dbSpectra

TECHBOOK

Series

RF FILTERS

- RF Filters
- RF Distribution Design
- Antennas
- Understanding PIM
- Intermodulation
- Sensitivity

What is dbSpectra TECHBOOK series

To ensure a high-quality RF distribution system there are subjects that must be understood. dbSpectra "**TECHBOOK**" series provide simple discussions of important topics and show ways to ensure the highest quality is designed into the delivered system. Understanding these topics and working with our professional RF system engineers, will allow the design requirements to be met in the first design. Each booklet will discuss topics in as low a technical manner as possible. The **TECHBOOK** series is the first step in understanding complex and complicated RF Topics. Detailed training is available from dbSpectra that will provide more in-depth discussions and understanding. Contact dbSpectra for more information and to schedule training.

dbTECHBook editors:

- Jim Bankston
- Bryan Corley
- Graham Jones

dbSpectra

1590 E Hwy 121 Business

Bldg A Suite 100

Lewisville TX 75056

Phone: 469-322-0080

Website: www.dbSpectra.com

Introduction

This TECHBOOK will explore the concept of filter design and how it is applied to an RF distribution system. There are several ways filters are used to enhance RF distribution designs. Filters are critical in the design of transmitter and receiver distribution systems. Transmitters must be conditioned to reduce out of band emissions and receivers require additional protection from high level carriers and interference.

What is Selectivity?

To understand filter application the concept of selectivity must be addressed. Selectivity is frequency selective attenuation and will always be related to a frequency or group of frequencies. The frequency component of selectivity is the major difference between selectivity and simple insertion loss. For a filter the insertion loss will be referenced within the passband while selectivity will be characterized outside the passband. Selectivity is also referenced in receiver specifications because receivers must have a significant frequency selectivity to allow reception of one frequency and reject others. The Selectivity of a component is provided by a curve as shown in ***Figure 1***. The selectivity curve shows the frequency response of a filter with frequency as the x-axis and power level as the y-axis.

Definition of design components and terminology

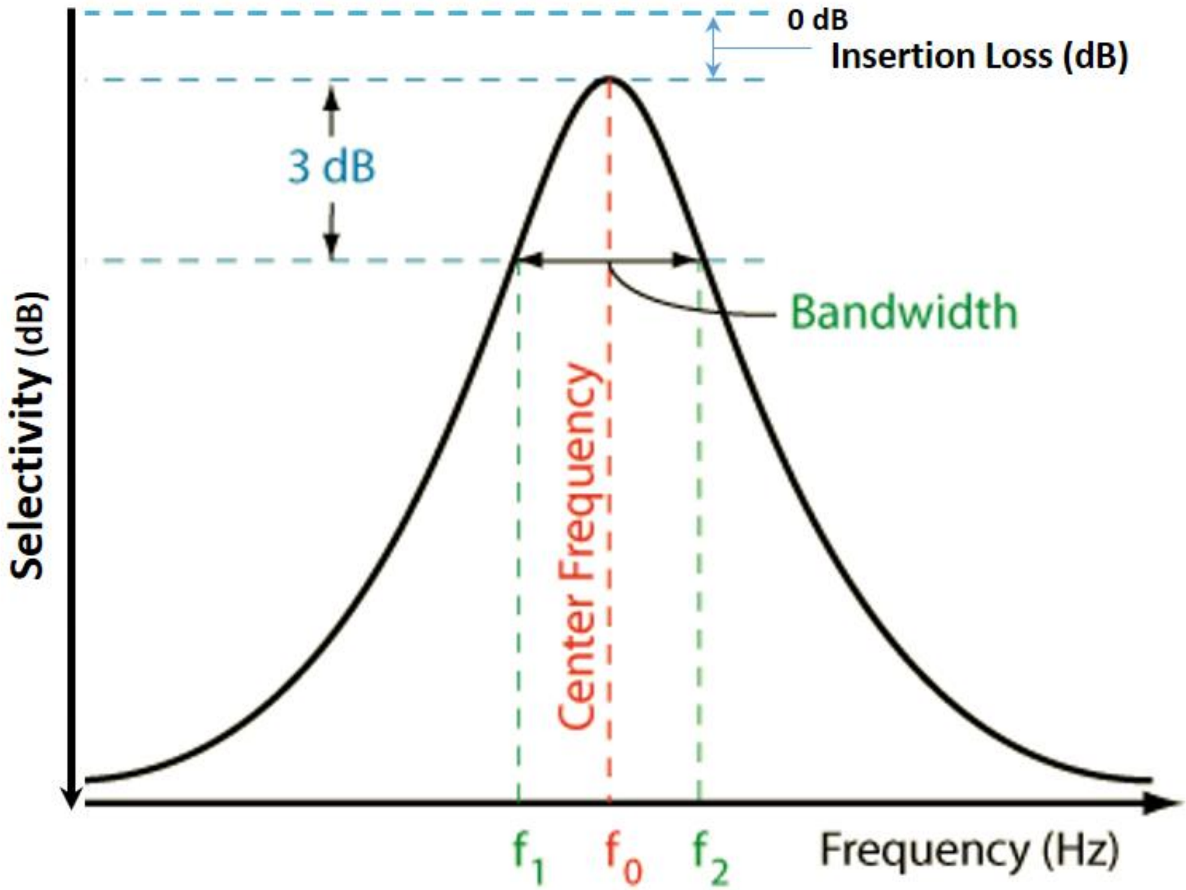


Figure 1: Definition of terminology

Cavity – The legacy building block for a frequency selective device is the cavity. While other devices provide better frequency selectivity, the cavity filter has been used for years and is still found and used on current system designs.

dB – The decibel (dB) is the increment by which the filter selectivity is measured and specified. Th dB a convenient way of showing large increase or decrease in voltage or power levels. It is related to voltage or power by the base 10 logarithm. A typical range for filter measurement is 0 to -120 dB.

Center Frequency – The center frequency is the resonant frequency to which the filter is tuned. The operation of the filter is designed around the center frequency.

Insertion Loss – The insertion loss is the minimum loss of the filter and may be associated with bandpass. The insertion loss point is the tuned operating point.

Bandwidth – The operational bandwidth is generally defined by the frequency separation between the highest frequency and lowest frequency where a 3 dB insertion loss is found. In RF filters the insertion loss may be the bandwidth over which the specified insertion loss exists. The bandwidth may be wide (several MHz) as found in a bandpass filter or sharp (tens of kHz) as characterized by a single cavity. The bandwidth may also be called the passband of the filter.

Q or Quality Factor – Quality factor is used to define the selectivity of a filter with a higher value meaning higher selectivity. Mathematically, Q equals the center frequency divided by the bandwidth.

Filter Types

Bandpass Cavity – The first selectivity component we will examine is a simple band pass cavity ***(Figure 2).*** The bandpass cavity, sometimes called a resonator or cavity resonator, is the basic building block for many complex filter systems. A cavity is a resonant device that is tuned to one frequency or one narrow band of frequencies. At the resonant or tuned frequency, the attenuation will be minimal (normally less than 2 dB depending on the Q of the cavity). As the observed frequency increases or decreases outside the passband the attenuation increases significantly. The increase in attenuation or insertion loss is called selectivity, rejection, or isolation. While the bandpass filter is characterized by steep skirts on either side of the bandpass, the actual bandpass is normally only a few hundred kHz wide and is dependent on the Q of the filter. At the resonant frequency, the Z (impedance) will be 50 ohms and increase as the attenuation increases. Some of the unwanted energy is absorbed by the cavity, but most is reflected back to the source due to impedance mismatch caused by the change in the cavity's impedance. The operation can be considered a frequency controlled variable impedance.

