

SEITS

Duplexer Theory and Tuning

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From the amount of questions we have received on the web page, I saw a need for an article to demystify the subject of duplexers and cavity filters. Duplexers and their cousin the Diplexer (note they are not the same thing) are electrically simple filters. They allow us to transmit and receive on the same antenna at the same time, reject unwanted signals and in the case of the Diplexer feed two different signals to the same antenna.

Electrically a duplexer is a device using sharply tuned resonate circuits to isolate a transmitter from a receiver. This allows both of them to operate on the same antenna at the same time without the transmitter RF frying the receiver. Note that there must be a separation of the transmit and receive frequency. This is called the "split." On two meters the split is 600 kHz. On 70cm the split is a much easier to do 5 Mhz.

Duplexers are often mistakenly called duplxers. The common application for a diplexer is to connect a dual band mobile radio's two antenna connections to a common feedline and antenna. Diplexers are completely different and much simpler to build devices than a repeater duplexer. While duplexers use narrow passbands and notches to work their magic, a diplexer is a simple high and low pass filter connected together.

There are several different ways to build a duplexer. The hybrid ring, cavity notch and bandpass/bandreject design are all found commercially. Each design has its advantages. The hybrid ring is rarely seen in Amateur service. It uses a combination of both cavities and phasing lines. The ARRL Handbook has an excellent explanation of how it works if you're interested.

For many years the Handbook also had plans for a six cavity notch duplexer. The Handbook has an excellent explanation of the theory behind this design. I have built these and they do work. I have also found this design to be extremely difficult to tune, noisy and not all that stable. I do not recommend it. Yes, I know some have been built, but there are better and easier to tune designs available now.

My all time favorite duplexer design is the Wacom four cavity Band Pass/Band Reject model with 8" cavities. Their only flaw is their expense (close to \$900 at this writing). By using larger high Q cavities and a better design, Wacom was able to get the performance of the six cavity notch duplexer using only four cavities.

Examination shows that two of the cavities are in series with the transmitter output, and two in series with the receiver input. The two "halves" are joined together with a "T" connector and connected to the coax line to the antenna (see fig. 1).

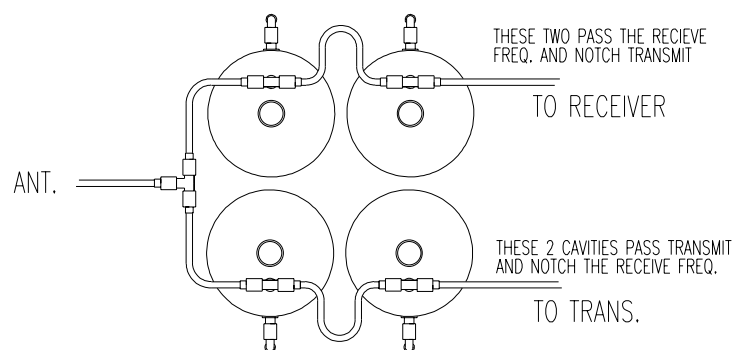


FIG. 1 FOUR CAVITY BP/BR DUPLEXER CONNECTIONS

Each cavity has two functions. First it must pass the desired signal (the "bandpass" or pass band).

Second, it must stop as much as possible of the undesired signal (the band reject or notch). In figure two I show the ideal response curve of a typical transmitter cavity. Note that it passes almost all of the signal on the transmit frequency of 145.37. And that it has a deep (30dB+) narrow notch at the receive frequency 600 kHz. lower.

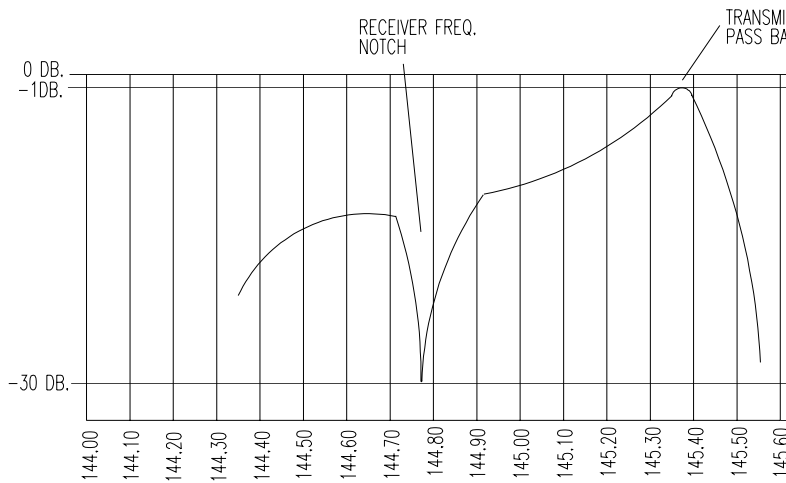


FIG. 2 TRANSMITTER CAVITY ATTENUATION CURVE

The two receiver cavities are exactly the same except that they have their pass band tuned to 144.77 the receive frequency. Their notch or Band Reject frequency is on the transmitter frequency of 145.37. Thus the transmitter cavities keep the wide band RF noise from the transmitter out of the receiver, and the receiver cavities keep the RF power from the transmitter out of the receiver.

