Basic Filters and Applications

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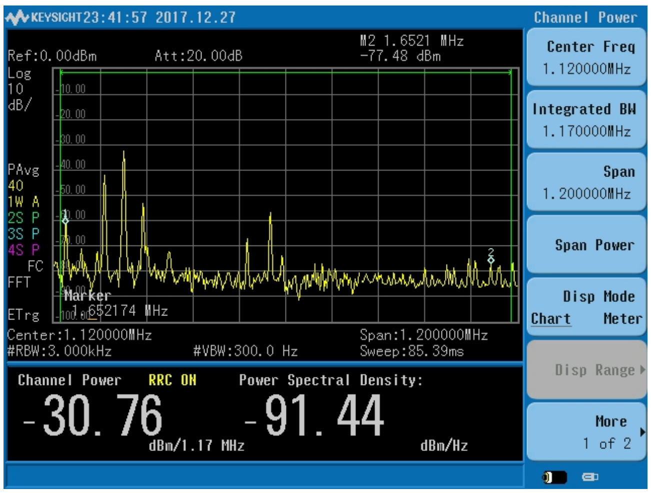
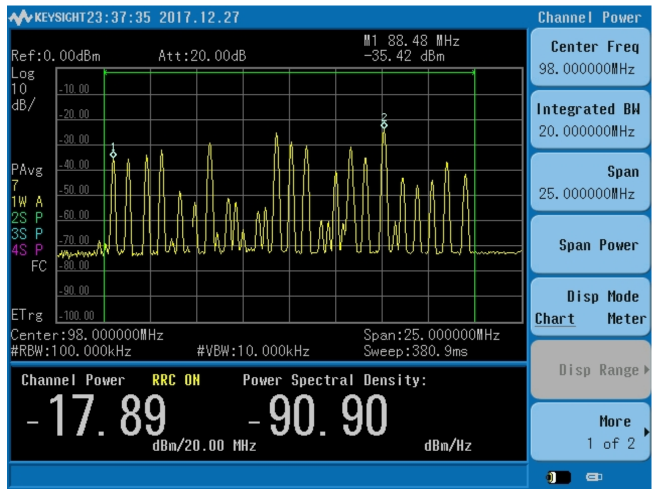
1. Introduction

Filters are used to alter the amplitude and phase response with respect to frequency of an ac circuit. In early electronics literature these are called *wave* filters. Here, I am concerned with the power amplitude response of radio filters used with receivers. Filters are important components in radio astronomy for shaping the frequency response of a radio telescope or rejecting radio frequency interference (RFI). RFI produced by broadcast stations can be especially troubling because the transmitters are powerful and pervasive (figure 1).





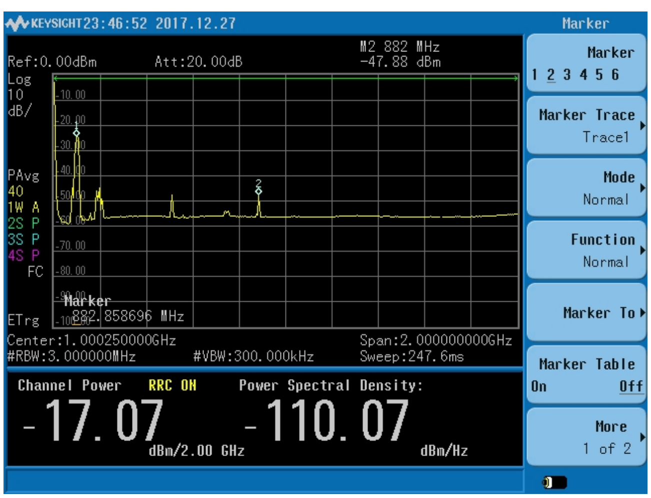


Figure 1 ~ Spectrum analyzer displays of potential RFI in three frequency ranges. The power levels shown in large numbers along the bottom of the display are (left) total power in dBm in the integration bandwidth and (right) power spectral density in dBm Hz^{-1}. All traces are averaged. Upper-Left: AM broadcast band from 535 to 1705 kHz; resolution bandwidth 3 kHz. Note the relatively high power response even though the frequencies are far below the design range of the antenna (see text). At least nine AM stations are visible. Upper-Right: FM broadcast band from 88 to 108 MHz; resolution bandwidth 100 kHz. Lower-Left: Band from 500 kHz to 2 GHz, which includes the AM and FM broadcast bands as well as the UHF television and cellular bands; resolution bandwidth 3 MHz. All FM stations appear as a single indication because of the wide resolution bandwidth. Images © 2020 W. Reeve

