learned in grade school science class that most substances in the universe expand as they get warmer. The metal used in a cavity is no exception. Table 4-1 is the thermal expansion of common metals, expressed in percent per degree F.

Metal	% / ºF
Aluminum	0.00131
Cast Iron, gray	0.00058
Chromium	0.00033
Copper	0.00098
Invar	0.00007
Iron, pure	0.00068
Red Brass	0.00104
Carbon Steel	0.00078
Yellow Brass	0.00113

Table 4-1: Thermal expansion of metals

Notice that copper expands or contracts 0.00098% for every degree F. Aluminum has a higher coefficient, 0.00131. How much then, you are probably asking, does this affect the tuning of a cavity? Let's take some real numbers and you'll see.

For a range of 100 degrees F – reasonably for a radio hilltop – the center frequency of a copper 2M cavity drifts 143 KHz. Our aluminum 2M cavity drifts 191 KHz. It would be 436 KHz for a copper 440 MHz cavity. These figures are obtained by multiplying the percentage of change of the length of the center conductor per degree, by the frequency and then by the total number of degrees. Thermal expansion is essentially linear over a wide range.

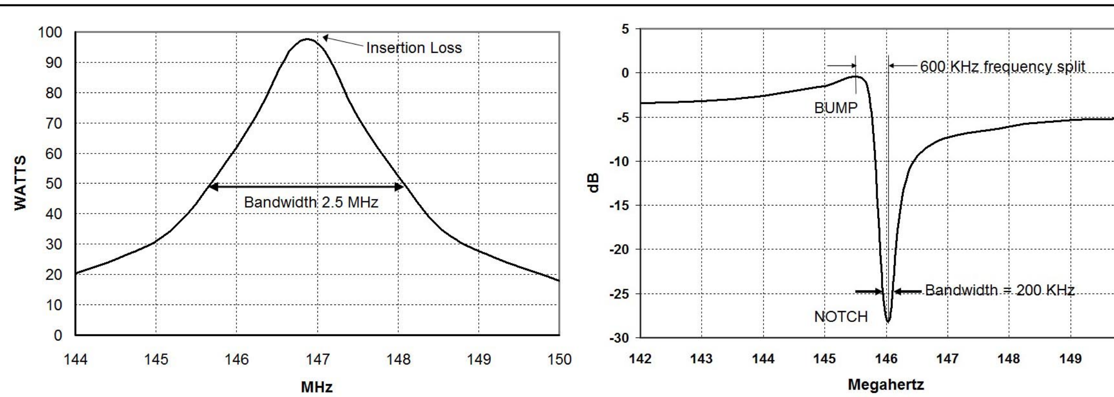

Figure 4-1: Bp vs. Br bandwidth

Now examine Figure 4-1. It is our sample cavity in both Bp and Br configuration. You'll easily see how significant temperature change is for the two. The bandwidth in Bp configuration is 3.6 MHz, for Br it is 200 KHz. Therefore, it is evident which configurations will experience difficulty with drift of 143 KHz, the Br notch cavity, the configuration that fulfills the main filtering responsibility in the duplexer.

If there were no temperature drift, uncompensated narrow-bandwidth notch cavities would always keep a repeater at full efficiency. But if the notch cavities drift down in frequency on a hot day, and no longer notch effectively, a noticeable loss of repeater performance will be experienced. Therefore, home-brew notch cavities clearly require temperature stabilization.

Stabilization Methods

The preferred method for commercially-built cavities is to employ a rod made of a metal, called Invar, a nickel steel alloy that has a uniquely low coefficient of thermal expansion (7% that of copper). See Table 4-1. The length of the center conductor is controlled by the Invar rod. It changes length so little that the cavity stays within acceptable limits as the temperature changes. Expansion of the outer shell of the cavity, as we learned earlier, does not affect cavity tuning.

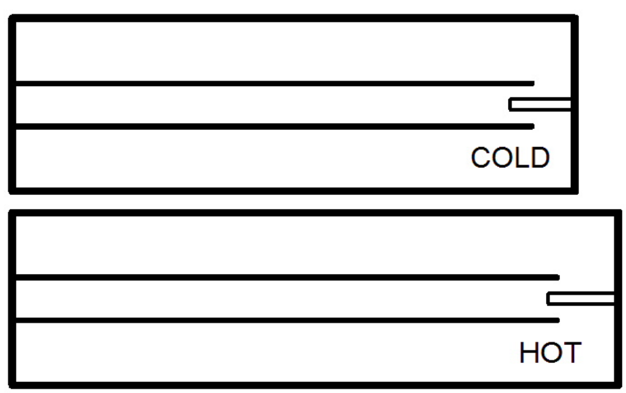

Figure 4-2: Temperature stabilization

Invar, however, is not a hardware-store material. Its use by the home builder is prohibitive. Also, sliding fingers to permit the center conductor to move up and down are required. They are well beyond home brew. So we will need to find another method. The one I prefer is simple, yet quite elegant. As a bit of trivia, it is based on a method devised over two centuries ago by famous British clock maker, John Harrison of sea-faring longitude fame. It kept the length of clock pendulums from changing length with temperature. Notice Figure 4-2 to see how this works.

If we allow a short metal rod to extend a short distance into the open end of the center conductor, we implement temperature stabilization. How? Quite simply. The small rod is attached to the opposite end of the cavity as the center conductor. As the cavity expands the short rod naturally tends to withdraw. It does so in that the outer wall of the cavity is longer than the center conductor. Further, if we make the outer wall of a metal that expands more rapidly, the effect will be greater. This is the case for our sample cavity. The inner conductor is made of copper and the outer wall aluminum. Aluminum expands more rapidly than copper.

How does this arrangement minimize frequency drift? The end of the center conductor and the rod make up a small capacitor that is in parallel with natural capacitance of the cavity. Recall that a resonant cavity act as if it were made up of discrete coils and capacitors, So in other words, the little rod “tunes” the cavity a small amount. The colder the cavity become the more the rod withdraws, thereby lowering the frequency, just as we want. The opposite takes place at warmer temperatures. The small rod, which I generally make from a threaded ¼ in brass bolt and a captive nut or a threaded hole, also provides, as a secondary benefit, a convenient way to make small adjustment to the overall tuning of the cavity. NOTE: The screw is designed to function correctly when it is screwed in half way. If you discover that you must move it near its ends to tune the cavity, change the length of the center conductor a small amount.

How long should you make the small rod, and how much shorter must the center conductor be to compensate for the presence of the rod? Unfortunately these are not simple to calculate. Like a good ham, I prefer a pragmatic approach. During the design phase of a cavity I first shorten the center conductor a little and introduce the bolt, screwed in half way. Then I retune the cavity to frequency by shortening the center conductor a small amount.

Next I perform a rough measurement of how much the cavity drifts with changes in temperature. A large cardboard box and a common hair dryer are quite adequate tools to accomplish this. If the resonant frequency still drops at higher temperatures, I install a longer bolt and shorten the center conductor a little bit more. After a few such adjustments I arrive at a reasonable value. Remember you don’t have to get it perfect. The temperature drift of commercial Invar rod stabilized cavities isn’t perfect either. All you need do is to reduce the temperature drift enough so that the notched frequency remains within the bandwidth of the notch. The dimensions given for the bolt and the center conductor of the cavity in this book satisfy these requirements for this cavity.

Duplexer cavities again are not black magic. The home builder can achieve very acceptable temperature stability for home-brew cavities with this simple but elegant little method. I have used it successfully on most ham VHF and UHF bands.

Chapter 5 – Performance

In this chapter well wade knee-deep into a sea of old wives tales often heard in the repeater world. Much misinformation commonly exists in knowing what to expect from a repeater's duplexer. There are useful compromises here that we can intentionally make that will benefit us? For all these performance factors must be coordinated if top repeater performance is to be achieved.

To begin to get at this vital area of knowledge, let's begin with the two most-common terms used to describe how well a duplexer must perform, that is how much loss it will introduce: (1) isolation and (2) insertion loss. Then, later in this chapter we'll also look at how well the (3) receiver and the (4) transmitter must perform. These are the biggest area of old-wives tales in the repeater world.

Isolation

Ideally, in the "perfect" duplexer, the transmitter of the duplexer should be "invisible" to the receiver on the opposite port, and vice versa. In practice, however, this is never totally true. Actually the cavities on both sides of a duplexer only ever "reduce" the unwanted signals, just sufficiently for the repeater to function. Determining how much this reduction needs to be is the key issue in knowledgably managing a repeater and its duplexer. We call this the isolation of the duplexer. It is generally stated in dB, the relative ratio of signal weakening. And again, it is never perfect.

Recall from Table 1-1, Chapter 1 that our sample receiver can hear a tiny 0.22 microvolt signal on an antenna also carrying a transmitter signal 150 dB (a thousand million, million times) stronger. But does the duplexer have to provide all these150 dB of isolation? Actually it doesn't, and this is an important repeater concept. The reason it doesn't is simple; the repeater's receiver provides some of the dB, all by itself. That's because its "front end" is frequency selective. This partially rejects signals not on center frequency. That's the meaning of selectivity. The cavities of the duplexer, therefore, only have to provide part of the total required 150 dB of isolation between receiver and transmitter.

This is also of course why a repeater has a frequency "split" or "offset." The input and output frequencies are intentionally placed apart. For example, on the 440 MHz band, the split is commonly 5 MHz and on 2M, 600 KHz. It's different for each band by convention, but the main function of a repeater's offset is to provide a large part the isolation needed in a repeater between receiver and transmitter.

Insertion Loss

The second main important performance characteristic of a duplexer is insertion loss. It's the amount of power or sensitivity that we give up for the duplexer to function. There is always some, again normally stated in dB. For example, if the output of our 100 Watt sample transmitter becomes 50 Watts after passing through the duplexer cavities, the transmit insertion loss is 3 dB (half power) . The same applies to the other side of the duplexer. Insertion loss is specified for both sides and is usually a different value for each.

Jumping ahead briefly, insertion loss is mostly caused by RF skin-effect resistance loss on the inner surfaces of the cavities. It is also affected by cavity diameter and the coupling factor of the loops. For now, merely recognize one basic fact about insertion loss. It is NOT always bad.