Note at this point that transmitters do not put out all of their energy on just the desired frequency! They also put out wide band white noise (hiss) for a considerable distance from the center frequency. If your transmitter (this is a rare problem) puts out excessive white noise, you may not be able to notch out it all out. Some transmitters radiate less white noise than others. A few very early solid state transmitters produced so much noise that they could not be used on repeaters.

How do they do this apparent magic of letting you transmit and receive at the same time? Surprisingly, a duplexer cavity is simply two carefully tuned resonate circuits! Electrically they are very simple. One tuned circuit sets the pass band, the other sets the frequency of the notch. That's all there is! Two cavities are used in series simply to provide more isolation between the transmitter and receiver. One cavity isn't enough to do the job.

The duplexers complexity comes from the mechanical design required. To make things simpler, lets just look at one cavity since they are all the same. A cavity is simple tuned circuit. Look at figure three. The body of the cavity and tuned line inside make up the parallel tuned circuit consisting of L1 & C1. Coupling of the RF energy into the cavity is done by L2 and C2.

Now why do we have to use a big cavity when a coil and capacitor tuned circuit for two meters can be made very tiny? The answer is in the quality of the tuned circuit, that is, its "Q." Our little coil and capacitor has a low Q, far too low to work as a duplexer. That is, it does not tune sharply enough. Its band pass peak would be too broad, and its notch too wide and shallow.

Now a interesting thing happens as we make the coil larger in diameter and reduce it turns. When we increase the value of C1 so it still tunes to the same frequency, the Q increases and the tuning becomes sharper. If we continue this evolution, our coil becomes a tuned line 1/4 wave long. The capacitor is replaced by a large metal tank (cavity).

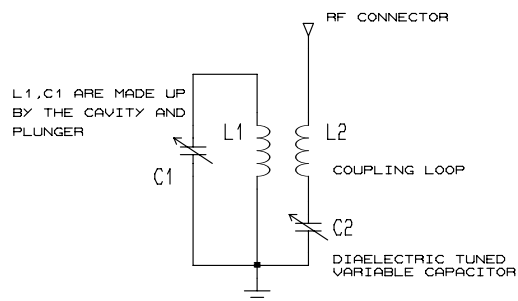


FIG. 2 BP/BR CAVITY SCHEMATIC

The larger the tuned line and cavity (in reason) the higher the Q. An 8" diameter cavity has a higher Q than a 3" cavity would and works better on the air.

Thus our tuned circuit becomes a cavity (figure four) 25" long and about 8" in diameter. The tuned line inside is a copper tube 1 3/8" in diameter that can be varied in length between 18 to 23 inches. Varying the length of this tube (often called the plunger) sets the band pass frequency the cavity is resonate on.

Look back at figure three. We still have to couple RF energy into our resonate cavity. L2 becomes a "loop" of copper wire or strap that dips down into the cavity from the top. The size or the loop and its position determines the amount of coupling of energy into the cavity. One last refinement is the loop resonating capacitor C2. It sets the frequency of the cavities notch. Together L2 and C2 form a series tuned resonate circuit.

So we now have a very simple electrical design! All of our problems from here on out are mechanical in nature. First of all, we have to fabricate the body of the cavity. Copper, aluminum or brass all will work well. Just as long as the top can be in one piece of electrically low loss material. It has to be closed on the bottom end. A simple plate pop riveted in place would work.

The tuning plunger can be a 18" piece of ordinary 1 3/8" O.D. copper water pipe. Inside of it a 20" long tuning shaft made of 1/4" threaded rod screws in and out a 6" section of 1" O.D. copper pipe. The only real problem here is the electrical conductivity of the plunger. The joint between the two pipes has to be made of a springy bronze contact material called "finger stock."