Even if broadcast station transmissions do not occupy the radio astronomer's frequency band of interest, they still can cause problems if not filtered out. Unfiltered frequencies may desensitize a receiver or cause unwanted responses because of front-end overload and spurious mixing products. The RFI-induced spurs can mask weak celestial emissions or cause false detections.

This article discusses basic filter types and builds on my previous article about measuring filters with a vector network analyzer {ReeveFilt}. Section 2 discusses the above spectrum analyzer display image in additional detail. Section 3 describes some receiver filter applications and section 4 describes basic filter types. Section 5 contains references and weblinks.

Future articles will cover specific filter types such as bandstop filters for the FM and AM broadcast bands and a filter specially designed for use with the Long Wavelength Array (LWA) antenna. The FM and AM bandstop filters reject frequencies in the VHF range 88 to 108 MHz and MF range 535 to 1705 kHz, respectively. These ranges apply in the United States, slight differences will be found in other countries. The LWA antenna filter is a bandpass filter with a nominal frequency range of 5 to 80 MHz and is designed to limit both the FM and AM broadcast bands. The spectrum measurements of the FM and AM broadcast bands shown above will be revisited in these later articles to show filter effects.

Filters can be built from lumped components such as inductors and capacitors, piezoelectric devices such as quartz crystals and ceramic and surface acoustic wave (SAW) technologies or from stripline, coaxial cable or waveguide transmission lines. Most of the filters discussed in this and future articles are based on packaged commercial filters that use lumped elements (figure 2). Throughout these articles I use the terms *loss*, *insertion loss* and *attenuation* interchangeably, all referring to the reduction in radio frequency power through the filter.

Some readers may wish to hand-build filters from their own or other people's designs, but these activities are beyond the scope of this series of articles. Section 5 includes some references on building and designing RF filters. Digital filters, which are achieved through digital signal processing, also are beyond the scope of these articles.

Figure 2 ~ Typical connectorized commercial filters of various types (highpass, lowpass, bandpass, bandstop) and covering various frequency bands. These filters include Mini-Circuits, Par Electronics, Industrial Communication Engineers, RTL-SDR.com, two exposed hand-built HF bandpass filters from kitandparts.com, and others. Note the variety of mechanical form factors and RF connectors, which include type SMA, BNC, pin header, and RCA phono jack. Not shown are specialized filters and a digitally controlled HF preselector that will be discussed in a future article. Image © 2020 W. Reeve

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2. Spectrum Analyzer Display of RFI

Because one of the main jobs of the filters described here is to reduce radio frequency interference, I will briefly discuss how the previously mentioned RFI measurements were made. The spectrum analyzer display images show potential RFI sources received by a 21-element log periodic dipole array designed for a frequency range of

50 to 1300 MHz and mounted at a height of 11 m above ground. The setup did not use a preamplifier. The measurements were made in the western part of Anchorage, Alaska with the antenna pointed south, generally away from the local broadcast stations. Even so, the spectrum images indicate many powerful transmitters that are not even close to the antenna design frequency range but still received by it. The LPDA antenna is not the only part of the circuit – some of the signals may have been picked up by the 20 m long transmission line from the antenna to the spectrum analyzer. People involved in radio astronomy either use antennas on purpose or use antennas not on purpose.

For reference, the spectrum analyzer was setup to measure power by the *Integration Bandwidth Method*. For this measurement, the spectrum analyzer resolution bandwidth (RBW) is set according to $RBW = k \cdot Span/n$, where k is a value between 1.2 and 4.0, *Span* is the frequency span over which the integrated power measurement is made and n is the number of trace points (461 for the Keysight N9342C handheld spectrum analyzer used for these measurements). Note that the displayed frequency span can be higher than the integration bandwidth. For example, for the FM broadcast band shown above, the displayed frequency span was set to 25 MHz and the integration bandwidth, the bandwidth over which the power was measured, was set to 20 MHz to cover the broadcast band from 88.0 to 108.0 MHz.