Insertion loss is the one performance characteristic of a duplexer that is most open to knowledgeable compromise, even if most repeater owners consider it their deadly enemy. For one can often derive increased repeater performance by intentionally increasing the insertion losses in the duplexer. I have often seen a repeater become better able to hear weak signals by doing just that. We'll give major attention to this later.

No Duplexer is Perfect

We of course would like to always have a "perfect" duplexer. Let's suppose that we could actually buy such a device – one with infinite isolation and zero insertion loss. Our "fantasy" duplexer would be a universal "fits-all," wouldn't it? It would behave flawlessly on any "RF dirty" hill top, no matter how much power our repeater is outputting and how sensitive and selective our receiver is.

Coming down the scale just a bit, how well will a high-cost "top-of-the-line" duplexer perform in the same situation? It would have perhaps 120 dB of isolation and as little as one dB of insertion loss on both sides. Again, wouldn't such a duplexer work well in NEARLY all situations?

Now, consider the other end of the spectrum, a small low-priced mobile duplexer with only 40 dB of isolation and as much as 3 dB of insertion loss. Can we use it? Actually, we can. Recognize here, though, that such a duplexer would not function well in nearly as many situations as the perfect duplexer or even the top-of-the-line model.

For example, a low-end duplexer might be okay for a small repeater at a quiet home QTH with a slightly "numb" receiver. But it certainly wouldn't be satisfactory for a sensitive high-power repeater on a dirty RF hill top. Also a repeater with a low-end duplexer might fail, had it been okay before, if its owner increases the transmitter's power output power or installs a receiver pre-amp. A high-end duplexer, on the other hand, would likely tolerate such additions.

The vital point here to realize is, the better the duplexer the more places one can use it without understanding it. This might seem to suggest that you should always use a top-of-the-line commercial duplexer. Not really. High-end duplexers are expensive. Can you always afford the price?

Wouldn’t it be better to exchange knowledge for cost? Well, there’s good news. Let’s now see some well-informed compromises we can make. You may net big savings here without any significant compromises in performance.

FACTOR ONE: Band Noise

The biggest factor in knowing how good (or expensive) a duplexer needs be is band noise on your hilltop. The radio spectrum is full of noise. Notice Figure 5-1. Most repeater owners pay little attention to the average band noise at their site, often to their detriment. On the other hand, hams who work the HF bands, know well how important band noise is. On a noise-free day one can often “work the world.” On a noisy day, a numb receiver is as good as an expensive one. To the repeater owner, noise is just as important. Working with it knowledgably is vital to maximum repeater performance.

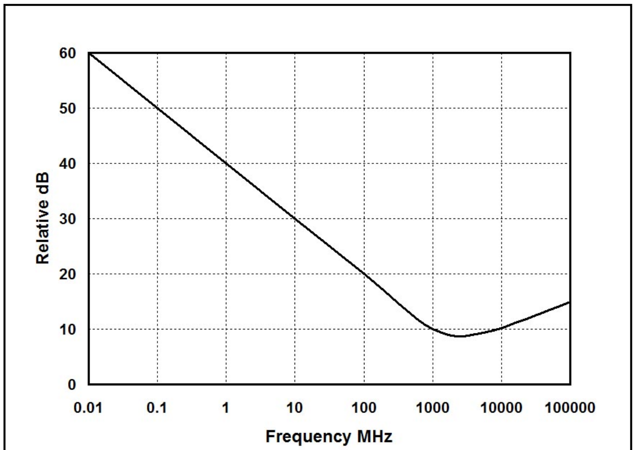

Figure 5-1: Generalized noise across the radio

RF noise comes from a variety of sources. The sun, the earth’s atmosphere and even our galaxy all make radio noise. We call this natural kind of noise QRN. Industrial machinery, power lines and other transmitters create man-made noise or QRM. Together all these sources create a background of noise at your site. It is very real and always there.

Most repeater owners pay little attention to it, however. Yet in deciding how good (how expensive) a duplexer needs to be, and how sensitive to make your receiver, the average noise level at your site is vitally important. Here now are the important basics.

As you can see from Figure 5-1, on average, noise in the radio spectrum is much higher for low frequencies than for high. In fact, total band noise decreases roughly in inverse proportion, all the way from VLF into UHF. As a simple “rule of thumb” for noise on the radio spectrum, ***when the frequency doubles, the noise drops to half*** **(**down by 6 voltage dB). Slightly above 1 GHz spectrum the noise finally reaches a minimum and then begins to rise again. New noise sources become dominant, such as atmospheric ions. We needn't, however, concern ourselves in this book with frequencies above a Gigahertz.

So what is the big concern about RF noise to the repeater owner? Simply this. Both the RF noise spectrum noise and the noise in our own receiver, set a very hard limit on how sensitive our receiver ever needs to be and how well a repeater can perform. I used to hear ill-informed repeater owners say that their repeater can hear a 0.1 microvolt signal. Well perhaps that is true when the signal is coming from a quiet signal generator. But if the noise floor at their repeater site never drops below say one microvolt, such a receiver is of no use.

Consequently, if you will knowledgeably match your repeater's overall system sensitivity to the hill top, you may well find that you do not need as much duplexer as you think or a receiver with "killer" sensitivity. It is a simple fact of repeater life, that a receiver can't hear signals lost in noise. If noise is high, all the receiver sensitivity in the world is fundamentally worthless.

If you don't believe this, just try telling an HF ham trying to work 40 M who can't hear anything because of a 10 over 9 noise level that he needs to raise the sensitivity of his receiver. He knows that all that will do is bring in more noise. Noise truly does set a very hard limit on how sensitive a repeater can practically be, and therefore how much insertion loss a duplexer can have and still function at peak performance at that site. I have several times seen that be intentionally increasing the insertion loss in a duplexer, to narrow the overall system bandwidth, enables a repeater to hear weaker signals in the noise.

For other bands, use the simple 6 dB per octave rule of thumb. That is, you can expect the noise to be on average 5 dB (three times) higher on 2M, or -111 dBm. This places the typical total noise on the average radio hill at roughly 1 microvolt. A receiver much more sensitive than is largely unnecessary, most of the time. If the noise drops below average, or if the user takes steps to reduce the noise figure of the overall system, a more sensitivity receiver help. These are of course "average" figures.

In actual practice, the noise on real hill tops does routinely rise and fall above and below the average figure for that site. Haven't you ever noticed that there are days when you can't get into your favorite repeater as easily from a particular location? This is most likely due to higher noise on that day. I have for example, seen the noise as high as -90 dBm (7.1 micro volts) at 450 MHz on an actual hilltop. At such a time A VERY "numb" receiver or a duplexer with a lot of insertion loss is perfectly okay. On a quiet day, it wouldn't be.

Impact of Noise on the Duplexer

Many repeater builders wonder why commercial manufacturers don't make their receivers more sensitive. Is it because they don't know how, or can't? Hardly. It is because they are aware of the noise floor. They have already likely given the receiver you are putting in your repeater as good a “front end” as it can reasonably use. In many cases, in fact, it may be more sensitive than you actually need. It is probably difficult for most hams to realize that a receiver can be “too” sensitive. Just recall, your duplexer has to match every dB of sensitivity your receiver has. Again, becoming knowledgeable of the average noise level at your repeater site is vital.

Measuring the Noise

Fortunately there is a relatively easy way to make a satisfactory estimate of the noise at your repeater site. just use your repeater’s receiver, a calibrated FM signal generator and your repeater’s normal antenna. You will also need two low-power 50 Ohm dummy loads or terminators and a hybrid combiner.

What a hybrid combiner? It is a passive mixing device that let’s you feed both your antenna (through the duplexer) and a calibrated signal generator into your receiver at the same time. The combiner keeps either signal from affecting the other. A hybrid combiner is required for a proper estimate of total noise.

It is quite easy to build one as a coaxial hybrid ring combiner. See Figure 5-2. Make it from 50 Ohm coaxial cable and BNC “T” connectors. The quarter wavelength (in coax) phase relationships between the ports create the needed isolation between the two signals. This kind of combiner is good only for one band, however. It is a “tuned” device. You can, however, make alternate cable sets for the same “T” connectors.

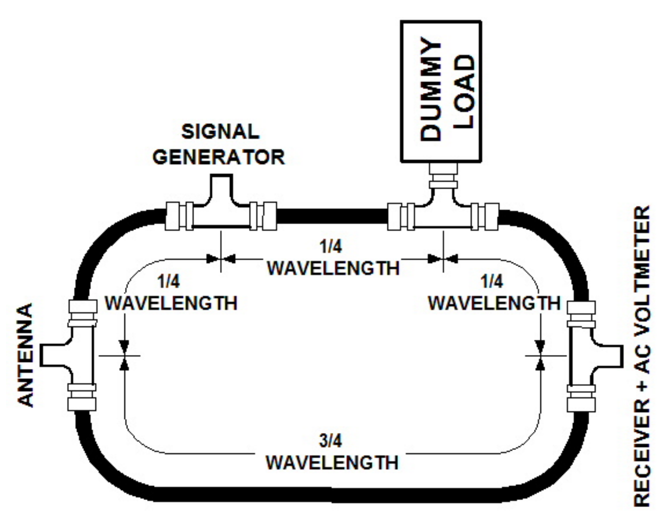

Figure 5-2: Ring hybrid combiner made from coax

Don’t forget that the coax section must account for velocity factor. On 2M, open air quarter wavelength in is roughly 20 in. You need, therefore, to make the distance from the center of one BNC “T” to the next connector, 20 in. multiplied by the velocity factor of the coaxial cable – typically 0.6. Look up the velocity factor for the cable you are using in a radio handbook. For a velocity factor of 0.6, the center-to-center distance on the righ would be 12 in. for a ¼ wavelength cable and 36 in. for a ¾ wavelength cable.

The Measurement Procedure

1. Connect both the calibrated signal generator and your antenna to the hybrid combiner. Figure 5-2.

2. Set the signal generator to the receiver's input frequency.

3. FM modulate the generator with a continuous audio tone.

4. Now alter the RF output level of the generator until the tone coming from the receiver's speaker roughly matches the noise coming from the antenna. A reasonable estimate here is completely adequate. You are not making a laboratory measurement of the noise, only getting an estimate.