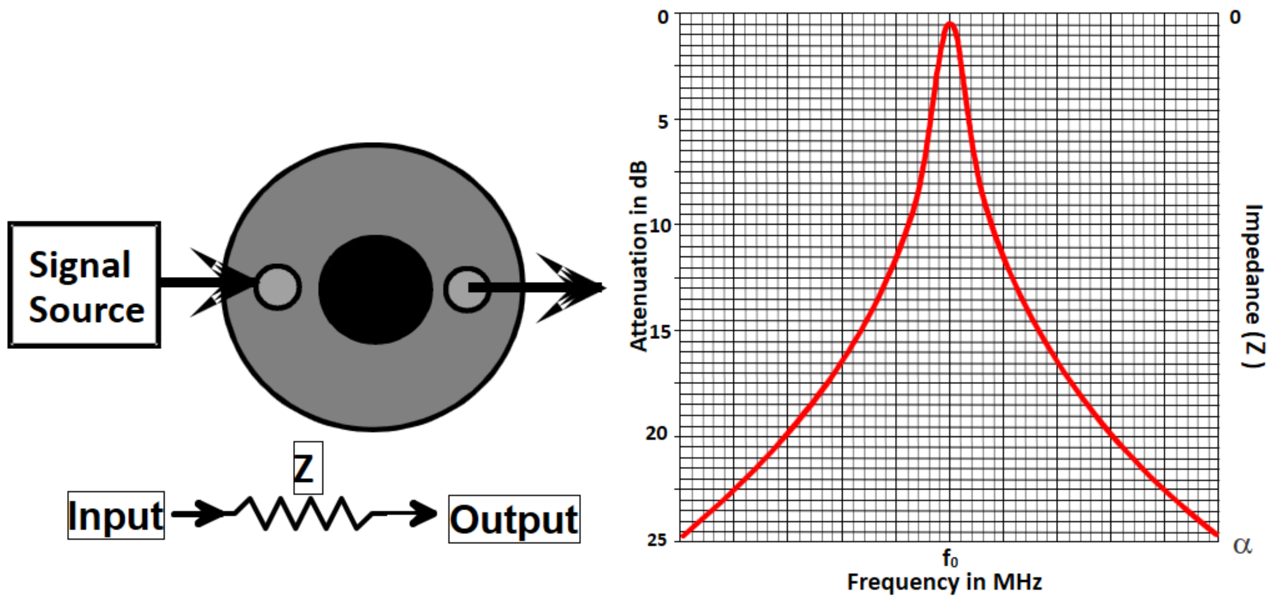


*Figure 2: **Fundamental characteristics of a Bandpass cavity***

A single cavity is limited in the amount of obtainable selectivity. The maximum selectivity achieved is called the depth of selectivity or isolation. As the cavity selectivity is examined further and further from the center frequency the selectivity will flatten and bottom out. A rule of thumb is that a single cavity will obtain 25 – 35 dB of obtainable selectivity before it completely flattens out and stops increasing. The slope of the selectivity or how fast the selectivity increases beyond the bandpass, is controlled by the Q of the filter. As the Q is increased, the selectivity will also increase while the bandwidth decreases. For a specific filter design, increasing the Q will also increase the insertion loss of the filter.

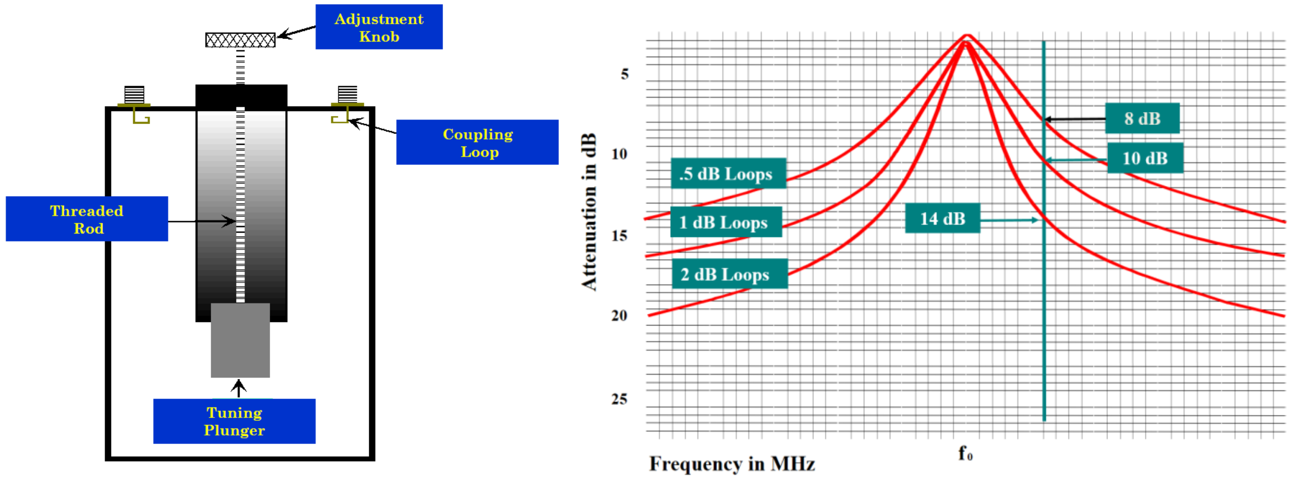


Figure 3: ***Selectivity vs. Q of cavity***

Most cavity filters have adjustable loops. Adjusting the loops allows the Q of the cavity to be increased or decreased as needed. When the Q is increased with the loop, the Q is said to be electrically adjusted. Increasing the electrical Q of a cavity comes with an increase in insertion loss. ***Figure 3*** demonstrates how adjusting the loops for improved selectivity increases the insertion loss.

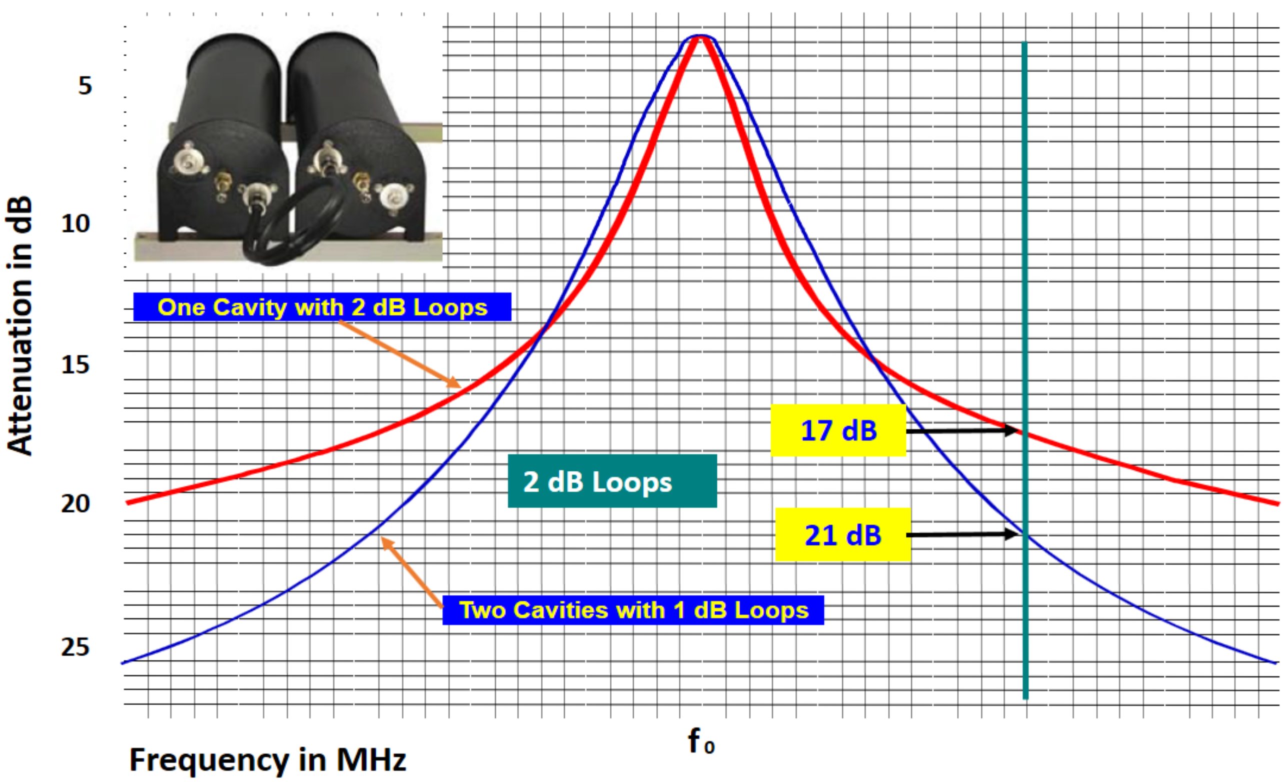


Figure 4: ***Multiple cavities to obtain improved selectivity***

Cascading filters can improve selectivity without the penalty of greater insertion loss. Coupling multiple filters is more efficient than trying to obtain increased selectivity in a single cavity. ***Figure 4*** shows that using two cavities with 1 dB loops each will provide over 21 dB of selectivity where trying to use only one cavity with 2 dB loops only delivers 17 dB of selectivity. An additional benefit in using multiple cavities is the depth of the selectivity far away from the center frequency. While the typical selectivity depth of a single filter is less than 30 dB, the depth of two cavities (with equal Q) increases to about 60 dB.

Another way to increase the Q of a cavity is to increase the volume or physical size of the cavity. This is called changing the mechanical Q. The mechanical Q is a design change not an adjustment. Larger cavities will allow improved selectivity while not significantly increasing the insertion loss. In most cases the depth of the selectivity will not change with a larger cavity. For example, dbSpectra offers VHF cavities with eight inch and five inch diameters.

Notch Cavity *(Figure 5)* – The band-reject cavity filter, or notch filter, is a high Q resonant circuit designed to attenuate a narrow band of frequencies while allowing all other frequencies to pass through with only slight attenuation. The notch filter can be considered the opposite of the band pass filter. Energy at the resonant frequencies, or center of the notch, enters the cavity and is reflected back, out of phase with the original. This creates a virtual short across the transmission line and results in a high percentage of the applied energy, at the resonate frequency, being reflected back toward the source.