The display images show the total power measured in the integration bandwidth and power spectral density (measured power that has been normalized to 1 Hz bandwidth). The two are directly related by

$$PSD = PWR_{Total} - 10\log(BW_{INT}) \text{ dBm Hz}^{-1}$$

where PSD is the power spectral density in dBm Hz^{-1}, PWR_{Total} is the total power in dBm in the integration bandwidth, and BW_{INT} is the integration bandwidth in Hz. For example, the spectrum shown previously for the FM broadcast band indicates the total power is –17.89 dBm in the 20 MHz bandwidth, so

$$PSD = -17.89 - 10\log(20 \cdot 10^6) = -17.89 - 73.01 = -90.90 \text{ dB Hz}^{-1}$$

The calculated value matches the displayed PSD.

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3. Examples of Receiver Filter Applications

All receivers are designed with filters built into their various stages. However, it often is necessary to supplement the internal filters with external filters. External filters may be placed at the input of the first radio frequency preamplifier stage, for example at the input to the antenna-mounted low noise amplifier or the receiver antenna input (figure 3). The purpose of such a filter is to reduce amplifier overload caused by undesired signals. Overload usually is manifested as receiver *blocking* or *desensitization* (also called *desense*).

A filter that rejects, or filters out, a band of frequencies is called a band rejection or bandstop filter. Using the previous example of the FM broadcast band, the measured total power in the 88 to 108 MHz band is about –18 dBm. This power level may swamp the receiver input circuits especially if the desired frequency band is near the FM broadcast band. If an external filter provides, say, 30 dB of rejection, it will reduce the total power by 30 dB to –48 dBm at the receiver input. Similarly, a filter with 50 dB rejection will reduce the total power to –68 dBm, which still is a significant amount of power but possibly low enough to not affect the receiver. These simple calculations assume an ideal filter. Ideal and practical filter characteristics are discussed in section 4. There are other considerations for this situation.

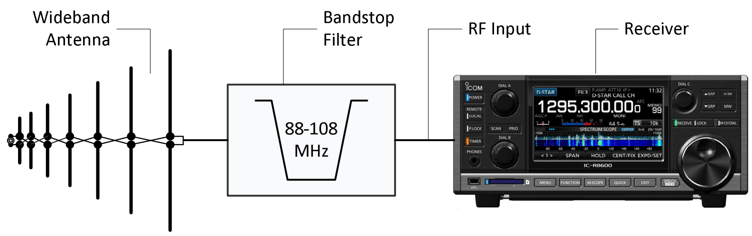

Figure 3 ~ RF input filter used to reduce receiver overload caused by powerful FM broadcast station transmitters in the 88 to 108 MHz band. Well-designed filters for this type of application have very steep band edges and low insertion loss. The system noise figure is increased by the filter passband loss. Image © 2020 W. Reeve

In the above illustration, the bandstop filter is placed between the antenna and the receiver. Unless a low noise amplifier is located at the antenna, the system noise figure is increased directly by any filter attenuation in the desired frequency band (passband). For example, a filter that introduces 2 dB passband loss and is located in front of the receiver's first amplifier stage will increase the system noise figure by 2 dB.

At frequencies below about 30 MHz, a noise figure increase of 2 dB usually is not important because system noise is dominated by the galactic radio background and atmospheric radiation (lightning) and not receiver noise. On the other hand, above about 30 MHz a 2 dB increase in system noise figure could cancel or reduce any positive effects of frequency filtering or even completely prevent detection of weak celestial emissions. In many cases, celestial emissions are only fractions of a dB above the system noise, so one must be careful to not degrade the system noise figure. In this case, the filter must be placed after the preamplifier or in later stages of the receiver system (perhaps requiring circuit modifications) with the corresponding risk of overload in the earlier stages. Clearly, filter applications require compromises in their application.