The noise level, and the output of the signal generator, are now roughly equal. Read this level from the signal generator. We call it the minimum discernible signal (MDS) your receiver can usefully detect. It incidentally also includes the noise made by your receiver. By repeating this measurement on a number of subsequent trips to your hill top, you can factor out your receiver's own noise and gather a perfectly reasonable estimate of total external hilltop noise. And from this you can determine the required receiver sensitivity for your site as well as begin to know how much duplexer you need. You may be surprised; I was.

FACTOR TWO: Receiver Sensitivity and Selectivity

By now it should also be evident that we need to know our receiver's performance if we ever expect to knowledgably match it to the duplexer and the hilltop. Two factors matter here: (1) sensitivity and (2) selectivity. The second, often totally overlooked by repeater builders, is most often much more important than the first.

Sensitivity is easy to measure. Radio technicians often do so when they visit a site. Merely connect a calibrated signal generator to the receiver and adjust the generator's output level until the receiver just barely can't hear the signal. This is the receiver's sensitivity.

Lets use a 440 MHz repeater as an example. Again we'll assume a receiver sensitivity of 0.22 micro volts or minus 120 dBm. Without any additional gain, this sensitivity is a naturally a good match to the average noise level at a typical UFH repeater site, that is -110 dBm. Remember, we want only a little more sensitivity than it takes to get down to the noise. An extra 10 dB is a realistic amount of headroom. Now let's measure our receiver's selectivity, the other vital factor we need to correctly match our receiver to its environment. Remember, a receiver with the same sensitivity as another, but with poorer selectivity may work poorly in a repeater where the other will perform flawlessly.

Selectivity Measuring Procedure

1. This time, connect your receiver through the hybrid combiner to two calibrated signal generators. You may substitute a hand-held transceiver for the second generator with a small tone generator connected to its mic input. Remove its antenna and wrap it in aluminum foil. Place it far enough from your test setup away to create a weak signal. In this case, keep the repeater's antenna connected to the combiner.

2. Set the remote transceiver or the second signal generators to make a steady weak FM modulated signal on the receiver's input frequency. Open the receiver's squelch so that you can hear the noise. The level from the second generator should be just sufficient to begin to quiet the repeater's receiver. Maintain this level throughout the measurements.

3. Make a series of measurements with the signal generator set increasingly off of the receiver's center frequency. For each, increase the level of the signal generator until you can just hear of "desense" caused by the off-channel signal. It will be an increase in noise from the receiver's loudspeaker. 500 KHz increments should be sufficient, on both side of the receiver's center frequency of the receiver.

Plot the results on a graph. It should look similar to Figure 5-3, a graph I compiled from an actual 440 MHz receiver. As you can see, at the center frequency, a very tiny signal (-116 dBm) will desense the receiver. But the more you move away from the center frequency the stronger the off-channel signal has to be to cause receiver desense. This is due to the receiver's selectivity.

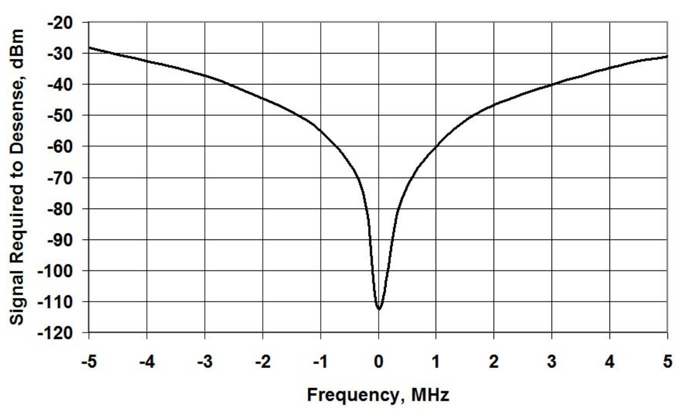

Figure 5-3: 440 MHz receiver desense profile

This curve shows us that for our example receiver an off-channel signal five MHz lower in frequency must be 88 dB stronger to cause desense than an on-channel signal of -116 dBm. So at the normal 5 MHz frequency spilt of a 440 MHz repeater, the receiver's selectivity already provides 88 dB of the total 150 dB isolation needed in our example. The duplexer, therefore, only has to provide 62 dB of isolation. That's a lot less than we pay for in a top-of-the-line duplexer.

We do though actually need a bit more than 62 dB for a couple of reasons. Something more like 90 dB is in order. Much of this, as we'll saw earlier, is because duplexer cavities drivt with temperature. So we add some additional dB of isolation to compensate for this. Also, transmitters are never perfect. They don’t put ALL their energy on only the output frequency. We often call a transmitter’s off channel energy “dirt.” Hence the dirt from our own transmitter causes additional desense. Outboard transmit power amplifiers are often notoriously “dirty.” Adding one will frequently demand a better duplexer.

Preamps

While we are on the subject of sensitivity, let's pause briefly to consider preamplifiers. In recent years preamps have become the shining star of the ham repeater world. At least a lot of hams look at them that way. Unfortunately, they can cause problems in respect to selectivity, hence how much duplexer is needed.

The reason it, after-market preamps are broad-band devices. They have little or no selectivity. They amplify the noise, the dirt and the grunge just as much as they do the signals we want. Yes, of course, they do add sensitivity an can also improve the noise figure of our receive system. But quite often they do this at the expense of an undesirable increase in total receive bandwidth. As we have painfully seen, reducing receive selective is deadly in a repeater. It instantly places an increased burden on the duplexer, which may now no longer be able to properly our isolate receiver and transmitter particularly if they are low-end models. So don't be surprised if a preamp increases the “grunge.”

A possible benefit of using an after-marked preamp, as I just mentioned, is an improvement in the overall receive system noise figure. Some high-end preamps employ higher-quality and lower-noise front-end devices than some older or ham-grade receivers. So if the repeater owner is also willing to add some additional outboard bandpass cavities. to help control the increased receive system bandwidth, a preamp can add useful overall noise figure reduction. This is often much more helpful than simply increasing the gain.

So before installing a preamp, in hopes of creating a "killer" repeater, spend the time to measure the sensitivity and selectivity of your receiver as well as the working noise level at your site. You may be in for a surprise. For if you already are slightly below the working noise floor, more gain from a preamp may not help.

I go by a simple rule of thumb with preamps. On really high mountain tops, where the desired signals are strong, and at remote sites that are difficult to get to, I avoid preamps. Most modern barefoot commercial receivers have sufficient sensitivity and noise figure for these situations. At lower altitude sites, such as at a home QTH, or where the site is easy to get to, a preamp may help. Never, though, look at preamps as a miracle cure.

Selecting a Receiver

In light of what we have seen, you may now be able to guess that some receivers are not suitable for repeater service. In commercial repeaters, the manufacturer designs the receiver accordingly. Ham repeater can rarely do this. So let's briefly talk about how to select a receiver for repeater use.

Commercial crystal-controlled mobile two-way transceiver receivers, the type most amateur repeater builders have long used to build repeaters, are generally a good choice. That's because the more-recent models of crystal-controlled commercial transceivers are narrow-band devices. They have good front-end selectivity, often employing narrow-band helical resonators. They were designed to operate on only a few adjacent frequencies in commercial mobile service. So the manufacturer designed them with narrow-band filters directly in the front end. This kind of receiver works very well in a home-brew repeater. Unfortunately they are disappearing from the commercial two-way radio world.

Instead, the receiver used in most ham transceivers, and newer fully-synthesized commercial mobile transceivers, are built to cover a wide range of frequencies. This precludes narrow-band front ends and good front-end selectivity. Instead, selectivity is created by IF filters. Compare the desense curve Figure xx, an older crystal-controlled commercial UFH receiver to a more recent synthesized ham 440 MHz transceiver, Figure xx

NOT COMPLETED
Figure xx. Desense curve of a synthesized ham 440 MHz receiver.

This method works okay in mobile service, but unfortunately the front end of such a receiver is wide open to off-channel interference when used in a repeater. Repeater builders should try to avoid this type. To state this as a simple rule of thumb, front-end receiver selectivity is much less expensive than having to add more cavities to a duplexer.

Fortunately at the time of the writing of this book, there are still many late-model crystal-controlled commercial mobile transceivers on the used commercial radio market. Thousands are still in regular service. Look for one when you are building a repeater. Avoid fully-synthesized receivers, especially those made for ham mobile service. They are normally a poor choice. Again, isolation is much less expensive in the front end of a receiver than as a higher-end duplexer or more cavities.

The type of transmitter you select for repeater use is also important. We got a clue of this above in mentioning the need for headroom in a duplexer. Two transmitter characteristics are important (1) power and (2) purity.

Transmitter Power

It is a simple law of physics, but the amount of duplexer you need is directly related to the power of your transmitter. Take the time to look back at Table 1-1, Chapter 1. It will be evident that a 10 watt transmitter needs 10 dB less duplexer than a 100 watt transmitter. I'm amazed how many repeater owners do not grasp this.

For example they assume that their duplexer will still automatically work well after they have installed a power amplifier. More power ALWAYS theoretically requires more duplexer. A duplexer that is entirely sufficient for a 10 watt repeater may now badly desense if a 100 watt power amplifier is installed. We can't escape basic physics. Though if you have made the measurements above, you will know if you have the headroom to tolerate a power amplifier.

Transmitter Purity

Transmitters, like receivers are not perfect devices. In Camelot, transmitters ONLY produce power on their center frequency. Unfortunately, in the real world, they don't. Considerable off-center-frequency energy always exists. Notice figure 5-4. It is a spectrum analyzer display of a portion of the FM broadcast radio spectrum containing several transmitters. Notice that each transmitter (the spikes) creates energy over a range of frequencies, not just on the carrier frequency.
Transmitter energy does not exist just on the carrier frequency. In other words, transmitters also have bandwidth. Further, by its very nature, modulating the carrier with audio, for example, creates sidebands – more off-carrier energy.