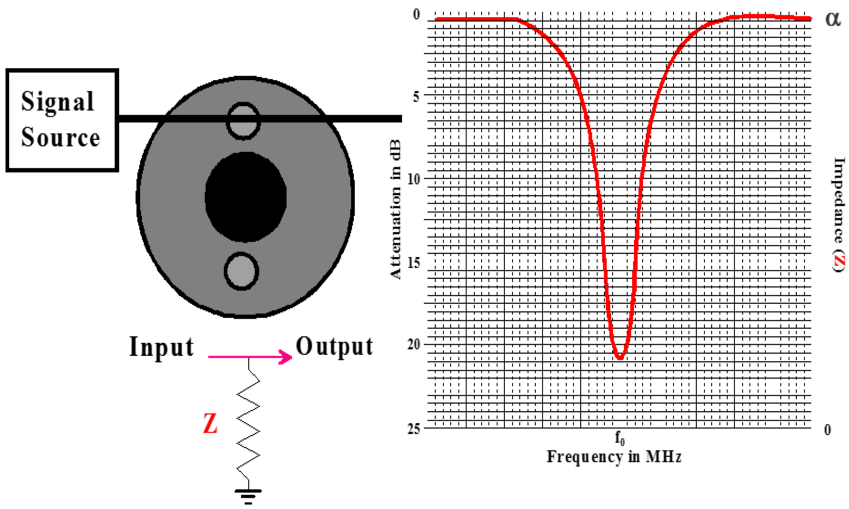


Figure 5: Notch Filter characteristic

Maximum attenuation occurs at the center (resonant) frequency while all others are attenuated to a lesser degree depending on their distance from the center frequency. At the resonant frequency, the filter has a very low impedance approaching 0 Ohms. This effectively creates a short across the line. A small amount of the energy is absorbed into the cavity and dissipated but most of the energy is reflected back to the source due to the impedance mismatch created by the near short frequency. It is very important to understand that a notch filter only provides attenuation at one frequency or one small band of frequencies. Above or below the center frequency or bandpass the filter looks like a high impedance and provides no attenuation.

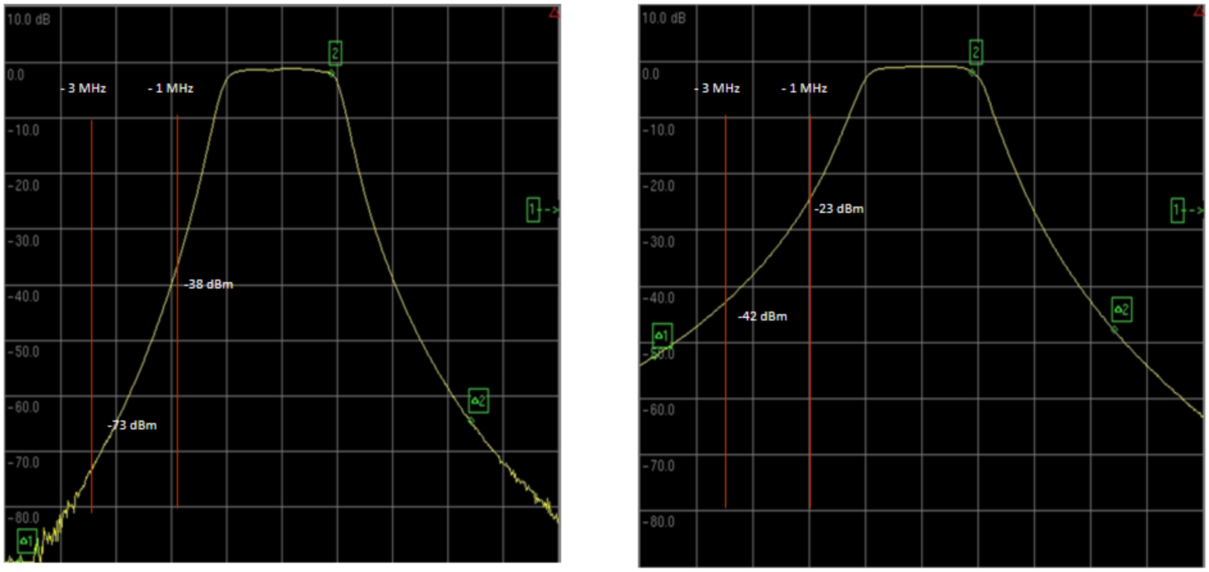
The spacing between the desired frequency and the frequency to be notched or rejected can be a few megahertz or 100 KHz or less depending upon the cavity's Q. If the attenuation or slope of the selectivity obtained is not adequate, several notch filters can be cascaded to improve the depth and slope of the notch.

Pass-Reject Cavity – Another useful cavity type is the pass-reject type cavity that is capable of providing both pass and reject filter characteristics. The trade-off is that both the reject or notch depth and the bandpass response are not as pronounced as pure reject or pass type cavities.

Milled Filter Technology – The most significant advancement in filter technology over the past 30 years is the milled filter. ***Figure 6*** shows example Milled filters used for various applications. Milled filters get their name from the way they are constructed. Instead of individual cavities being phased together, the milled filter is computer designed from a block of aluminum which is milled out to create the housing with multiple internal cavities. Milled filters are much smaller in size, have lower insertion loss for a given selectivity, and deliver significantly more selectivity depth. The biggest disadvantage of a milled filter is that it cannot be tuned in the field.

Figure 6: ***Milled Filter applications***

As more radios are being collocated the filter requirements have increased to allow the radios to operate without interference. ***Figure 7*** shows a comparison between milled filter performance and standard cavity configurations. Where a cavity provides only 25 – 30 dB of selectivity depth, the milled filter selectivity continues to increase as the off-frequency increases. The depth of selectivity can approach 100 dB far away from the center frequency. It is very important to note that a milled filter cannot be field tuned. dbSpectra has led the industry in development of milled filters and offers milled filters in all bands and various applications.



New Milled Filter

Multi Cavity Preselector

Figure 7: ***Milled Filter vs. Standard Cavity performance curves***

Not only do milled filters provided advantages compared with cavity bandpass filters but also compared with legacy filters. ***Figure 8*** and ***Figure 9*** show a comparison of legacy filters compared with a milled filter design.

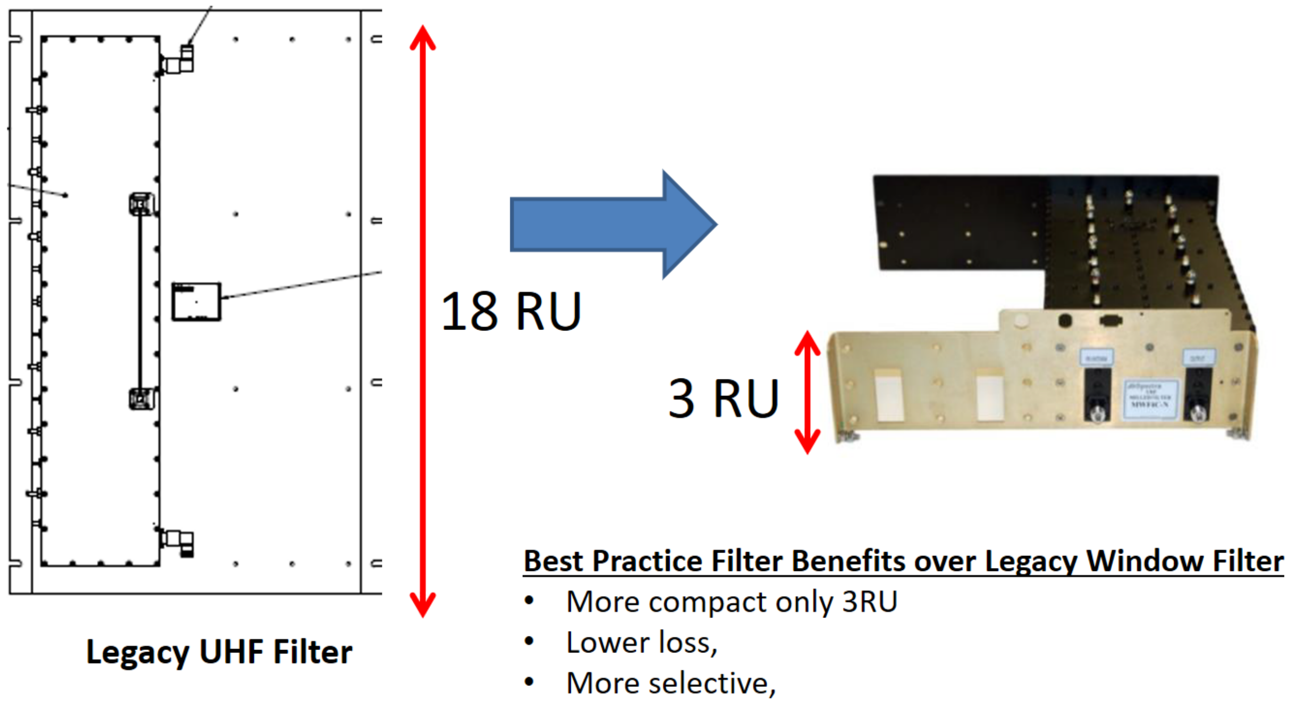


Figure 8: Bandpass milled filter compared with Legacy filter

Figure 9: Bandpass Duplexer response compared with Legacy filter response

Filter Applications

The bandpass and notch filters are only building blocks for specific applications. There is a misunderstanding of filters that simply adding a filter will solve all problems. This cannot be further from the truth. Filter application must be engineered for a specific purpose.