In some applications it may be necessary to place a filter in the intermediate frequency (IF) output path of a receiver. A common example is a filter placed at the IF output of a general coverage receiver used as a down-converter front-end for a software defined radio (SDR) receiver back-end (figure 4). The Icom R-8500 and R-8600 are typical but not the only examples of where a filter can improve the system performance. In this situation, the SDR receiver and associated software are used as a spectrum processor.

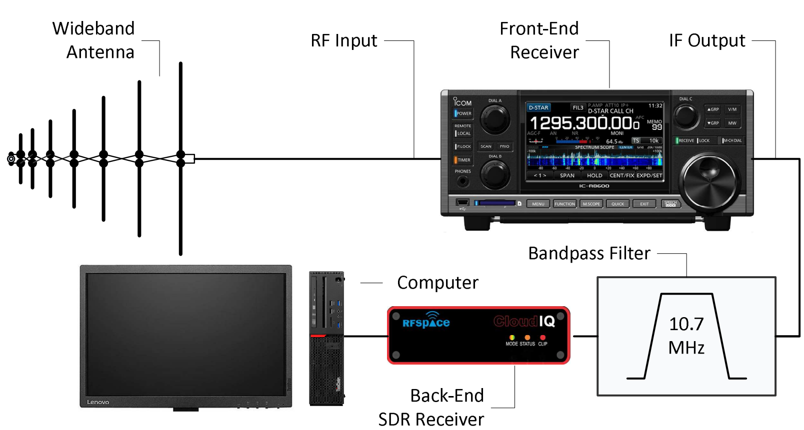

Figure 4 ~ IF output filter used to reduce spurious receiver signals outside the IF passband. The IF output of the receiver shown has a bandwidth of 10 MHz centered on 10.7 MHz (IF frequency range from about 6 to 16 MHz). Although a bandpass filter is shown, a lowpass filter may work just as well depending on the spurious signals present. Some SDR receivers may require an external attenuator (not shown) between the front-end IF output and SDR receiver RF input to prevent overload caused by high-level IF outputs. Image © 2020 W. Reeve

The IF output filter will not directly help the front-end receiver but it may help the SDR back-end because most SDR receivers are quite sensitive to the RF input power levels of both desired and undesired signals. Generally, the less expensive the SDR receiver, the more sensitive it is to input overload due to poor internal filtering.

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4. Basic Filter Types

Any discussion of filters immediately goes to broad classifications and basic categorizations. Filters are broadly classified by names such as Elliptical, Butterworth, Bessel, Chebyshev, Constant-K and so on. Some of these names are after the person who worked out the solutions to the complex mathematics associated with specific filter characteristics such as minimizing variations (ripple) in the passband, transition from passband to stopband, roll-off, out-of-band rejection or phase delay. No one filter has optimum characteristics.

Filters can be categorized into four basic types: Lowpass, highpass, bandpass (*selection*) and bandstop (*rejection*) (figure 5). Lowpass and highpass filters pass only frequencies below and above a design value or *corner frequency*, respectively. A bandpass filter passes (selects) frequencies in the desired band and reduces undesired out-of-band signals. A *preselection* filter is a relatively wide bandpass filter, usually in front of the first RF amplifier in a receiver. A bandstop filter stops (rejects) undesired signals that may be within the observation frequencies but passes all others. Bandstop filters often are called band reject or notch filters, although notch filters usually are very narrow. Special application filters include diplexers and triplexers, which are discussed later.