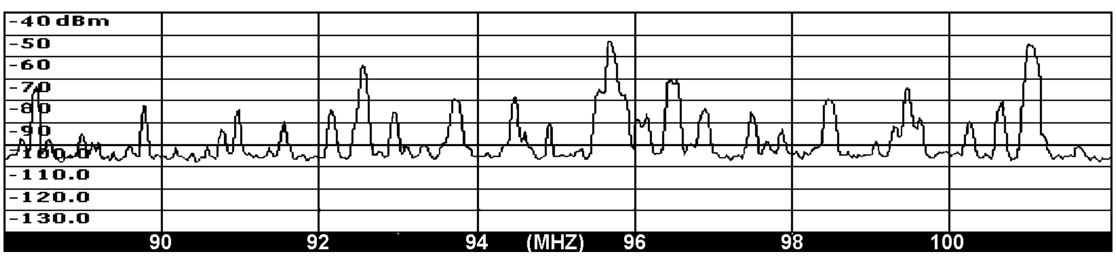

Figure 5-4: Spectrum analyzer display of part of the FM radio broadcast band

As we said earlier, we affectionately call the energy that exists off of the transmitter's carrier frequency "dirt." Much to our dismay, some of it always is present on the center frequency of the receiver. Transmitters very a great deal in how much dirt they generate, but getting rid of transmitter dirt is the primary job of the notch filters on the transmit side of the duplexer.

So again we ask the question, how well must the transmit notch cavities work? It probably won't surprise you, but the answer is similar to the notches on the receive side. It depends on how strong the dirt is, and how selective and sensitive the receiver is. Sound familiar?

Let's expand this just a little for emphasis. Dirt is definitely weaker than the signal the transmitter is generating on its carrier frequency. But it is always still far too strong not to need to be notched out on the transmit side. Remember, the receiver is very sensitive. The dirt only has to be 0.22 micro volts for the receiver to hear it quite well. Again by using Table 1-1, Chapter One, we discover that 0.22 micro volts is a mere 0.000,000,000,000,001 Watts. The cleanest transmitter in the world makes a lot more dirt than this on the receiver's frequency, even with the repeater's frequency split. That's again why we need notch filters on the transmit side of the duplexer. They remove transmitter dirt.

Therefore, just like on the other side, we need to know the strength of the dirt before we can specify how much isolation we need from the transmit-side notches. To measure dirt, a spectrum analyzer IS required.

Transmitter Dirt Measurement Procedure

1. Connect your transmitter directly to the input of the spectrum analyzer, through an adequate attenuator pad. This is required to protect the spectrum analyzer's front end from the transmitter's power and to keep the load impedance on the transmitter a constant 50 Ohms.

2. Set the spectrum analyzer to display just a bit more than the frequency split of the repeater.

3. Cause the transmitter to make power, but without modulation. Adjust the spectrum analyzer to display the center frequency at roughly full scale. Note the reading in dBm.

4. Now observe the strength of the dirt at the receive frequency. Note how many dB lower it is at the receive frequency than at the transmit.

Let's say its 85 dB weaker than the transmitter, with an absolute level of -35 dBm. Our duplexer, therefore, only need to have enough isolation in the notch filters on the transmit side to reduce the dirt to below the noise of -110 dBm in our example. This means that the filters on the transmit side of our duplexer would have to provide at least 75 dB of isolation. I've added another 10 dB for headroom. Even so, 85 dB is much less than provided by a top-of-the line duplexer.

As a final point on dirt, add-on power amplifiers normally generate more dirt than barefoot transmitters. Therefore, if you add a power amplifier to your repeater, be forewarned. You may need to add quite a bit of additional transmit-side notch cavity isolation.

A Simple Desense Test

If you don't have access to a spectrum analyzer (most hams don't) there is a simple useful way to evaluate everything we have covered in this chapter. It is a simple test all repeater owners should perform on their repeater(s). It won't show you where the problems lie, if they do exist, but it will tell you if your transmitter is desensing your receiver.

In other words, if your repeater passes this test, it is working fine despite how much power you are running, how expensive your duplexer is, what kind of antenna your repeater has, if it has a receiver preamp or after-market power amplifier. This test also won't however tell you anything about the noise level at your site. But it is a good starting point.

1. Make provision so that you can manually key the repeater's transmitter, instead of the receiver doing so via the carrier/PL operated relay.

2. With the repeater otherwise in normal operating mode, with the duplexer well tuned, generate a weak signal on the input frequency. It should be at a level that just begins to quiet the receiver. Again, a foil-wrapped hand-held transceiver works well for this or a signal generator connected to a small antenna.

3. Then, will receiving the weak signal, manually switch on the repeater's transmitter.

If the duplexer is properly isolating the receiver from the transmitter, you will hear no desense in the weak input signal. If you do hear a change, you are experiencing desense. If you have installed either a preamp or an accessory power amplifier, try disabling it. If the desense goes away, you now have some indication of what the desense is being caused by. I never take a new repeater to a hill top until it can pass this test.

In review, isolation, insertion loss, receiver and transmitter performance are all critical to knowledgeably work with. Mainly by not asking too much of any of these we arrive that the most efficient and economical configuration for a repeater. Many hams, and perhaps a few commercial operators, need to re-evaluate the many old-wives tales that exist in this arena.

Chapter 6 – Duplexer Tuning

We'll now assume that you have built a complete duplexer or that you have a commercial unit to tune. How do you do it correctly? It's quite easy, even in the field. Again, a spectrum analyzer with a tracking signal generator makes things easier, but you can definitely also do it with the basic setup.

First, review the basic architecture of a duplexer, Figure 6-1. It is essential to keep it in mind as you are tuning. I've seen many an ignorant novice badly misadjust a duplexer by not paying careful attention to this basic structures.

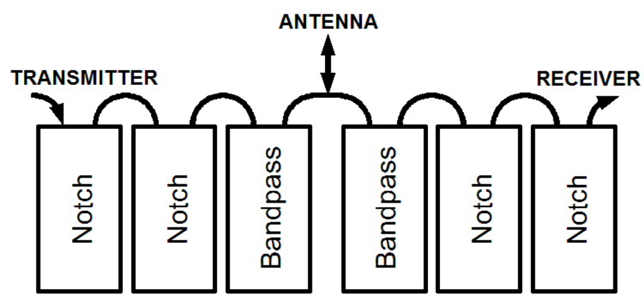

Figure 6-1: Layout of the average duplexer

Again, there are two sides, receive and transmit. Both typically have two notch cavities and a single bandpass cavity, configured as shown. Figure 1. The Bp cavities are adjacent to the antenna input. Despite the disposition of the cavities, the tune-up procedure will be similar.

Tune-up Procedure

Table 6-1 lists the basic rules for tuning a duplexer. Notice that there are four combination. One pair applies to the transmit side, the other to the receive side. At a casual glance both may seem the same. Look closer. The frequencies are reversed. Hence there are four rules, one for transmit Bp, one for transmit Br, one for receive Bp and one for receive Br. Note the distinct differences and the pattern. Memorize these rules; they are absolutely basic and essential..

TX Bp	Max. at the **transmit** freq.
TX Br	Min. at the **receive** freq.
RX Bp	Max. at the **receive** freq.
RX Br	Min. at the **transmit** freq.

Table 6-1: Tune-up rules

For the actual tune-up procedure, there's an overall rule that I consider mandatory – *tune each cavity separately, first* . Completely disconnect one cavity at a time from the duplexer by removing its normal inter-cavity cables. Then tune it on its own. The need for individual cavity tuning is this: a mistuned cavity down the line can very easily induce incorrect tuning in the one you're working on. What's more, individual cavity tuning will almost always get you very close to an ideal over-all tune up. You'll rarely need to readjust cavities assembled as a complete duplexer.

When tuning a duplexer, it is not necessary to make a graphs as we did during the design phase of the cavities. All you are doing now is adjusting for either a peak or a dip. Here an MFJ-259, or similar, is easier to use than the simple transceiver method. With it you'll find the Br notch at maximum SWR, the Bp peak at minimum SWR. Notice that this is the reverse of power.

Tuning is also a little easier, if you realize something else. Duplexer cavities are symmetrical. In other words, they have no specific input or output. The two inputs are the same and can generally be reversed. You may therefore connect the Wattmeter and a 50 ohm load to either connector, and your transceiver or MFJ-259 to the other.

FIRST, as Table 6-1 shows. tune the bandpass cavities for ***maximum*** through-put power (or minimum SWR). Remember, always tune Bp first, it's always vital. Also don't forget to select the correct frequency when you move from one side of the duplexer to the other, again according to Table 6-1.

Then, **only after you have tuned all the Bp cavities**, tune the notch cavities on BOTH sides. Again, as Table 6-1 shows, tune the notch cavities for ***minimum*** power (or maximum SWR). Once again remember to change frequency as you change sides. Notch cavities are more critical to tune. You could use a receiver with an S meter for a finer adjustment. If so, place a 50 Ohm pad (20 dB or more) in front of the receiver to prevent damage to its front end. The pad also insures that the receiver presents a 50 Ohm load to the duplexer. Without proper loads you WILL always misadjust.

Finally, after tuning all the cavities individually, reconnect the entire duplexer. Now you may, if you still feel it is necessary, perform a fine adjustment of the whole unit. DO NOT go straight to this without first tuning the cavities individually. The importance of this can not be overemphasized.

For an overall fine tune, connect the Wattmeter and dummy load to either the transmit or the receive port of the duplexer. Also terminate the other port with a 50 Ohm load. This is very important. Then connect your transceiver (or MFJ-259) to the antenna port . Again following Table 6-1, first touch up the Bp cavity(s) on both sides. Finally, touch up the Br cavity(s). Never "tweak" just the notch cavities without going through the full procedure. Experience has shown me that notch cavity adjustment in a fully-connected duplexer can be the pathway to disaster, especially for the newcomer.

For the Home Builder

In the following chapters we'll now complete the picture, especially for those who want to roll their own or modify a commercial unit for ham-band use. We'll dive into loops a little deeper and then into lines and losses. Even for those who do not choose to build their own, these final chapters involve important comprehension principles.