Then all of the pieces are silver plated. The silver plating is ultra important! Bare copper alone is too lossy at two meters to make a practical cavity. Plus the surface of the copper (where the RF travels) oxidizes making a even poorer connection between the fixed and moving section of the tuning plunger. The result is often a cavity that is almost impossible to tune due to the noise generated by the moving contact.

The tuning plunger, finger stock and all RF parts inside the cavity must be silver plated. Plating really makes a difference. Remember that you have to keep total losses in your duplexer to less than 3dB. Small improvements in efficiency are very important.

The last item is capacitor C2. A simple air variable would be too critical to tune. Wacom solved this problem by using a cleverly designed capacitor that works by varying the dielectric constant! Going back to your basic theory, remember that two things determine the value of a capacitor. One the size of the plates, the other is the dielectric constant (quality) of the insulating material between them.

The Wacom capacitor consists of a 11" section of 1/2" I.D. brass tube making up one plate of the capacitor. The other plate is a 1/8" O.D. copper rod inside the tube. A plastic tube slides into the 1/2" brass tube and over the interior 1/8" rod. Varying its position, changes the dielectric constant of the capacitor and thus its capacitance (you are varying the amount of plastic dielectric replacing the air dielectric and no the device is not air tight).

This capacitor and the coupling loop make up a series resonate circuit (refer back to figure three). The resonate frequency of this circuit determines the frequency of our cavities notch (or as Wacom calls

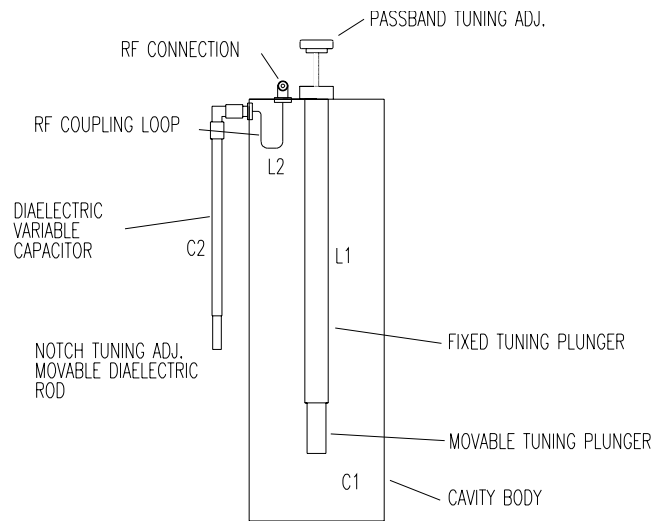


FIG. 4 BP/BR CAVITY CONSTRUCTION

it, the "Band Reject"). The great beauty of the Wacom design is simple smooth adjustment of the notch frequency by this clever variable capacitor. In other duplexer designs I have worked with (for example the Handbook six cavity notch design) the tuning of the passband and notch are very difficult.

Another problem is temperature stability. If the duplexer is in an area that is not temperature controlled, the metal will expand and contract with temperature changes. This could possibly detune the cavity slightly. Wacom gets around this problem by using a tuning rod made of a special and very expensive alloy called INVAR that compensates for the temperature changes. We do not have a source of these rods.



Yes, SEITS did homebrew a set of two meter duplexers, and no it was not easy. Harvey NOLBG did most of the work and he tells me he will never build another set!

Our cavities are 1/4" wall 10" diameter copper pipe. We have no idea where the pipe came from, it just appeared one day. Honest! The notch tuning capacitors are mounted on the top of the cavities to eliminate the troublesome elbow connectors. Everything but the outside of the cavities is silver plated to reduce losses.

These are installed on the Iowa City, Iowa 145.47 linked repeater. They work very well and are stable even though they are installed in a unheated building.

Apologies to Wacom...

If you do build a homebrew duplexer and it is kept in a temperature controlled environment, then there is no need for self compensation. If you tune the duplexer at 72 degrees and keep it close to that temperature, then NO PROBLEM! In practice, we have found that our homebrew duplexers do work well in an unheated building. Or at least well enough that the users have not complained.

The next issue on duplexer design is the coupling of the RF between the various components. This is done with electrical 1/4 wave coax lines. If your working with surplus cavities that were used in the high end public service band you may have to replace the coupling cables with longer ones. Tune the cavities and test them on the air. If you can not get sufficient isolation, contact the manufacturer for their recommendations. Or you can go ahead and fabricate a new set of cables yourself.

A RF wave traveling in coax is shorter than one traveling in free space. The difference between free space length and the wave length in coax is called the velocity factor. The ARRL Handbook has charts giving the velocity factor of various coaxes and explains how to calculate the correct length for the 1/4 wave lines.