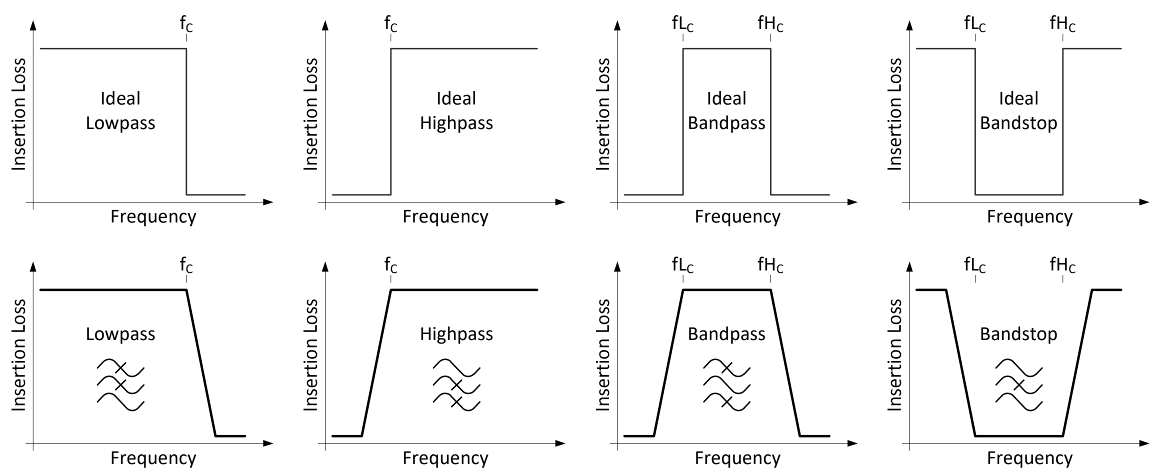

Figure 5 ~ Basic filter types. f_C is the corner or cutoff frequency (L and H indicate low and high). Upper: Ideal filter frequency response curves showing vertical band edges; this is a *brick wall* response, which is impossible to achieve in real analog filters. Lower: Filters with a sloped transition region between the passband and stopband and sharp corners are still idealized to some extent. Practical filters do not have sharp transitions at the corner frequencies as shown here but are more rounded. The steepness of the band edges and other characteristics depend on the filter design. An alternate block diagram symbol also is shown in the middle of each lower drawing. Image © 2020 W. Reeve

Ideal filters have full response (zero attenuation) at pass or inband frequencies and no response (infinite attenuation) at blocking or out-of-band frequencies. Practical filters do not have ideal responses. The block, pass and transition regions usually are tradeoffs in the filter design or are limited by the components used. For example, a filter designed to block the FM broadcast band centered on 98 MHz may have poor or reduced response in the desired band or bands such as in the HF band at 20 MHz (far below the interfering frequencies) or UHF band at 1.4 GHz (far above the interfering frequencies). All analog filters have a transition region between the passband and stopband (figure 6). Depending on the filter design, the transition region, or roll-off, may be sharp or gradual and not very steep. For a stopband or passband filter, the transition region effectively widens the stop or pass band.

Figure 6 ~ Response of a Mini-Circuits FM broadcast bandstop filter. Markers 1 and 2 are set to the 6 dB corner frequencies (other values may be used such as 1, 3, 10 or 20 dB). The FM broadcast band edges are indicated by markers 3 and 4. The passbands are flat with rounded transitions into the stopband. The response decreases by about 50 dB in a span of only 10 MHz on the lower side and about 40 dB in a span of about 12 MHz on the upper side. This filter provides over 50 dB average loss in the band between 88 and 108 MHz. Image © 2020 W. Reeve

In some applications, a single filter may not sufficiently attenuate the undesired signal. For this situation, filters may be cascaded to increase the out-of-band loss; however, there is a tradeoff in that the passband loss also will increase. In principle lowpass and highpass filters can be combined to form bandpass and bandstop filters. Lowpass and highpass filters can be cascaded (connected in series) for a bandpass response and paralleled for a bandstop response (figure 6). When this is done with separate filters, the actual response may not be as expected because of poor impedance matching between the filters themselves or between the filters and their terminations.