Chapter 7 – Loops

Before I began my study, the coupling loops in cavities were especially mysterious. I could not find much about how to design or modify them in the published literature. Why were there so many variations? I'd seen fat loops, thin loops, wire loops, strap loops, side loops and top loops. Why had the designers made these choices? Is one better than another for the home builder, I wondered? I couldn't see a pattern. That's why I devoted a great deal of time to coupling loops in my early experiments.

First, is the shape critical, and what about the placement? Do either of these require great precision? How about loop material? How important is that? My intention in answering these questions in this chapter will be to take you through the experiments that gave me the answers. The principles here present a practical picture of how to design your own loops for peak performance.

Loop Shape

My first question was, is there a magic shape for cavity coupling loops? As I mentioned, I had inspected many duplexers, and the loops came in a baffling variety. I wanted to know what effect loop shape would have on duplexer performance. So I built a cavity, something like the one illustrater in an earlier chapter and I began to experiment.

When I first began experimenting with loop shape, I kept confusing several factors. For examples, two loops of different geometry have a different inductance even if you use the same amount of wire. They also have a different geometric center. Since the magnetic field in the cavity is not uniform, two different loops will couple differently to the field.

Fortunately, though, I found a way around this. Just keep changing two loops until they exhibit the same bandwidth and losses and you eliminate everything but loop shape. So using this technique I then tested circular loops, rectangular loops and loops of irregular shape. What I discovered was that the shape of the loop makes little difference, provided it is made to perform the same as a loop of another shape.

This led me to realize that the only characteristic of a coupling loop that matter very much is the total area of the. I later found in an engineering book that coupling is proportional to the square root of that area. Therefore, if two loops have the same area, they will perform much the same place in a cavity even if shape and the amount of wire is quite different. This simple generalization has limits of course, but for practical purposes, loop shape and size is not significant factors in cavity design. Only the area of the loop and how it is oriented in the cavity determines how much it will couple to the magnetic field.

Where Do You Put the Connectors?

Another factor I wanted to know about, was where to put the connectors attached to the loops? I had seen a lot of variations in commercial and amateur-built duplexers. Two locations seemed to be common. The connectors were typically installed either in the shorted end of the cavity or a short distance down the side wall. Is one better than the other, or will it change how well the cavity performs, I wondered?

Once again, the answer to these two question is no. For any given loop, it does not make any significant difference whether its connector is in the side of the cavity or in the end. As long as it ends up in the same place in the cavity, it performs the same.

So why the difference in connector location in cavities? Why should you select one over another? It is my opinion it is only a matter of convenience. If it is handier for the connectors to be in the side, then put them there. Where you put the loops in a cavity also does not turn out to matter very much. We'll see this in a moment. But as far as connector position goes, if a designing a single cavity application I often employ the side position. For a group of cavities, such as for a duplexer, the end is generally easier. Though take your choise.

Loop Construction Materials

Next I wanted to know if the piece of metal or wire used to form the loop matters. I knew for example that conductors of different dimensions have different characteristic impedances when used in transmission lines. Does this affect the loops in a cavity? For, example, in that the loop in a cavity is fed with a 50 transmission line, does it also perhaps have to look like a 50 ohm line section?

Again I began experimenting. I tried round wires of widely differing diameters. As before, I adjusted all factors until the performance of each loop was equal to those of another loop under comparison. Then I tried flat metal straps bent into loops. I did this in that I had seen loops made of flat strap in commercial cavities. But again, after trying all these variations, while always keeping performance equal, I came to the conclusion that loop conductor size, shape or material has little significant affect of loop performance. Ordinary wire is perfectly acceptable. In fact, it is probably the best choice.

There is, however, one factor that does matter in the material used for loop construction – current handling capacity. Notice Figure 7-1. It shows RF current in the transmission lines (and loops) of a repeater at different power levels.

These values may not seem high if you think in DC terms, but RF conductors need to be much larger conductors due to skin effect. We will go into the problems caused by skin effect in a later chapter, but as a general rule, above about 100 watts, loops should be made from heavy wire. Below that power level, 16 AWG wire is completely adequate.

1 watt	.14 Amps
3 watts	.25 Amps
10 watts	.44 Amps
30 watts	.77 Amps
100 watts	1.4 Amps
300 watts	2.5 Amps
1000 watts	4.4 Amps

Table 7-1: Loop current vs. transmitter power at 50 Ohms

Flat strap actually turns out not to be a good choice. It has skin effect problems compared to round wire. But it's easier to bend into loops for cavities used at higher power levels, and if made a bit larger, it works fine. It is a common choice in commercial cavities.

Loop Placement

In an earlier chapter we saw how a loop must be placed in a cavity in order to couple to the magnetic field. The H or magnetic field, as you will recall, lies concentrically around the center conductor. The loop couples best when it is perpendicular to the H field. This is along the cavity's length and radial along its diameter. We also learned that the magnetic field is strongest near the shorted end of the cavity and close to the center conductor.

If, however the loop is moved within the cavity or it is rotated compared to the magnetic field, coupling will be less. But does that matter? Must loops always be perpendicular to and placed where the magnetic field is maximum in order to work well? I spent a lot of time researching this too, and once again concluded that the answer is no. I experimented with loops at several locations, near the shorted end, away from the shorted end, near the center conductor and away from the center conductor.

I also experimented with rotating a loop so that it was not perpendicular to the field. In fact, making a loop so that it can conveniently be rotated from outside a cavity is a useful feature found in some commercial cavities, especially large bandpass cavities. To accomplish this, the connector and loop are installed on a small circular plate. The plate can be rotated in the field and locked down with a set screw. This adjustment permits the user to determine how much insertion loss and bandwidth the cavity will exhibit. As we saw in an earlier chapter, the decrease in bandwidth caused by looser coupling can be a big asset.

To study the effect of loop location, I would merely keep changing the area of the loop in a different location until it would again couple equally to the field present at that location in the cavity, And when I did I would obtain performance equal to any other location. This includes both insertion loss and bandwidth. So my final conclusion was, that as long as the total amount of coupling between the loops and the cavity is made to be the same by adjusting loop area, shape, material and orientation, the position of the loop within the cavity, loop position does not matter, at least within wide practical limits.

Loop Grounding

Armed then with knowing how tolerant loops are, it then came to me as no surprise that it also does not matter much how you ground a loop. That's probably why I again saw many variations in commercial and amateur designs. The three common configurations are shown in Figure 7-1.

As we have learned, only the area of the loop matters. For example, in the left cavity of Figure 7-1, a section of the loop is actually a part of the cavity's outer wall. The area contained by the wall and the remainder of the loop performs the coupling. My personal favorite for loop grounding is the right configuration. If you ground the loop to the body of the connector that feeds the loop, the loop and the connector can be made easily removable and rotatable. The convenience of this method makes it a very common grounding configuration.

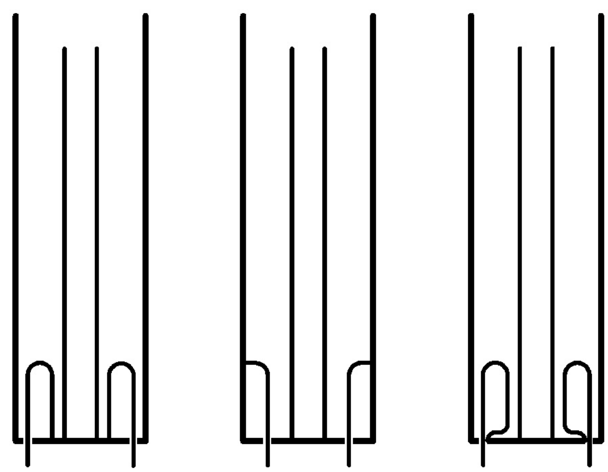

Figure 7-1: Loop grounding, end, side, to connector

All this leads to a Golden Rule. ***Nothing about loops is critical***. All you need do is to alter the area and the orientation of the loop until it correctly couples to the magnetic field and you will obtain the same results for a wide range of cavity locations. I like a little analogy here. Imagine you are pushing a child on a swing. Where on the ropes should you push? Actually anywhere is fine. If you push at the bottom, you only need to push gently, over a long distance. If you push nearer to the top, you'll have to push harder but over a shorter distance. This is a perfect analogy to the size, placement and orientation of the loops in a cavity.

Feel free to experiment with the loops in the sample cavity, it is excellent instruction. They are only mounted on the ends, on the baking pans, for simplicity and to permit easy rotation, should that be desired. A side-mount position would work well too. It would, however, not likely be as convenient for use in a complete duplexer.

Chapter 8 – Losses

This is undoubtedly the most important chapter. It contains the hidden secrets. Wrapped up here are the major compromises that create optimum performance with maximum economy. We'll talk about energy transfer, skin effect, cavity proportions, and most important of all, bandwidth vs. insertion loss. These are vital concepts.

Energy Transfer

How does energy, our receiver or transmitter signal, get into and out of a cavity? It works the same way for all cavity types, Bp or Br. Energy enters from an input transmission line most often via an input loop. The loop, for all practical purposes is just a small inductor. It is more complicated then that, but this is an adequate approximation.

The magnetic field around the loop excites the cavity into oscillation. As we said earlier, it is like blowing air across the top of a soft drink bottle. In so doing, the cavity absorbs the energy delivered to the loop by the input transmission line. At the output loop, provided it has been configured to have the same performance as the input loop, the complement takes place. The energy returns to the transmission basically unchanged, little is lost except for that which we don't want.

Said in simpler terms, what goes in at the frequency we want comes out. Said another way, a cavity should essentially be invisible to energy passing by at the resonant frequency. At other frequencies, however, the losses are made as high as we can. That is the basic idea of a cavity filter – keep the good stuff, get rid of the junk.

But unfortunately cavities are not perfect. They always loose a little of the good stuff even at the resonant frequency. It is unavoidable and is called insertion losses. Not all the energy that goes into the cavity at the resonant frequency comes out. Understanding what causes the loss and how to minimize it, though, is the main subject of this chapter. Knowing how is vital to home-brew design in particular.