I have had duplexer connecting lines go bad on older duplexers so it is useful to know how to replace them. I've also found that when I determine the length of the lines experimentally they came out a little different than the Handbook calculations led me to believe they would be. The lesson here is that if you are not sure, make some tests!

The choice of connecting cable is important. The coax must be the double shielded type with 100% coverage. It does not have to be solid heliax (that would be pretty hard to work with). If you can locate it, double shielded mil-spec teflon coax is the best. The new Times coax with a metalized mylar shield works very well. The coax does not have to be large diameter if your running under a couple of hundred watts. The lengths are so short that losses are not a consideration.

Pay careful attention to the duplexers connectors. Most of the mysterious noise problems I have heard in repeaters have been traced to the coax connectors. My favorite Wacoms do use UHF connectors on them. I have had minor problems with noise that was easily cured by cleaning and tightening the UHF connectors.

If I had a choice, I would use N or BNC connectors on any new duplexers. N series connectors are the best and well worth the extra money. They are lower loss and I have never had a noise problem with one. Be sure that the connectors you use are U.S. made and silver plated! There is a difference in connector quality. Be super careful of UHF elbow connectors. We have had very serious problems with imported elbow connectors. Most work better as RF chokes then connectors. Avoid using any of them if you can. Some we tested introduced severe losses in the system.

Tuning of the bandpass/bandreject design duplexer is easy compared to conventional notch duplexer. The cavity plunger sets the passband frequency. Here you want as much RF to pass through the duplexer as possible. The tuning capacitor C2 sets the notch frequency. Clearly mark the pass and reject (notch) frequencies on each cavity. Remember that they are opposite for transmit and receive!

EXAMPLE:	RECEIVER CAVITIES	Pass 144.77Mhz	Reject 145.37
	TRANSMITTER CAVITIES	Pass 145.37Mhz	Reject 144.77

The easiest way to tune cavities is with a FM service monitor equipped with a tracking generator and a spectrum analyzer. If at all possible, contact someone with this type of test equipment to do the tuning for you. If this is not possible, do not despair. Simpler amateur methods are possible and will work just fine. You just have to take more care.

Your going to need some kind of stable signal source and method to measure RF amplitude. A old fashioned tunable RF signal generator that can put out at least a volt of RF is very useful. You can use to sweep the cavities for initial passband tuning. For a stronger signal source a HT will work.

With the HT your passband indicator can be a RF wattmeter. For the finer job of tuning the reject (notch) frequencies, a simple RF voltmeter will work. You could also use a "S" meter equipped receiver with a step attenuator in front of it. This would be perfect for fine tuning the notches. Just be careful how much RF you inject into the duplexer while tuning, you would not want to fry your receiver front end when you hit the correct passband!

If your going to build your own RF voltmeter probe, see the ARRL Handbook for details. Build it in a connector that you can attach directly to the duplexer connecting cables. For the RF voltmeter use a old fashioned analog moving needle meter like a VTVM or a simple microamp meter. Its much easier to tune for peaks and notches with a analog then a digital meter.

Start with just one cavity connected. Turn the RF output up all the way on the generator and sweep up and down the band till you see a peak on your RF voltmeter or S meter. Remember that turning the plunger in lowers the pass frequency. Turning the plunger out raises the pass frequency. Set the output of the generator to keep the meter in the linear portion of the scale.

All we are doing is a rough tuning first, so don't try to get things perfect. Connect the next cavity in the chain and repeat the process to put it on the pass frequency. Then set the second set of cavities to their pass frequency. Here is where it is easy to get confused and why it is important to have the frequencies clearly marked on the cavities. Doing that will save you a lot of trouble.

With both the transmit and receiver cavity sets rough tuned to the pass frequency, connect all of the cables on the duplexer set. Connect a wattmeter and a dummy load as in Figure 5 to the antenna connection. Set your HT on simplex to the pass frequency of the transmitter cavity set. In my example this is 145.37Mhz. Key the HT and tune the cavities for the maximum amount of power output.