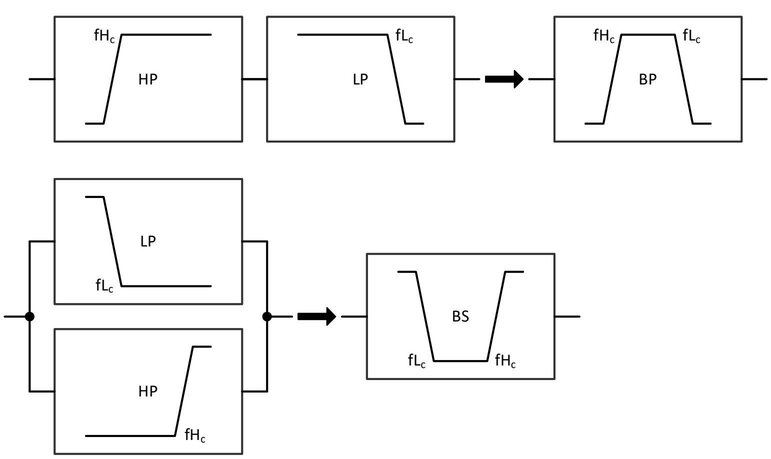

Figure 6 ~ Combining highpass (HP) and lowpass (LP) filters. <u>Upper</u>: The HP and LP filters are connected in series to obtain a bandpass (BP) filter. In this case, the corner frequencies $fH_c < fL_c$. <u>Lower</u>: The LP and HP filters are connected in parallel to obtain a bandstop (BS) filter. In this case, the corner frequencies $fL_c < fH_c$. Image © 2020 W. Reeve

Generally, individual highpass and lowpass filters cascaded to form a bandpass filter perform better if the low and high cutoff frequencies are separated far enough to minimize mismatch and interaction in the passband. To minimize undesired interaction and coupling between the two cascaded filters, they may be built in two physically separate shielded enclosures (figure 7).

Figure 7 ~ AEL MW11200-167 bandpass filter for the 225 to 400 MHz US military aerospace frequency band. This is a cascaded filter designed as two mechanically and electrically separate lowpass and highpass filters (upper and lower sections, respectively). Each section has its own cover and RF connector (see at left). Both filters are made with lumped elements and were obviously hand-built and aligned by adjusting the variable piston capacitors and by bending the coils to adjust their inductance. A copper plate shields the lowpass section, and a red insulated conductor connects the two sections through a hole between the two enclosures on the right side of this image. This conductor has significant inductive reactance at VHF and UHF and so is part of the overall filter design. The filter components are mounted on printed circuit boards that consist only of isolated pads for soldering the component leads. The enclosures are machined from aluminum blocks and have tight-fitting covers. This construction is typical of AEL filters for the HF, VHF and lower UHF bands. Image © 2020 W. Reeve

In addition to forming a bandpass filter from lowpass and highpass filters, cascaded filters can be used to sharpen a circuit's frequency response or increase the bandstop attenuation. For example, two or more identical lowpass filters could be cascaded to sharpen the roll-off at the band edge and to provide higher out-of-band loss (figure 8). The transfer function or response of the combined filter equals the product of the transfer functions of the individual filters. However, impedance matching problems can be just as severe as with the bandpass arrangement and it should be remembered that the passband loss in dB is at least the sum of the individual filter losses.

It is mechanically simple to connect connectorized filters in a series arrangement. However, if connectorized filters are placed in parallel, such as for a bandstop filter or diplexer, additional effort is required to ensure proper impedance matching and isolation. Combined filters for bandstop applications usually are designed that way from the outset. At first, it might seem that RF splitters/combiners could be used in on the inputs and outputs of individual packaged filters to isolate the filters from each other when used for a bandstop filter (figure 9); however, impedance mismatch in both the passband and stopband likely will prevent proper operation.

Filters in RF applications usually are designed for 50 ohms resistive input and output impedance (75 ohms in cable television and satellite television applications). With most filters the design impedance is a *compromise* or *nominal* impedance. In other words, practical filters are not perfectly matched to 50 ohms and the voltage standing wave ratio (VSWR) is not exactly 1.0:1 throughout their passband.

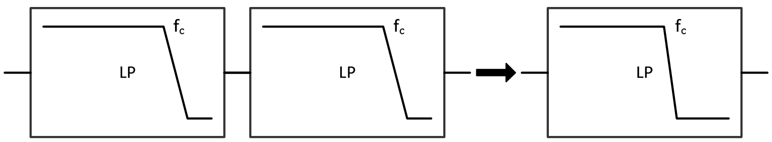

Figure 8 ~ Two identical lowpass filters may be cascaded to sharpen the frequency roll-off at the band edge and to increase bandstop attenuation. However, this also will increase bandpass attenuation and may not yield the desired response if there is poor impedance matching. Image © 2020 W. Reeve