Skin Effect

The biggest cause of cavity loss is conductor loss on the inner surfaces of the cavity, particularly as it is affected by RF skin effect. In most RF devices, skin effect is not a problem, but in a cavity it is a very major factor. Energy on the transmission line coming to the cavity becomes RF current on the surface of the inside of the outer wall of the cavity and also on the center conductor. If these surfaces could be resistance free, that is perfect conductors, there would be virtually no insertion loss. But the walls of all real cavities do have real resistance, more than we realize. It is what causes insertion loss in a duplexer primarily.

As many hams know, the resistance of a electrical conductor increases as the frequency increases. A conductor carrying RF exhibits more Ohms of resistance than if it were carrying DC current. The reason is, as the frequency increases, AC current in a conductor moves to the surface of the conductor. This is called skin effect. As a result, deeper in the conductor there is less current for RF. At low RF frequencies the effect is small, but at VHF and UHF skin effect is quite significant.

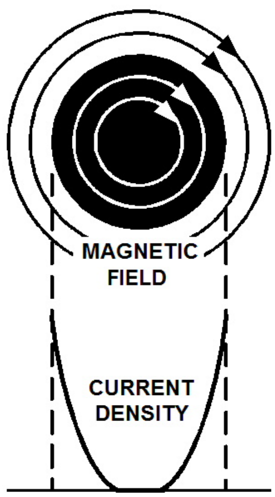

Figure 8-1: Current distribution in round wire (black). No current at center/

Current in the wire creates a magnetic field concentrically around the wire. But because the wire can never be 100% conductive, there also exists a weak internal magnetic field. This internal field links to the current flowing in the wire causing a progressive increase of inductance toward the center. The net result is that the current is forced outward in the conductor.

The net result is that the effective cross section of the conductor is less electrically than it is physically. Notice the current density graph in Figure 8-1. It illustrates that no current at all exists at the center of the wire shown. Another way of looking at this is to say that the current tries to redistribute itself to be encircled by as few magnetic field lines as possible.

In conductors that do not have a round cross section, skin effect is even worse. Round conductor are the least affected by skin effect. Notice Figure 8-2

What significance does this have? Simply this, round conductors are best for RF. It is counterproductive to make the coupling loops of a cavity from flat metal strap. Commercial manufacturers often do use strap loops. This is only because they are mechanically easier to make for high current cavities. I prefer round conductor loops. Similarly, square cavities are less efficient than cylindrical cavities. The effect is not great, however, and successful duplexers can be made by soldering flat sheets together.

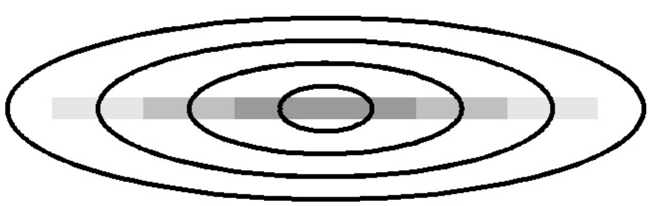

Figure 8-2: RF current and magnetic field in flat conductor. Current mostly at ends.

Another case in point, not

related to duplexers, where flat metal straps are definitely not a good idea, is for compact transmitting loop antennas, sometimes called magnetic loops. These perform better made from round tubing, precisely for the same reason.

How bad is skin effect?

Skin effect is definitely a major problem in duplexers. It is significant at VHF and higher at UHF frequencies. Above that it becomes extreme. Let's look at some real numbers. The complete equation for calculating skin effect resistance is complex, but it may be simplified to:

One skin depth (inches) = 0.0026 / square root of Frequency (MHz)

To avoid calculation, Table 8-1 is this equation solved for RF frequencies 1 MHz through 1 GHz.

Frequency	Skin Depth
1 MHz	0.0026 in.
3 MHz	0.0015 in.
10 MHz	0.00082 in.
30 MHz	0.00047 in.
100 MHz	0.00026 in.
300 MHz	0.00015 in.
1 GHz	0.000082 in.

Table 8-1: One skin depth vs. frequency

We consider a skin depth to be the depth at which the current has decreased to 36.8%. Obviously some current is still flowing at one skin depth, but it will again decrease by another 36.8% for every additional skin depth. In practice we consider the current below three skin depths insignificant. Quite close to the surface is where most off the current is flowing.

At 450 MHz, skin depth is 0.00012 inches. Therefore, the effective thickness of the conducting surface is only .00036 in. Copper and aluminum may be good conductors, but for a conductor this thin there is now appreciable resistance. Multiply these figures roughly by three at 2M

Surface Treatment

A common way to reduce skin effect losses is to electroplate the inside of the cavity with a more conductive metal. Since most of the current flows on the surface this technique can be effective, but generally only at or above UHF frequencies.

Silver, and sometime copper are the only practical choices for plating, and neither is possible on aluminum. Surprisingly, gold is not a worthwhile option here. As we saw earlier, gold is only used on connectors for corrosion resistance not conductivity. Copper is a better conductor than gold, and silver is only marginally better than copper.

For ham use, the cost and the marginal benefit of silver plating is impractical. Below roughly 1 GHz the thickness of the plate required is too great. At 450 MHz and below, especially for home construction, bare copper is perfectly adequate.

However, at lower frequencies there is one case, where electroplating can be effective. That is copper on steel. Unlike silver, as a plating material, copper is relatively inexpensive even if heavy plating is required,. Several commercial manufacturers make excellent cavities out of copper-plated steel. Steel is otherwise totally unacceptable as we saw due to poor conductivity. I have personally not attempted copper plating at home, though I suspect it could be successfully done by some home builders.

Corrosion of Copper and Aluminum

What about the corrosion that forms on copper or aluminum? Won't that reduce the effectiveness of a cavity? I had the same question when I first started making cavities. So I did an experiment. I took one of my copper UHF cavities, and measured its performance while it was still very dirty. I hadn't cleaned it up after assembly. It was black with copper patina.

Then I polished its inner surface to a mirror shine. I was dumbfounded to discover that the cavity's performance remained the same. Apparently the patina, as it is called, that collects on the surface of copper is not a problem in cavities, most likely because it is very thin and is also a conductor. Skin effect works for us here. As a result, and since that time, I only give my cavities modest cleaning merely for aesthetic reasons.

Aluminum is more or less the same, though the nature of the surface corrosion on aluminum is quite different. Copper patina is conductive, aluminum corrosion is an insulator. It is aluminum oxide, the very same substance rubies and sapphires are made of. Aluminum corrosion also has no noticable effect on the RF currents running on the inside surfaces of a cavity.

Cavity Impedance

The second major loss issue in duplexer filters is induced by the characteristic impedance of the cavity itself. Remember, a quarter wavelength coaxial cavity is just a section of large-diameter open-air transmission line. Like any transmission line it has a characteristic impedance. For air-insulated circular coaxial transmission line, the characteristic impedance is determined simply by the inner to outer conductor diameter ratio.

An early question for me was, does the characteristic impedance of a cavity have anything to do with its performance in a duplexer? That is, is the inner to outer diameter ratio important? And the answer is yes, quite a lot. I was surprised to find out that there actually is a "magic" characteristic impedance for a cavity. Figure 8-3, though surprisingly it isn't 50 Ohms, but 77 Ohms. At the specific inner-to-outer ratio for 77 Ohms, cavity loss is lowest.

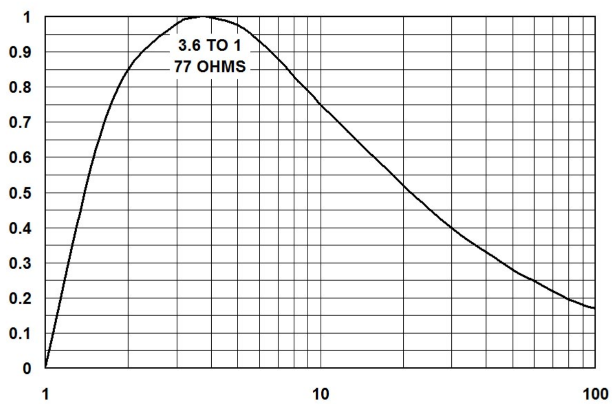

Figure 8-3: Inner to outer conductor diameter radio vs. relative loss

Notice that insertion loss is lowest when the inside of the outer conductor is 3.6 times as large as outside of the inner conductor. Again this translates to a characteristic impedance of roughly 77 ohms.

Table 8-2 is the 3.6 to 1 ratio calculated for commercial aluminum cake pans with the copper pipe size to use for the center conductor. As you can see from the graph, small variations do not introduce significantly greater losses. Also, the price of copper pipe takes a sharp jump above 2 in. I stick to 10 in. or smaller cake pans, even for 6M or 10M cavities. For example, the inner conductor of our sample cavity is 1¼ in. copper pipe. This is a little small, but is close enough. If you intend to build an actual duplexer from this design, 2 in. pipe will yield slightly better insertion loss.

Pan Size	Center Conductor	Copper Pipe
12 in.	3.3 in.	3 in.
10 in.	2.8 in.	2 ½ in.
9 in.	2.5 in.	2 ½ in.
8 in	2.2 in.	2 in.
7 in.	1.9 in.	1 ½ in.

Table 8-2: Cake pan vs. center conductor pipe size

As a sidelight, the graph also illustrates why 75 ohm coax is normally used for receiving purposes, such as TV cable. At this characteristic impedance, coax has the lowest losses? Why then, you may ask, do we use 50 ohm coax for transmitters? Shouldn't they also use the lowest loss coax? Yes, they should if one only considers loss. 75 Ohm coax can't handle nearly as much power as 50 Ohm coax. The best power handling capacity in coaxial line is achieved at roughly a 30 Ohm characteristic impedance. 30 Ohm cable is difficult to manufacture, so 50 Ohm cable has become the accepted compromise for coax carrying RF power. In a cavity, however, losses are extremely important. So we want to use the optimum impedance of 77 Ohms, again an outer-to-inner diameter ratio of 3.6 to 1.

When I learned about this magic ratio, I wondered, "Doesn't that create a mismatch between the 50 ohm coax and the cavity?" Yes it does, but it does not matter. I'll have more to say on this later when we talk about lines, but for the moment, let me state another basic cavity principle. Any mismatch that takes place at the input of a cavity is reversed at the output, that is provided both loops are equally configured.