To understand filter application in RF designs the characteristics of the transmitter and receiver must first be understood.

Transmit Sideband Noise – A transmitter generates a single carrier on a specific frequency at power levels of typically 50 W (+47 dBm) to 100 W (+50 dBm). While most the transmitted energy is on the specified frequency, other energy is also generated. In addition to transmitter harmonics, broadband noise outside the transmitters allocated bandwidth is also radiated. FCC and ITU Regulations limit the radiation of noise and harmonics to be attenuated by 43+10log (P) dB at great than 250% of the authorized bandwidth. For a 100 W transmitter, that would be 63 dB attenuation.

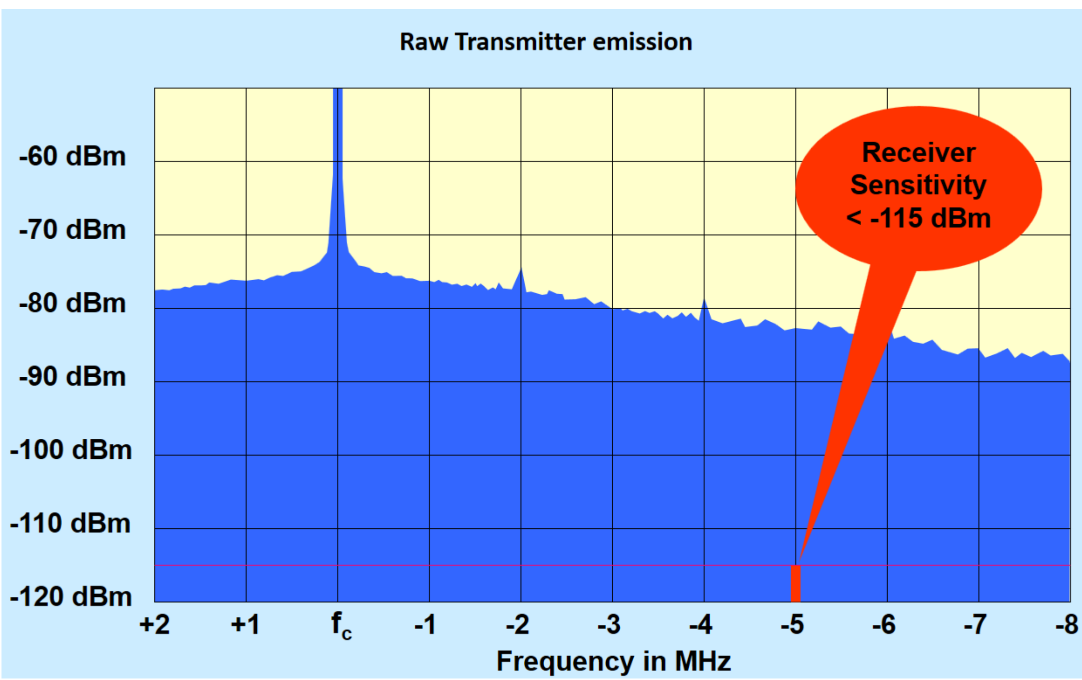


Figure 10: Sideband noise emitted from a Transmitter

The RF energy emitted above or below the transmit frequency is called Sideband Noise (SBN). ***Figure 10*** shows a representation of the radiated energy by a transmitter. While the SBN is attenuated significantly below the carrier frequency, it is significantly above the sensitivity of receivers. There is no difference between energy radiated from a subscriber talking into a base receiver than energy emitted by a transmitter on the same frequency.

If a transmitter generates the carrier frequency at 100 W (+50 dBm) and the receive sensitivity is -115 dBm, the dynamic range of operation is greater than 165 dB. This means that the sideband noise energy must be reduced by over 165 dB. The transmitter reduces the sideband noise as part of its design, but more reduction is required for the transmitter and receiver to coexist. It is important to note that sideband noise must be eliminated at the transmitter. After it is generated it is undesired energy on the receive frequency. Any emission causing interference must be eliminated at the source.

If the sideband noise is not suppressed below the sensitivity of the receiver the operational sensitivity will be degraded and coverage will be affected. Considering regulated limit of 63 dB attenuation of noise and harmonics, the level of SBN might as high as -13 dBm. However, SBN decreases as the separation in frequency between the transmitter and receiver increases. Typical duplexer attenuation requirements are 80-110 dB. With a conservative margin over actual requirements being desirable.

- **Reducing Sideband Noise with a Bandpass Filter** – When using a bandpass filter to reduce sideband noise the filter is placed in line with the transmitter. All RF energy transmitted will pass through the bandpass filter and have little attenuation at the center frequency but increase significantly further from the center frequency. ***Figure 11*** shows the improvement possible with a bandpass filter. The amount of improvement will depend on the Q of the filter and the number of filters used. To achieve the necessary sideband noise suppression, it may be necessary to use multiple filters. A controlling factor on how much filtering is required is the frequency spacing between the transmit center frequency and the point of protection. The amount of frequency spacing is called the guard band.

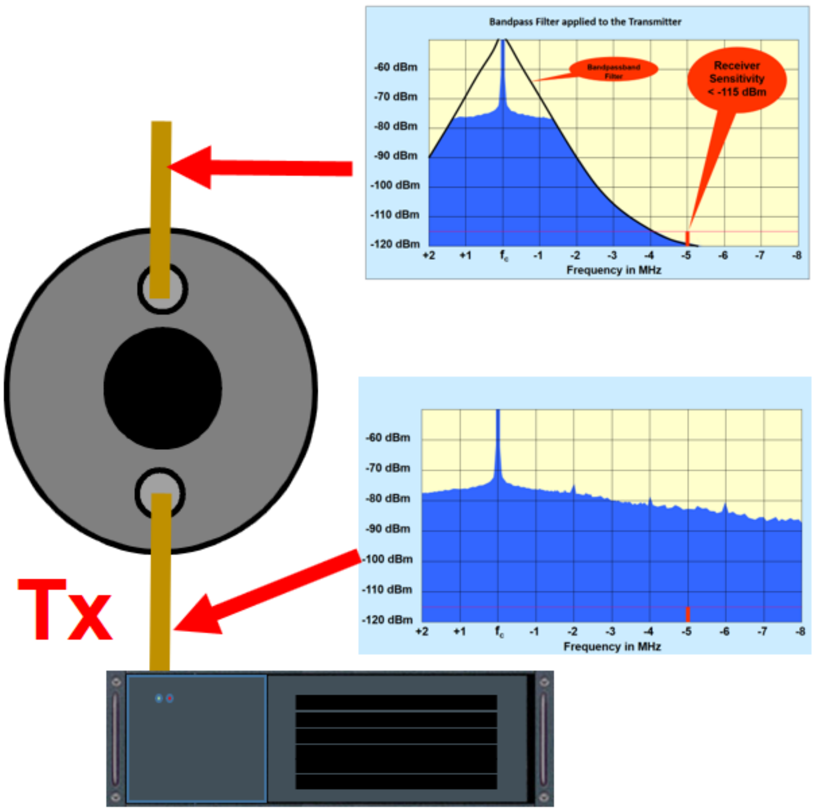


*Figure 11: **Bandpass Filter used to reduce sideband noise***

- **Reducing Sideband Noise with a Notch filter** – A notch filter can be used to reduce sideband noise but it should be done with care. ***Figure 12*** shows the reduction that can be obtained with a notch filter. Notch filters have the advantage of reducing the noise very close to the transmit carrier. The guard band can be a few hundred kHz for a notch filter where a bandpass filter may require over 1 MHz and possibly multiple filters to obtain the same sideband noise reduction. The major disadvantage with the notch filter is that it only reduces the sideband noise on one specific frequency or one very small band of frequencies. Above or below the notch, the selectivity will be negligible and little benefit will be realized. This type of filtering should be limited to sites without collocated transmitters or multiple receivers in the same band.