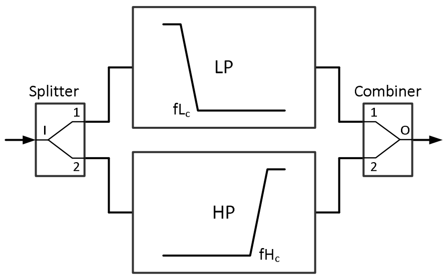

Figure 9 ~ In principle, identical 2-way splitter/combiners could be used for isolation of packaged lowpass and highpass filters when connected in parallel. However, impedance mismatch in both the passband and stopband can prevent proper operation. Also, the inband signals are subjected to at least 3 dB splitting/combining loss in each 2-way splitter/combiner for a total of at least 6 dB. Image © 2020 W. Reeve

Several related and equivalent parameters are used to specify impedance matching, including reflection coefficient, and return loss. The input and output matching characteristics of commercial filters often are specified by their VSWR but this can be readily converted to any of the other equivalent parameters (for example, see {CALC}). The in-band and out-of-band impedances may be complex (resistive and reactive components), in which case they vary with frequency. Filters can be reflective or non-reflective (reflectionless). Reflective filters reflect out-of-band energy back to the source, in contrast to non-reflective filters that absorb the out-of-band energy and dissipate it as heat. Most filters are reflective.

A *diplexer* is a 3-port filter that splits an input signal on a common port into high and low frequency ranges and directs them to separate ports – a highpass port and lowpass port (figure 10). Diplexers are bi-directional so they also will combine high and low frequency inputs and direct them to a common output port. A filter related to the diplexer is the triplexer, which has lowpass, bandpass and highpass ports in addition to the common port. Generally, there is a frequency gap between the high, low and bandpass sections of a diplexer or triplexer. This gap provides a guard-band for isolation of the ports.

In receive applications the diplexer can be used to combine the outputs from two separate antennas, say a highband and lowband antenna. The common port may then be connected to a single wideband receiver. Similarly, the output from a wideband antenna connected to the common port may be split and then connected to two separate receivers, one each for the high and low frequency bands. However, in all setups, unless the antenna impedance is well behaved and well matched to the diplexer, the combination may not perform as expected. Another application of the diplexer is to provide a path to absorb harmonics in the output of an oscillator (figure 11).

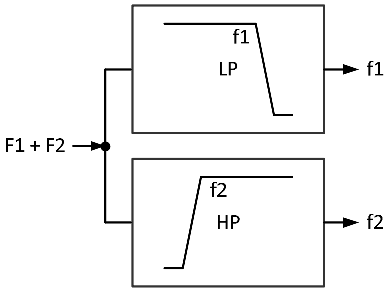

Figure 10 ~ Diplexer has a highpass and lowpass leg and is used to separate two frequency ranges from a common wideband port on right to two separate ports on left. For the situation shown, f1 < f2. Diplexers are bi-directional so, instead of signal flow from left to right as shown, signals may flow right to left. In this case, signals entering each of the two ports on right are combined at the common port on left. The two corner frequencies f1 and f2 must be separated enough so that their respective ports are sufficiently isolated. Image © 2020 W. Reeve

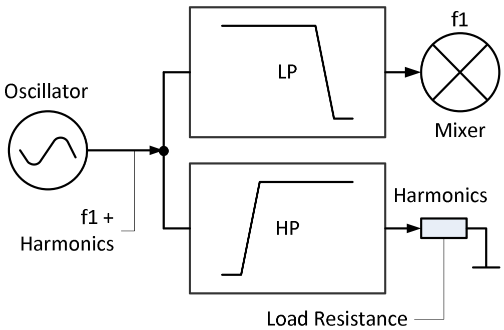

Figure 11 ~ Diplexer used to direct oscillator harmonics (on left) to a load resistance (on lower-right) where they are absorbed rather than reflected to the oscillator and cause distortion. Image © 2020 W. Reeve

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5. Weblinks, References and Further Reading

{CALC} https://www.microwaves101.com/calculators/872-vswr-calculator

{ReeveFilt} Reeve, W., Filter Measurements with a Vector Network Analyzer, 2017, available here: http://www.reeve.com/Documents/Articles%20Papers/Reeve_FilterMeasVNA.pdf

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