Bandwidth Verses Insertion Loss

Next we come to the most important duplexer concept of all, bandwidth vs. insertion loss. If everything were perfect, a duplexer would pass only the frequencies we wanted and totally reject all others. What's more, there would be no insertion. In other words the bandwidth would be extremely narrow and the insertion loss would be zero. As we know, this does not happen in practice.

It is, though, possible to have reasonably narrow bandwidth. Bandwidth is directly proportional to the Q of the cavity. The Q is determined mostly by skin effect losses. If we assume that we have the ideal conductor diameter ratio of 3.6 to 1, a reasonable approximation for the Q of a copper cavities without any load is,

Q = 107 x Diameter (in.) x [root-2 Frequency(MHz)]

From this we can determine the bandwidth by,

Bandwidth = Frequency / Q

Table 8-3 lists value calculated from these equations vs. outer conductor diameter, at 450 MHz.

Notice the bandwidth figures. You may be surprised that they are so narrow. If you've had practical experience with duplexers, you probably were expecting bandwidths of Megahertz not Kilohertz, and you’d be right.

The reason for the difference is quite simple. The values are for unloaded cavities. In use, duplexer cavities exhibit far poorer bandwidth because they are loaded by the external equipment connected to them. In a real duplexer, there is a 50 ohm load on both the input and the output. One is the 50 ohm load of the antenna at the tee junction. At the other ports, the duplexer sees the 50 ohm load of either the receiver or the transmitter. Each individual cavity also sees the same loads, since in a well designed duplexer the cavities are more or less transparent, as we learned above.

Diameter	Q (unloaded)	Bandwidth(MHz)
1 in.	2300	195 KHz
2 in.	4500	98 KHz
3 in.	6800	65 KHz
4 in.	9100	49 KHz
5 in.	11300	39 KHz
6 in.	13600	33 KHz

Table 8-3: Q vs. bandwidth for 450 MHz copper cavities with a 3.6:1 ratio

Therefore, every cavity is doubly loaded by 50 ohm loads. What this does is to establish a new effective working Q for each cavity called the loaded Q. It is far, far less than the unloaded Q given in Table 8-3. That's why the working bandwidth of duplexer cavities is much greater.

The Effect of Coupling

Before we can get an idea of how much the external loads reduce the unloaded Q of the cavity, however, we must look at another process that happens inside a cavity, that is, coupling. The 50 ohm load impedance created by an external device is fixed, but the amount it actually loads the cavities is not.

The amount of loading depends on the arrangement of the loops in the cavities. You will recall from an earlier chapter that the size and orientation of a loop determines how much it couples to the cavity. If a loop is made large enough and correctly positioned, it will place the entire external load on the cavity. If, however, it is made smaller than this, or is rotated away from being perpendicular to the field, it will not place the entire external load on the cavity.

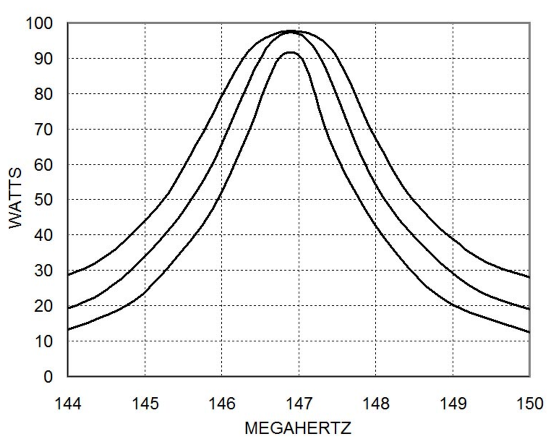

Figure 8-4: Bandwidth and insertion loss vs. coupling. for over coupled, critically coupled and under coupled.

This leads us to a most important cavity concepts: **the tighter the coupling, the wider the bandwidth**. Notice Figure 8-4

Well if that's true, you may be thinking, then let's never use tight coupling, and the rejection in our duplexer of unwanted signals will always be good. That's a valid idea, except for one thing – and it leads us to another important principle: **the less the coupling the more the insertion loss**. Notice Figure 8-4. Here I show the same cavity with the loops progressively adjusted for loose (under) coupling, optimum (critical) coupling and tight (over) coupling. Notice that bandwidth decreases as the insertion loss increases. We can't have both – it's simple physics.

If we did not care how much insertion loss our duplexer has than under coupled cavities would provide all the Q we would ever need for good isolation between receiver and transmitter and protection against the neighbors. But if we don't want to lose receiver sensitivity and transmitter power, we need to use critical coupling and the largest cavities we can afford. In review, remember this. The loaded Q of a large critically-coupled cavity can be the same as that of a small under-coupled cavity, but the insertion loss will be less.

A Basic Compromise

It should be obvious then, that the correct balance between bandwidth and insertion loss needs to be established in every duplexer. If we try to achieve for too little insertion loss, bandwidth and isolation will suffer. Anything tighter than critical coupling is counterproductive. The small improvement in insertion loss is not worth the price of the increase in bandwidth.

Therefore, when one is building a duplex for general purpose applications, you should set the loops for critical coupling. Most commercial duplexers are this way. I also begin with In my home-brew designs I make the loops a little larger than necessary to achieve critical coupling when they are perpendicular to the magnetic field. Then all I need do is to rotate them slightly to achieve critical coupling. As we learned earlier, rotating the loops does not degrade the basic performance of a cavity, it merely reduces the amount of coupling.

What is a "Reasonable" Insertion Loss?

A very significant point here is to ask how much loss should we expect to have at critical coupling? This is where the uninformed duplexer may hear misinformation. Hams often strive for too little insertion loss. By now you should realize that learned, insertion loss is determined almost entirely by skin effect, which is a function of cavity diameter and cavity construction material. The informed user realizes that insertion loss is a fact of life. It is unrealistic to expect otherwise. Table 8-4 gives my personal rough guidelines, based on experience, for aluminum cavities for 2M. For copper cavities at 450 Mhz, divide the diameters by three and the insertion loss by the conductivity difference between aluminum and copper of 1.5.

Diameter	Insertion loss
3in.	2.2 dB
6 in.	1.1 dB
9 in.	0.75 dB
12 in.	0.6 dB

Table 8-4: Insertion loss for 2M aluminum cavities.

The figures I have given are for loaded cavities installed in a completed duplexer. Therefore, a small amount of the loss included here is due to other factors. With care you may be able to achieve slightly better results.

The Next Step

Now that we have a starting point, critical coupling, we are going to take another step that most duplexer users will complain loudly if told to do so. We are going to increase the amount of insertion loss, to knowledgeable decrease the bandwidth of our duplexer. The object is achieve the best balance between economy and loss. For as we've seen, an oversized, overpriced critically-coupled duplexer will always work, but it is often not the best economy. This of course will evoke an attitude problem for some repeater owners. They do not like ANY increase in insertion loss, even if it will bring benefits.

Let's begin on the transmitter side. Again hams probably won't like this, but the two-way industry is generally willing to accept a 3dB loss of transmitter power to achieve the correct bandwidth. Yes, that's giving up half of the transmitter's power in the duplexer. Admittedly, that's not what we'd like, but it truly is an acceptable compromise. Amateurs want "absolutely every microwatt" of power they can get. Commercial operators usually know better.

So unless you have all the money in the world and have all the space you need in a repeater cabinet, transmitter insertion loss of 3dB is acceptable in practical repeater installations. Often we can do better, but don't feel "put upon" if you can't.

The reason this is so is because losing half the power in a worse case situation is really not that bad. Especially at UHF, but even at VHF, the service area of a repeater with only half the power is actually very little different than it would be at greater power. Terrain is a far bigger factor than power. That's why most commercial repeaters are less than a hundred watts. Modest power is really quite adequate. A kilowatt isn't necessary. So neither is there any need to cry over losing half of your power in a duplexer if it will net significant gains in economy with performance. A couple extra watts isn't worth the price.

The same is true for the receiver side of a duplexer, except that acceptable insertion loss can surprisingly sometimes by much greater. Again we would like as little loss as possible, but once again it is not always that important. I've seen several cases where intentionally increasing the insertion losses on the receive side beyond of 3dB has improved the repeater's actual performance quite noticeably. It's ALWAYS an option worth investigating.

As we saw in an earlier chapter, the average level of band noise at your repeater site is the biggest determining factor of how much sensitivity you can practically use. For example, in chapter 1, we saw that if the average noise level at your location is -110 dBm, then all you need is an overall receive sensitivity of roughly 0.71 microvolts. But if your receiver has a natural sensitivity of 0.22 microvolts, like our sample receiver, simple math says that you can afford to take a big 10 dB loss in insertion loss on the receive side of your duplexer without any loss in system performance whatsoever. Again, don’t get upset at having to give up 3dB on the receive side of your duplexer to achieve good filter action.

Never forget that if you intentionally reduce overall system sensitivity by admitting greater insertion loss on the receive side, you will always instantly improve system bandwidth. So don’t strive for the last microvolt of gain and the absolute minimum of insertion loss in a duplexer. It is not always the best choice. You will gain much more by using only enough gain and as much insertion loss to let your receiver hear efficiently, and no more.

I can recall the first repeater site on which I saw this principle applied. I had adjusted my home-brew duplexer for the absolute minimum insertion loss on the bench. When I put it on the hill top it worked okay, but I was experiencing a little interference from a nearby paging transmitter. So reluctantly, I twisted the loops in the receive bandpass cavities for an increase of insertion loss to eliminate the paging transmitter. The interference immediately went away, and to my great surprise the repeater could now actually hear weaker signals. Case in point.

Increasing receive-side insertion loss in a duplexer in order to narrow the bandwidth is always a compromise worth considering. It is much like adding another cavity. And if you are using a preamp or an outboard power amplifier, it can be worth its weight in RF gold. Duplexer insertion loss is NOT always your enemy.