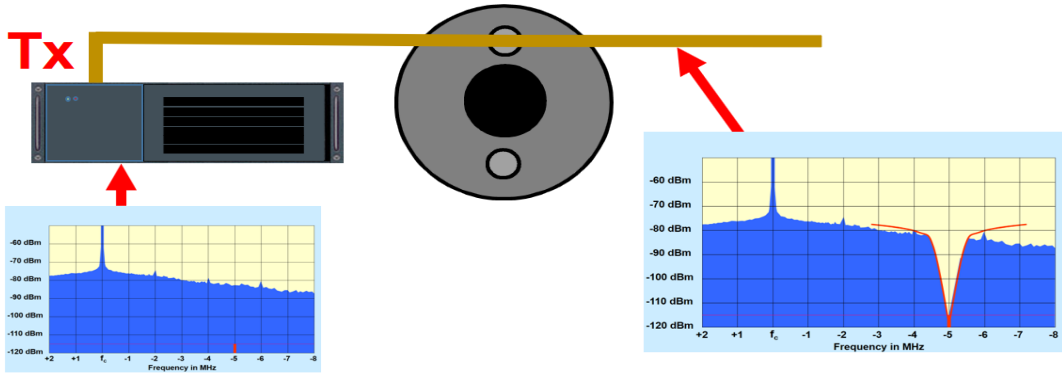


Figure 12: Notch Filter used to reduce sideband noise

- **Receiver Filter** – Communications receivers have designed-in internal filtering that provides selectivity to help protect against high-level carriers from entering the receiver. In repeater applications, the filtering is limited and must be supplemented to protect from its own transmit carrier and other transmitters collocated on site. Receivers can guard against carriers below -35 dBm but must have additional filtering when strong carriers above -35 dBm are present. For example, the level present on site from a collocated transmitter may be greater than 0 dBm. In this case, additional filter must be used that provides the filtering required to fully protect the receiver. The filter that precedes the receivers is called the preselector or simply receive filter. When many frequencies are located on a site or in the nearby area, a bandpass filter or preselector is normally required. When an amplifier is used in front of a receiver or group of receivers (as in the case of a receive multicoupler) the preselector is mandatory to protect the amplifier and receiver. An external receive amplifier should **NEVER** be used without a preselector. Filtering greater than 60 dB is normal to achieve complete isolation from transmitter carriers. Filtering required may vary depending on antenna isolation and guardbands provided.

Duplexer application of filters – When two-way communications began, technology allowed transmitting and receiving on a single frequency (simplex operation). In this application, an external filter was applied to both the transmitter and receiver by connecting the filter between the radio antenna port and the antenna. As radio systems evolved, base stations and even mobiles were design to allow duplex operation. Duplex operation means the radio can transmit and receive simultaneously on different frequencies.

When a transmitter and receiver are connected to a single antenna the RF distribution system used is called a duplexer. The duplexer combines the transmit sideband noise filtering and receive preselector filtering into a single assembly. The filtering provided stills follows the requirements outlined to suppress sideband noise and protect against transmit carriers, but also must phase these two networks together to a single antenna. There are several configurations for a duplexer which makes it important to choose the one that fits the application.

- **Notch Duplexer *(Figure 13)*--** The simplest duplexer is the notch duplexer. The notch duplexer uses multiple notch filters to achieve the necessary filtering. The pure notch filter provides a flat low insertion loss response up and down in frequency until some distance in frequency away where a steep notch will exist. The notch can provide a high degree of isolation (80 dB is typical) depending on the number of cavities and the frequency separation. However, the flat response around the pass frequency means that the receiver is not protected from other nearby transmitters and that other receivers near the transmit frequency are not protected from the transmitter's sideband noise. Due to this characteristic, notch duplexers should not be used at multiuser sites. In most cases the notch duplexer is only used as a mobile duplexer in subscriber vehicles.

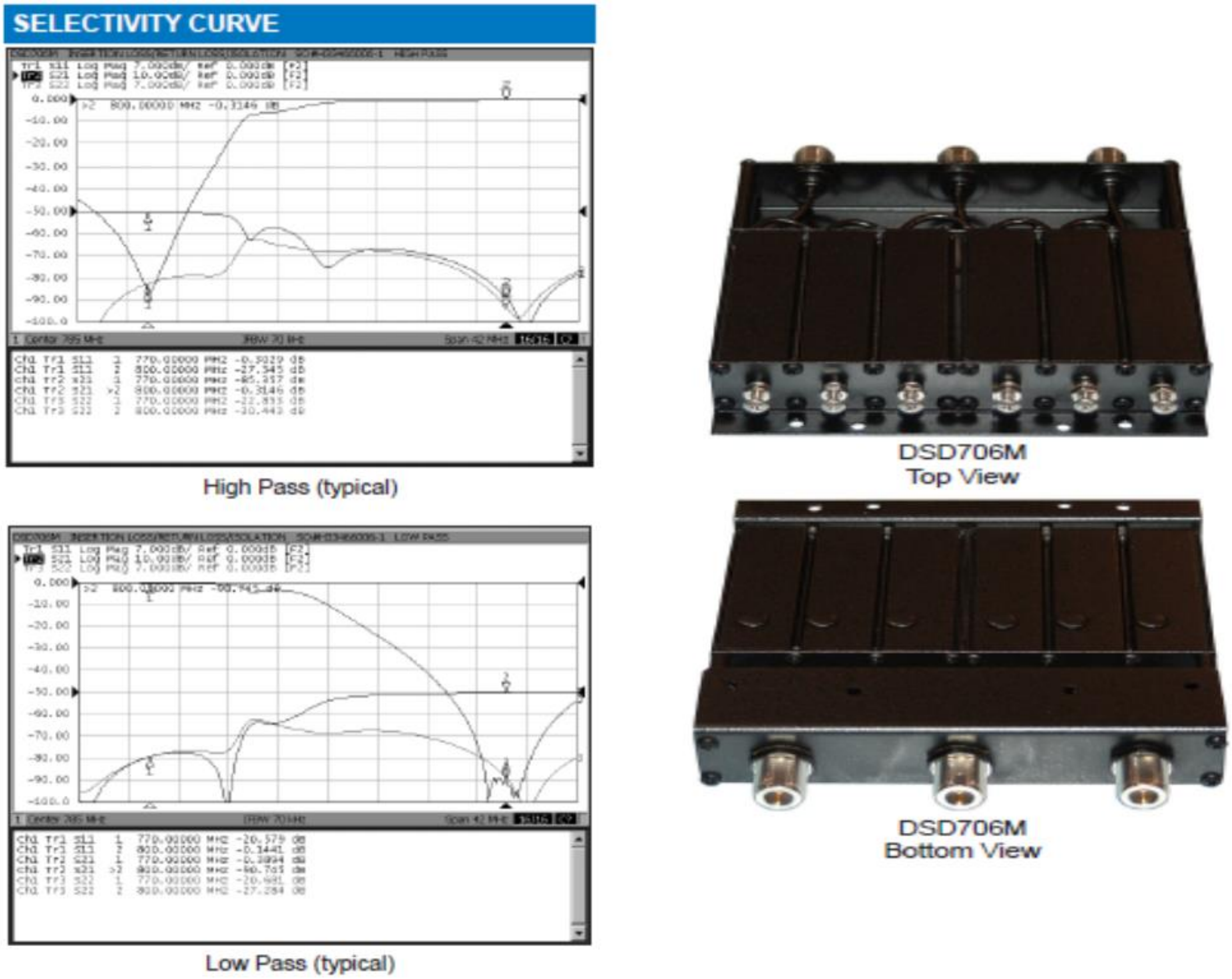


Figure 13: Notch Duplexer

- **Bandpass-Reject Duplexer** ***(Figure 14)*** – Another type of duplexer is the bandpass-reject duplexer. The bandpass-reject duplexer uses pass-reject filters to achieve the necessary filtering. The bandpass-reject duplexer attenuates other frequencies around the pass frequency, but the degree of selectivity is limited and varies with the amount of guardband. The bandpass-reject type duplexer should judiciously be used on multicarrier sites. There is a risk of degradation, interference, intermodulation or desense if other transmitters are too close in frequency to your receiver or you may interfere with other receivers if their frequency is too close to your transmitter. DbSpectra offers bandpass-reject type duplexers in all major land mobile radio bands (VHF through 800 MHz).