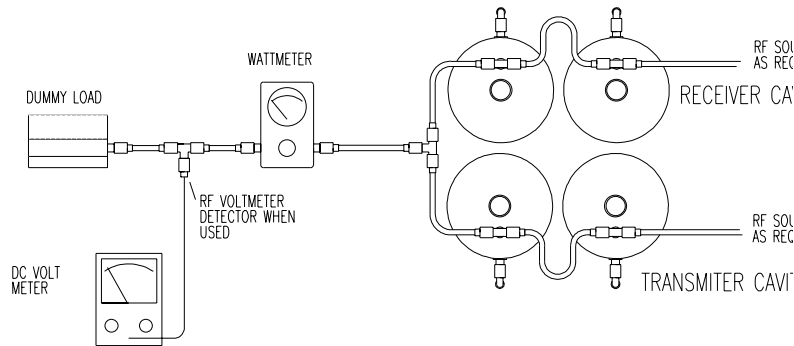


FIG. 5 TUNING SET UP

Connect the HT to the receiver cavities and set the HT frequency to 144.77Mhz simplex (-600 split from the transmit frequency in this example). Repeat the process of tuning the pass-band plungers for maximum RF on the wattmeter. Note that if by acci-

dent the reject frequency is too close to the pass band you may not be able to tune a cavity properly. If you suspect this, move the reject frequency adjust rod a short distance and try the passband tuning again.

Tuning notches is a little more difficult. You need a vastly more sensitive detector than the wattmeter used so far. If your signal generator can put enough RF into the cavities, a simple RF voltmeter probe will work. Remove the wattmeter and replace it with a T connector. Connect the RF probe to the open port of the T. Your cavities will now be properly terminated with a 50 ohm load and you will be able to measure the RF voltage across that load.

It is critical that your RF source be dead on frequency. A old fashioned tunable generator will not work. If your HT has a low power position, you can start with that. Warning! The HT will not be seeing a 50 ohm load when its signal is notched out. If you are uncertain if the HT can sustain high SWR's, don't use it.

Key the transmitter and adjust the first cavity for the proper notch frequency. You may have to increase the meter sensitivity or RF power to clearly see the notch. It should be quite sharp. Then repeat the process on the next cavity. Other than changing frequency, the process should be the same for the other set of cavities.

If everything went well you should be 99% in tune at this point. Go back and touch up the passband tuning and the notches one more time. Calculate the pass frequency loss across the receiver and transmitter cavities. It should be less than 2dB and no more than 3dB. If the loss is excessive, check your tuning again. If that is not the problem, check the loss of each of the cables and connectors.

The main reason I like the bandpass/bandreject design so well is the ease of tuning. They also rarely need retouching when connected to the repeater. In some rare cases you may want to touch up the notch adjustment to eliminate the last trace of desense white noise from the receiver. You need a weak unmodulated off the air signal to do this and a AC voltmeter connected across the repeater monitor speaker.

I use a whip antenna on my service monitor output to supply the weak signal. Adjust the output till you have about 10dB of quieting with the squelch open. Turn the transmitter on and off (you do have a local service switch don't you?) and observe the difference in the background noise. Any additional hiss



This is the test bench setup used to tune the SEITS homebrew duplexers. From left to right is FM service monitor with a wattmeter and HT sitting on top of it. Next is a HP spectrum analyzer and a frequency counter. This equipment was used for the final testing and tuning. Next is the simple equipment that NOLBG did most of the development work with. Atop the oscilloscope is the old Heath VTVM used with the RF voltmeter probe. The old HP tunable signal generator supplied the RF. Most of the work was done with simple test gear. Thanks to NOLBG and KOVM.

s that is heard when the transmitter is on the air is white noise from the transmitter. If you feel the noise level is excessive touch up the notches.

Most repeaters I have heard do have some audible white noise on the receiver. Perfection is hard to achieve in the real world. Worry about it only if the noise level is so high that it obscures the weakest modulated signal that you could normally expect to communicate with

For example, lets say that you can clearly hear a .25uV signal on your receiver with the transmitter off. With the transmitter on the noise level increases 2dB. This you could accept after final tuning. If the same signal disappears completely when the

transmitter is keyed, then the desense is excessive and there are still problems in the system.

Can you build your own duplexers? The answer is yes, but it is not easy. Nor is this intended to be a construction article. You can't find all the materials at the local hardware or plumbing store. You have to be able to do some simple lathe work and other metal fabricating. And you need the proper test equipment and tools.

As I said before, silver plating of the internal components is very important. I do silver plating on a regular basis and it is not difficult. I am not going to publish instructions on the web due to the extreme toxicity of the cyanide compounds used in the baths. Actually the process is quite safe, but I don't want some idiot killing his family by pouring the plating bath in the orange juice. If your interested in electroplating, go to your local library and research the subject. Jeweler supply houses sell the plating baths and supplies. Check the Yellow Pages.

Nor can I give technical details or tuning procedures for all of the duplexers on the market. The smartest thing you can do is to contact the manufacturer and buy the manual! Its a small expense for the trouble it will save you.