Chapter 9 – Inter-Cavity Lines

This chapter will probably be the most mysterious if you've ever tried to modify a duplexer for a different band. Of all the parts of a duplexer, the lines that connect the cavities and those that connect the duplexer to other devices, generate many questions. They also spawn many old wives tales. Fortunately, we'll learn that determining the length of the lines is actually quite easy, especially if we employ a practical approach.

In this chapter we will look at the types of cable to use and the basic theory what the line lengths between the cavities must be. We'll then explore a practical way to determine those lengths easily. Finally we'll see what to do with the lines that connect the duplexer to the repeater.

Line Type

Like almost everything else in a duplexers, my experiments demonstrated to me that the type of coax that you use to couple the cavities together is not critical. Only three things matter. The first is shielding. All the coax that you use in a repeater must be 100% shielded. It is basically a necessity. Otherwise all of the effort to isolate your receiver from your transmitter or from the neighbors can easily be lost by direct pickup through the shield of the coax.

Ordinary coax, with a single braided shield, the kind we most often use, is inadequate. It is too leaky. Only two types of coax are satisfactory for repeater use, double-shielded flexible coax or so-called hard line. Most of the common varieties of flexible coax are available in double-shielded versions. The only difference is that they has two layers of either braided wire loom as the outside conductor instead, or one of braid and one of foil. Double-shielded coax essentially 00% shielded.

Hard line, either rigid or semi-flexible is also totally shielded. Its outer conductor is solid copper or aluminum tubing not braid. Hard line, though, is impractical to use inside a repeater or between the cavities of its duplexer. We normally employ is only for external feed lines. Its main benefit is its ability to withstand weather. Braid-shielded coax with a single or a double shields over a period of time allows moisture to pass through. This eventually corrupts the dielectric of the coax. Except for a few high-quality coax types, losses increase rapidly in braid-shielded coax exposed to the weather at VHF and UHF. Inside a repeater, though, braid-shielded coax is no problem as long as it is double shielded.

The second factor to consider in the type of cable that you select, is the connectors. Especially for the home builder, this can increase costs considerably. You can find connectors to fit almost any type of cable, but the cost varies dramatically. You won't need many feel of cable to build a duplexer, but you will need quite a few connectors. Shop for connectors carefully.

The exact type that you use is not critical, as long as it is correct for the cable type. I personally prefer crimp-on connectors for convenience and durability, but the tool to attach them does add some expense. The screw on type are totally satisfactory, however, even if obtained from a local bargain retail electronics outlet.

I recommend two types: N and BNC. If you are running roughly 50 watts or less, BNC is the best choice. They are moderately priced and have good RF characteristics. N connectors are better for higher power and similarly have good RF characteristics. Do not, however, be tempted to use SO/PL 239 connectors above 2M. Even at 2M they are marginal. Such are common on RF devices, but can have poor RF characteristics. One or two in a repeater is not usually a problem, but try to avoid them if you can. Many commercial duplexer manufacturers do use them, but generally they select SO/PL 239 connectors made from special materials. The local radio store variety can cause grief.

The third consideration in selecting cable is power handling capacity. As with connectors, for power levels under roughly 50 watts, double-shielded cable similar in size to common RG-58 is quite satisfactory. I use an economical variety of foil double-shielded RG-58 that is similar to the cable developed for cable TV applications. Most cable manufacturers now offer it. My point is that almost any type will work. If you wish to use the expensive silver plated double braid varieties, that's fine, but less-expensive types work just as well.

Determining Line Length

We now come to a very important issue of comprehension for the duplex builder or the home repeater builder wishing to retune a duplexer to another band. It is how we determine how long the lines should be between cavities. It is not common knowledge. And the best part is that it will lead us to a simple practical way to quickly configure the lines between cavities. It will also explain why one cannot simply proportionately rescale the lines for a change of bands.

Here is the concept in a simplified nutshell. We need to make the electrical pathway from one cavity to the next "disappear." In other words, we must "tune" the length of the line until the two cavities think there is no line between them.

To accomplish this perhaps-seemingly difficult feat, we employ a very basic fact about transmission lines, including coax. That is, ½ wavelength of transmission line does not change the impedance of what it is connected to it on one end, at the other end. This is of course ½ wavelength electrically, not physically. The velocity factor of the line must be factored in.

But because whatever we connect to one end of an electrical ½ wavelength of transmission line also appears unchanged at the other end, effectively, as we require, the line does not exist. This simplification ignores losses in the ½ wavelength line section, but for the small involved, the losses may be ignored.

So theoretically we need to make the total length of the pathway between the cavities such that the cavities think they are directly connected to each other, essentially with no line in between them. For when we do this, the cavities behave as they should and only then.

But here is something very important. The ½ wavelength pathway we need is not made up just of the coax between the cavities. It also partially includes of the coupling loops at both ends to some degree. Notice Figure 9-1. The ½ wavelength pathway is roughly the total length shown as the dotted line in the figure, not just the electrical length of the inter-cavity coax.

The full theory is more complex than this, but for the technique we will use to actually constructing the lines, this simplification is quite adequate. The practical procedure we will use, bypasses the theory. I give it merely to help the reader visualize what is going on with inter-cavity lines.

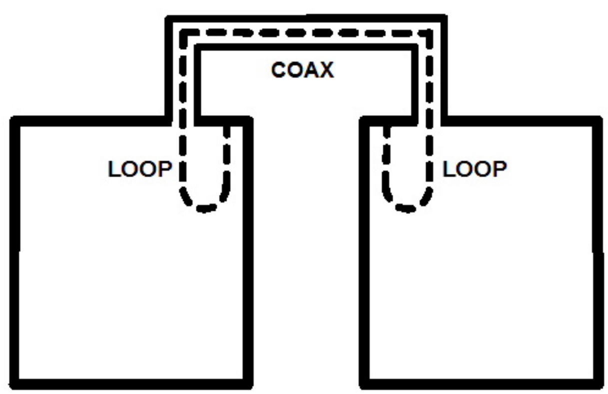

Figure 9-1: An inter-cavity line. Total electrical length = 1/2 wavelength

In properly inter-connected adjacent cavities, the total length of the dotted line, Figure 9-1, should appear to be ½ wavelength. Notice that the coax is only a part of the total length. The loops must also be included.

Realize then, that if you need to reconfigure a duplexer for another band, the length of the inter-cavity lines is almost impossible to compute. It isn't just a matter of simply rescaling the coax lengths proportional to frequency. This will severely upset the filtering properties of the duplexer. Insertion loss and isolation will suffer.

Instead, the best way I have found to easily determine the correct length for inter-cavity lines is a pragmatic approach. I never attempt a mathematical solution. Actually, the method I use is also used by some commercial duplexer manufacturers.

Make up a set of a dozen cables of the same type of coax and connectors that you'll be using in the final configuration. Make each cable just a little longer in small equal increments. The total set needs to span a full ½ electrical wavelength. For example, ½ wavelength on 440 MHz is roughly 12 inches. Multiplying this by the velocity factor of the cable I used (0,6), twelve cables in 1 inch increments is a suitable. For 2M, 3 inches increments are fine. Label each cable for easy identification. Make the shortest one roughly 18 in. long for 2M, 6 in. for 440 MHz. Any beginning length is fine as long as it will fit between the cavities.

To use the cable set, begin with either the longest or the shortest cable and connect together two adjacent cavities. Each cavity must have already been individually tuned to frequency. Do not alter cavity tuning during this procedure

On one side of the pair of cavities connect a spectrum analyzer or your transceiver. On the other side of the pair, connect a though-line wattmeter with a 50 Ohm dummy load or the input of the spectrum analyzer. The lengths of the outboard cables are not critical as long as the source and load impedances of the outboard equipment are truly 50 Ohms.

Now evaluate the cavity pair as described earlier in this book. For the simple setup, collect data points and draw a graph for the cavities in combination. If you have a tracking spectrum analyzer available, it will display the response curve for you. Then simply change to the next cable increment and re- evaluate the cavity pair.

Once you go through the complete set of cables, the correct cable length will be very evident. If two cables seem similar, use either. This is now the cable length that best satisfies a ½ wavelength electrical pathway between cavities. Make up a cable of the same length for permanent use.

In essence what you have done pragmatically is to essentially eliminate the inter-cavity line, making the loops think they are in both cavities. At this line length your inter-connected cavities will perform in the complete duplexer without difficulty. They will perform very close to basic cavity theory. Incorrect inter-cavity line lengths cause serious problems.

Then, after you have interconnect all the cavity pairs individually, assemble the compete duplexer and then re-evaluate it as a complete unit in much the same way. Do the input side and output side separately. Just remember to keep any unconnected ports terminated with 50 Ohm dummy loads.

At this point you will be able to estimate the total isolation and the total insertion losses of your complete duplexer from the graphs or the spectrum analyzer display.

External Lines

You may now be wondering about the lines that connect the duplexer to the receiver, the transmitter and the antenna. Do they also have to be a special length? The simple answer is no, not if you have tuned and configured your duplexer correctly. All external devices should present a 50 Ohm load to the ports of the duplexer, and if as such the lengths of these external lines is not important. Do not tune external lines; it is unnecessary.

There is one exception to tuning an external line – an add-on cavity. Let's say you want to add a pre-amplifier to your repeater. Furthermore you decide that an additional outboard bandpass cavity in front of the preamp would be a good idea.

In this case you also do not need to tune the lines. The preamp isolates the outboard cavity from your duplexer, and presents a 50 Ohm load to each. But if you decide to connect the outboard cavity directly to your duplexer, then you do need to tune the line. For now the external cavity is a working part of your duplexer. Do so in exactly the same way you tuned the inter-cavity lines in the duplexer. Remember, if a line is terminated in 50 Ohm devices, the line does not need to be tuned. A cavity is not a 50 Ohm load, so any line to it needs to be tuned.

Always keep the basic principle in mind for inter-connecting cavities. The total electrical length of the line, including the coupling loops should be ½ wavelength. This essentially causes the lines vanish from the picture hence not to change the filtering action of the cavities in any way. That's the objective for inter-cavity lines.

Author's Note

Well, that's as far as I got. I think, though, that most of it has been said, and in pretty simple terms. So enjoy! Roll your own. You will be pleased

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