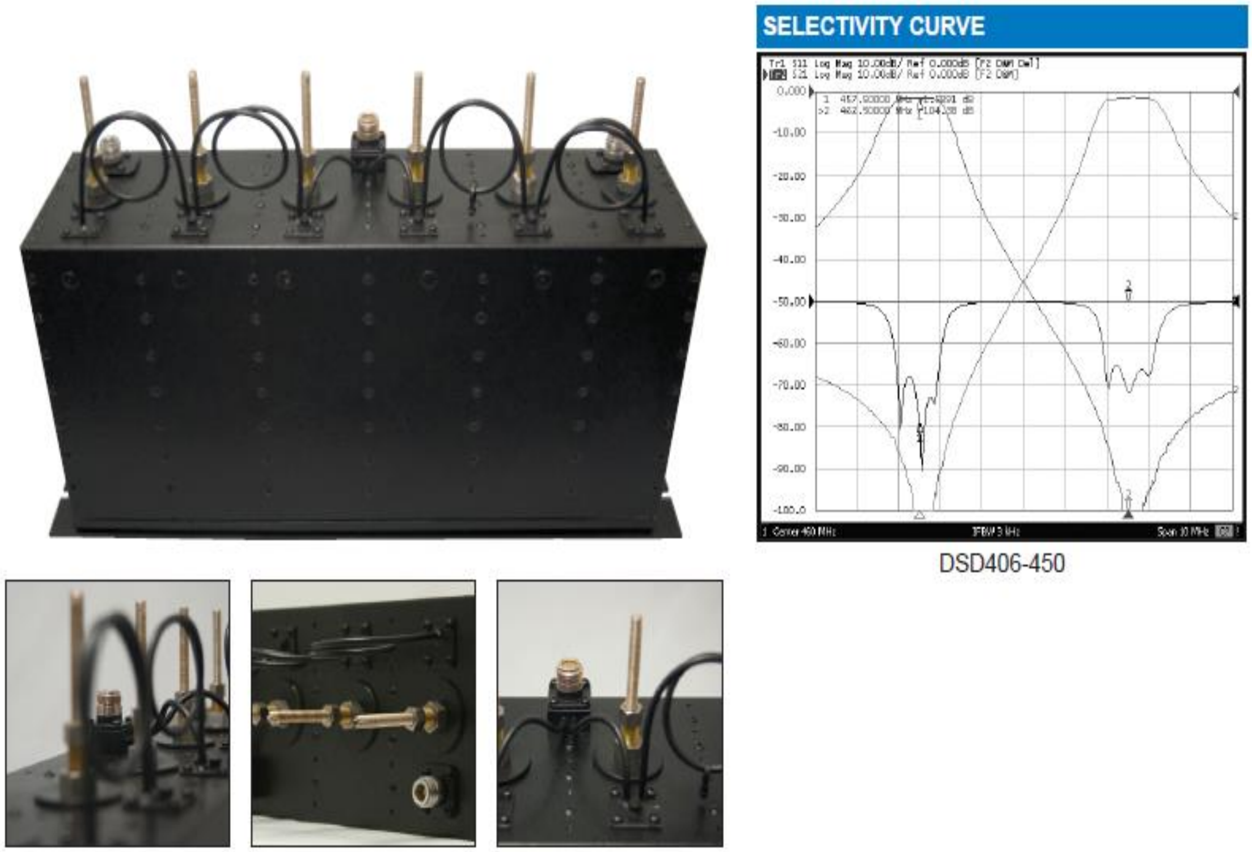


Figure 14: ***Band-Pass Reject***

- **Bandpass Duplexer** – Bandpass or window filter duplexers utilize filters with bandpass characteristics. Frequencies within the bandpass of the filter will pass with little attenuation. Frequencies outside the bandpass will be attenuated by the selectivity of the filters. The objective is still to reduce the transmitter sideband noise and reject high level carriers into the receiver. This type of filter may have a bandpass of a few hundred kHz or several MHz depending on frequency band and the design of the bandpass duplexer. The window filter duplexers offered by dbSpectra are design using milled filter technology. The bandpass duplexer ***(Figure 15)*** is the best choice for sites with multiple transmitters and other users operating in the same band. The bandpass duplexer uses two bandpass windows to filter the transmitter and receiver frequencies. The selectivity obtained is common to all frequencies above or below the bandpass frequency.

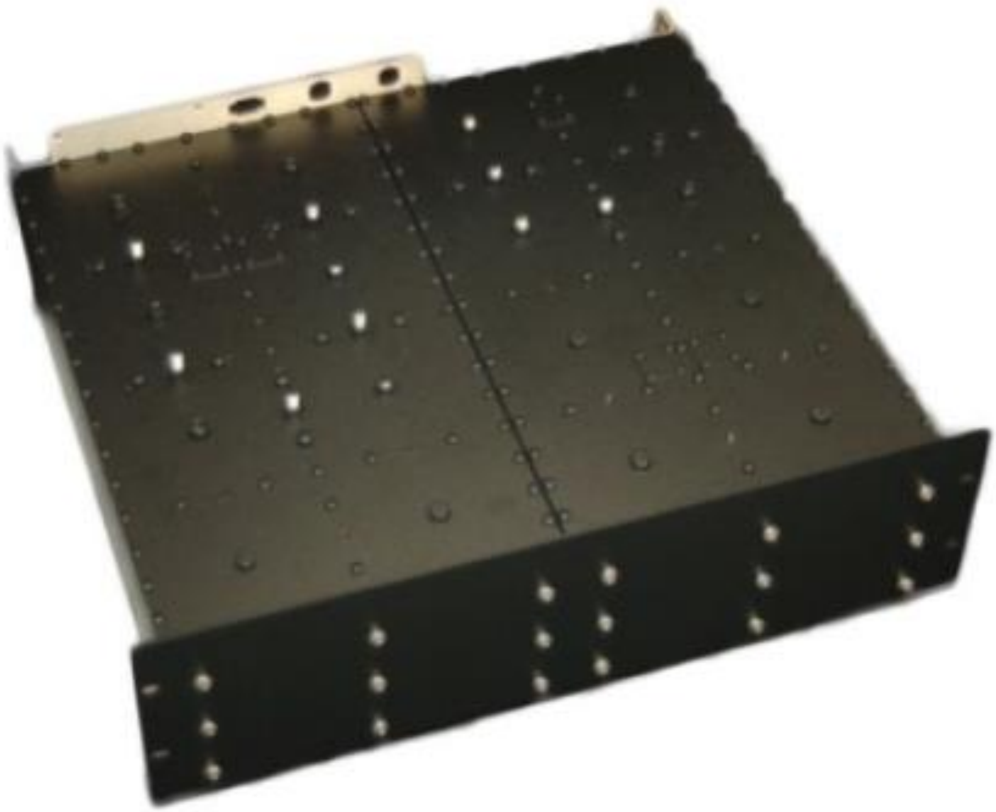


Figure 15: Bandpass Duplexer

Duplex System – Previous duplex discussions focused on components to allow duplex operation. Unfortunately, while the components alone may allow proper filtering when used alone, they do not provide the best system performance on dense sites with other collocated transmitters. Transmitters require isolators to prevent transmitter intermodulation and the receiver needs additional amplification to allow the best sensitivity possible. In the past, these components needed to be acquired separately and integrated into the duplexer design. dbSpectra provides all the components required for maximum performance in a complete duplex system. Both the receive and transmit filters are bandpass and allow any frequency within the bandpass of the filter to be used. No tuning or alignment is required within this bandpass.

- **Single Channel Duplex System** – The single channel duplex system ***(Figures 16 and 17)*** allows a transmitter and receiver to operate at the highest performance possible.

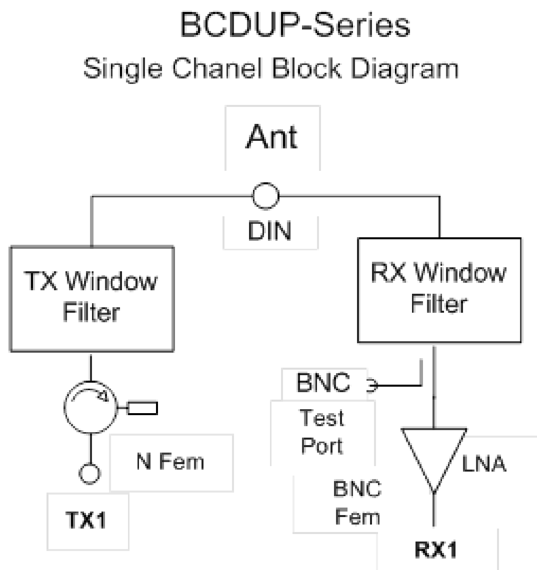


Figure 16: ***Single Channel Duplex System***

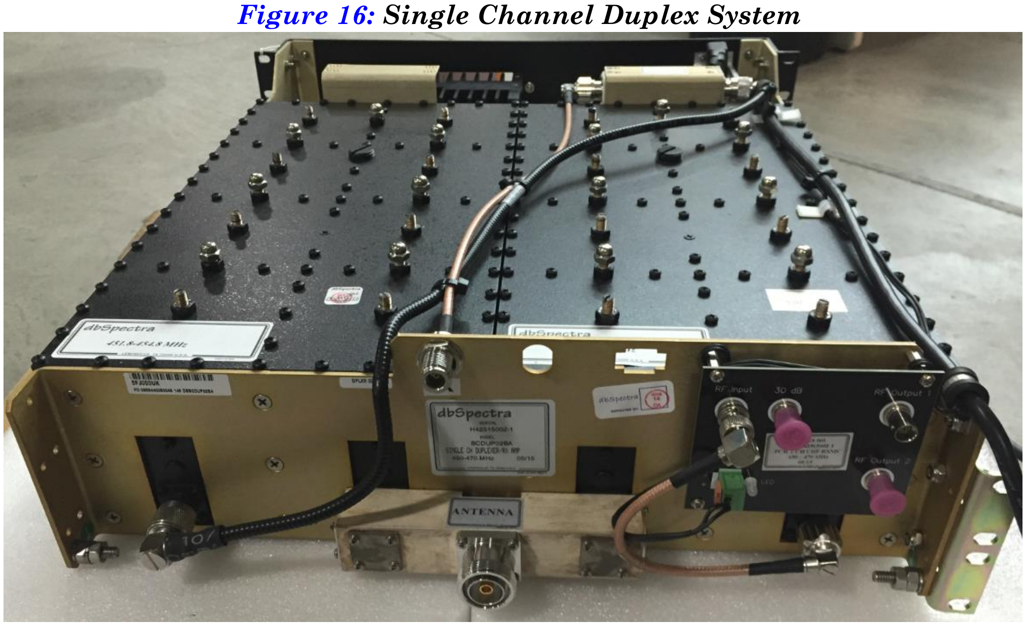


Figure 17: ***Example of a single Channel Duplex System***

- **Two-Channel Duplex System** – The two-channel duplexer combines two transmitters and two receivers together onto a single antenna. In the past multi-channel duplexing was discouraged but the new two-channel duplex system is designed to provide very low PIM characteristics and minimize the risk of interference. This new design concept reduces the cost and significantly reduces the size of the RF distribution system. Used in conjunction with dbSpectra multi-element collinear antennas the two-channel duplexer offers opportunities never previously available. ***Figure 18*** shows the components included in the two-channel duplexer and ***Figure 19*** shows the actual products available.

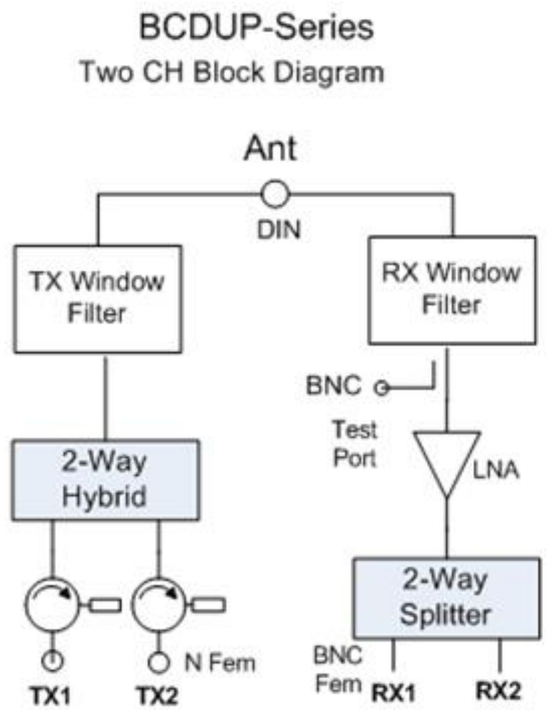


Figure 18: Two-Channel Duplex System drawing

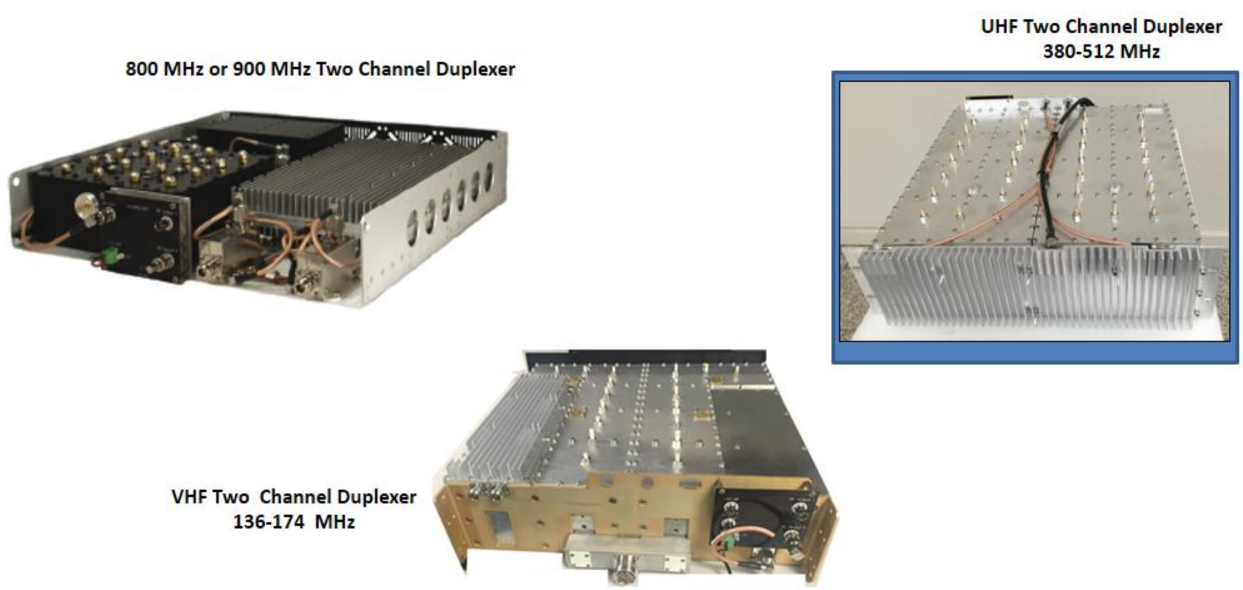


Figure 19: Two-Channel Duplex Systems

The two-channel duplex system can be used as a building block to economically combine 4 channels, 6 channels, or even 8 channels using multiple antennas ***(Figure 20).*** Using this configuration with a dual antenna also requires less tower space since only a single antenna radome will be required.

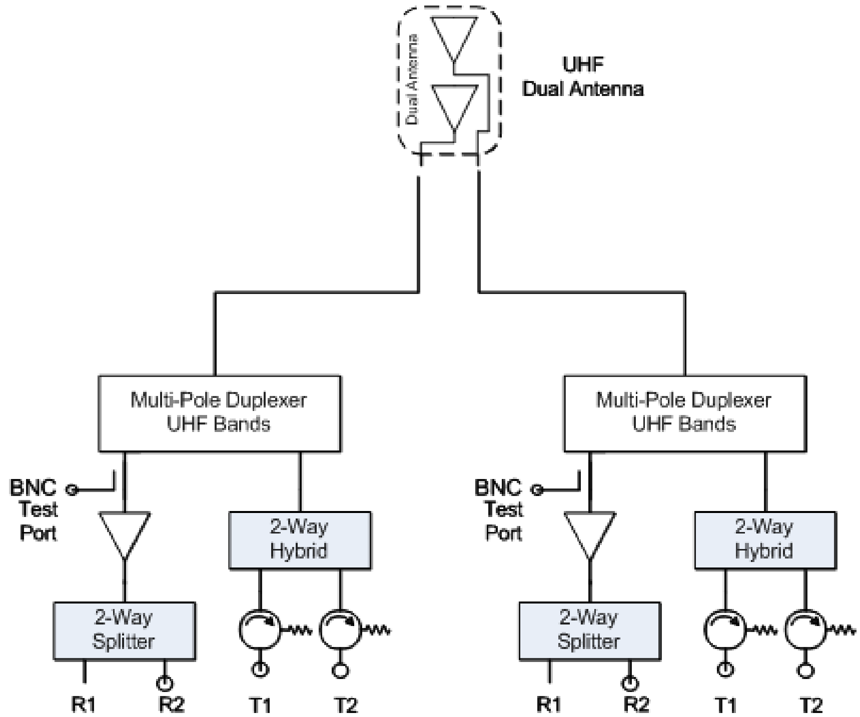


Figure 20: ***Four Channel System Using 2 CH Duplexer Configuration***

Figure 21 shows the comparison between the typical 4 channel RF distribution system and two, two-channel duplex systems.

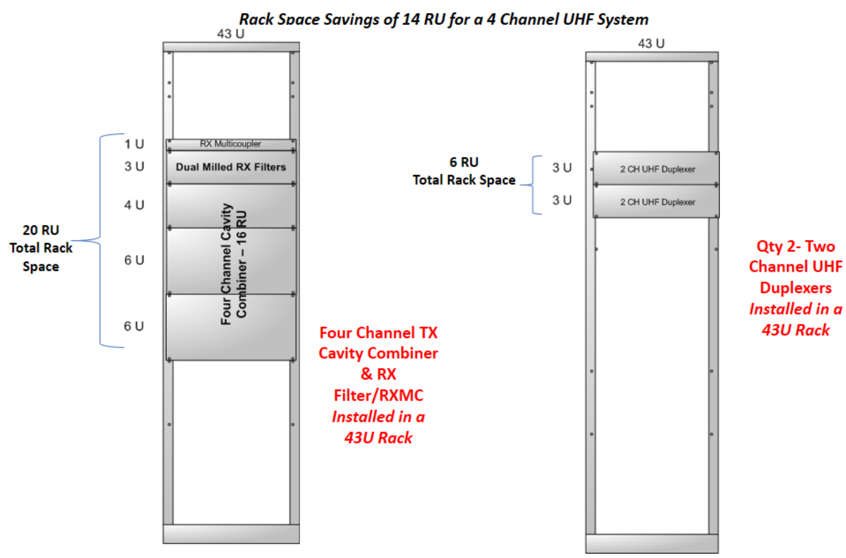


Figure 21: ***Rack comparison of Two-Channel Duplexer***

There are several advantages when designing multi-channel systems with the two-channel duplexer:

- Turn key solution provides combining, duplexing and receiver multicoupler capability all with one model number.
- Milled Filter Design for maximum selectivity
- Low Loss, Compact & Highly selective for maximum receiver performance.
- Can be adjusted to meet unique passband and isolation requirements
- Up to 8 channels can be supported with only two antennas using dual or triple models.
- PIM Tolerant (100% PIM tested)
- Models are designed and tested to deliver very low PIM
- Saves valuable rack space for VHF and UHF Applications
- No Tx – Tx spacing requirements
- No tuning when changing frequencies
- Broadband operation
- Optimum isolation inherent in design
- Lower cost
- Less rack space
- Plug N Play

Transmit Combiners

The transmit combiner is used when multiple transmitters are combined to a single antenna. Combining is important in conserving the valuable tower or building roof space. Combiners allow multiple transmitters to share a single antenna and feedline thus reducing cost, wind loading and weight stress of multiple antennas and feedlines while, if done correctly, reducing the chances of interference between users at the site.

The objective of the combiner is the same as the duplexer, reduce the sideband noise, but on multiple frequencies. An important operational specification is the transmit to transmit frequency separation. The Tx – Tx separation identifies the minimum frequency spacing that should be considered in the frequency plan. If this separation is less than recommended the insertion loss will increase.

When multiple frequencies are combined the possibility of the frequencies mixing and producing intermodulation is high. To mitigate this risk any combiner chosen should be PIM hardened to minimize PIM. The higher the PIM rating the lower the generated intermodulation and risk. See TECHBOOK on PIM for more information on the risk of PIM. dbSpectra offers a free service of performing a computerized frequency analysis and intermodulation (FAIM) study when quoting combining systems or when an order is placed. Depending on the actual band and frequencies, sometimes special, custom designs are needed.

Even with good design and construction the risk of PIM resides in all combiners. For this reason, the maximum number of channels combined should be considered. For VHF and UHF, the recommended limit is six channels. For 700/800 MHz, the recommended number is twelve channels. Duplexing transmitter combiners should be done with care. While higher order intermodulation carriers are minimal risk with a standard transmit combiner, duplexing removes the antenna separation and increases the risk of intermodulation. See TECHBOOK on Intermodulation for more information on this subject.

Transmit combiners have several components used to filter and combine the frequencies together to a single antenna. ***(Figure 22)***

- **Isolator** – The isolator is a unidirectional RF device that allows RF energy to pass in the forward direction with little attenuation while providing high attenuation in the reverse direction. The isolator protects transmitter from high level RF energy within the combiner and on the site, that can produce transmitter intermodulation.
- **Combiner Filter** – The combiner filtering consists of a single or multiple cavities (usually bandpass) that reduces sideband noise and, along with a coaxial combining harness, bridges each

frequency together onto a single antenna. If properly designed, each frequency will electrically appear to be a single network.

- **Transmit Window Filter** – The transmit window filter is a low insertion loss bandpass filter that is used to supplement the combiner filter to further reduce the sideband noise. The transmit window filter passes all frequencies within the bandpass of the combiner. An additional advantage of the transmit window filter is to minimize Passive Intermodulation (PIM) in the combiner and reduce the risk of higher order intermodulation products.

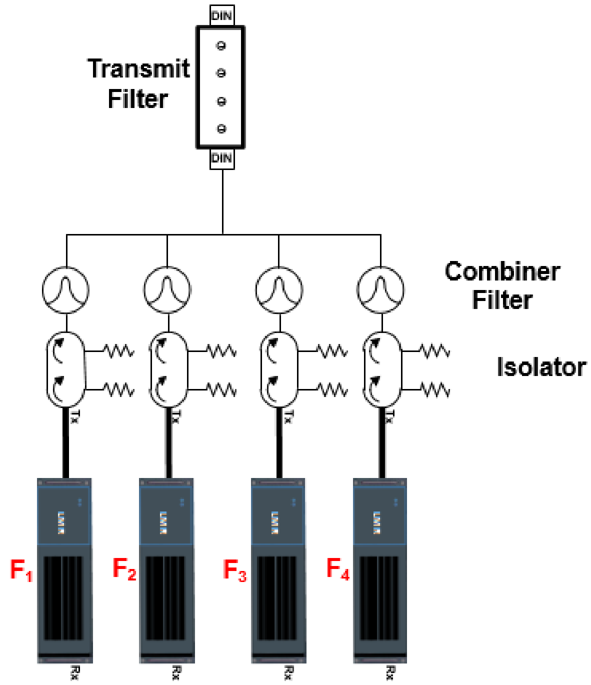


Figure 22: Transmit Combiner

Current Combiner Technology

Recent improvement in filter technology has allowed new combiner filters to be available. Recent ceramic designs at the 700, 800 and 900 MHz bands provide a significantly improved performing combiner. *(Figures 23 and 24)*

Advantages of the ceramic design over conventional combiners are:

- Small package size: 3 channels – 4 RU, 6 channels – 8 RU, 12 channels – 12 RU
- Single channel expansion kits available

- Robust isolator design with test port.
- Any frequency any port tuning capability.
- No warm-up time required for tuning
- Lower cost than standard cavity combiners with 150 kHz channel to channel spacing
- 700 MHz, 800 MHz, and 900 MHz versions
- Lower insertion losses vs legacy combiner designs.

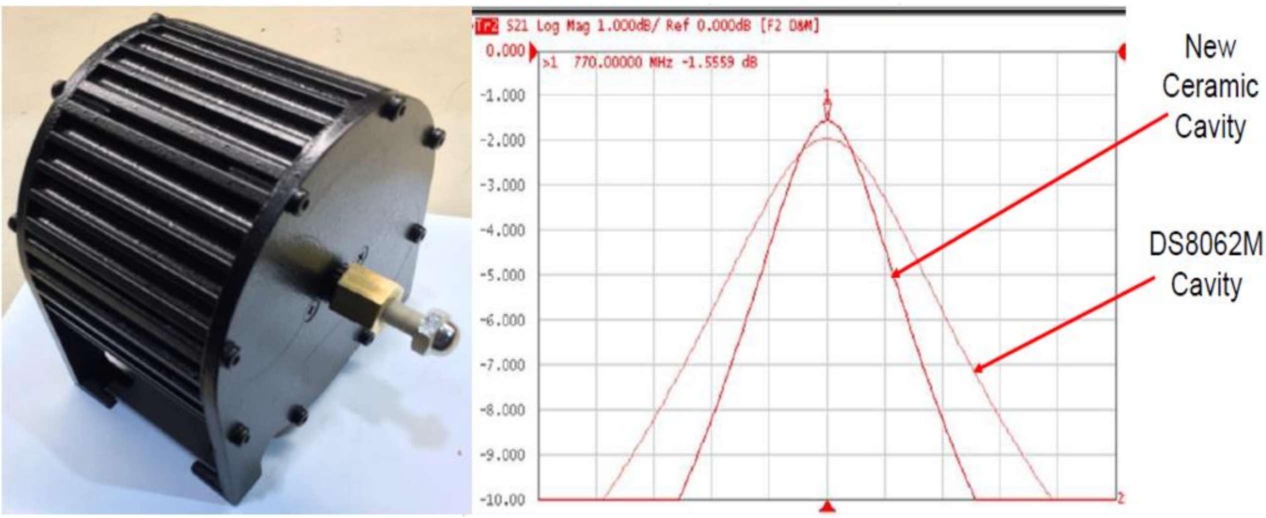


Figure 23: Ceramic Combiner

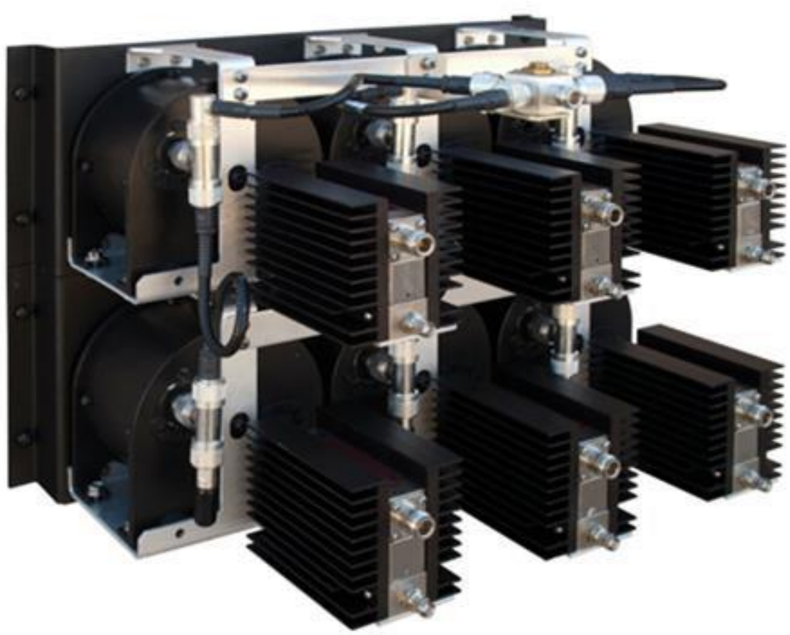


Figure 24: 6 channel 700/800 MHz Ceramic Combiner

Release History

Release 1.0 – March, 2017

Release 2.0 – September, 2019

Notes