Shively Labs®

FM Combining Systems

Abstract

Transmitting several frequencies from a single broadband antenna system requires the use of a combining system, or combiner, composed of RF filters and interconnecting transmission line. In general, a combiner can be categorized as one of two types: branched (star point), and balanced (constant-impedance). Any of these types may employ band-reject (notch) or bandpass filters. This chapter discusses the use of filters, other components in FM combiners, and the hardware used to combine an In-Band-On-Channel (IBOC) digital signal into an analog signal.

Document No. tb-fm_combining_systems (150320)

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Applications

For years, both the FM spectrum and the FM channel were straightforward and uncomplicated. Until the early 1980s, the number of stations on the air in all but the largest metropolitan areas was low by today's standards. In most areas, the frequency spacing between stations exceeded the 0.8 MHz minimum that is common in all parts of the country today. These wider frequency spacings, the relative ease of developing new tower sites, and the limited station ownership in any market worked against the economics of combining stations. Therefore, most stations operated on single-frequency antennas and large, multi-station antennas were generally only found in a few of the largest markets.

In the late 1980s, with the arrival of Docket 80-90, the FM spectrum in the US became increasingly crowded. Ensuing changes in ownership regulations, tightening zoning regulations, and the dramatic increase in tower space required to accommodate DTV changed the economics of combining. It has become increasingly common to combine stations in even the smallest markets, including stations with very low powers. Further complicating the spectrum is the dramatic increase in auxiliary antennas that began as a result of the need to accommodate DTV construction and accelerated after 9/11. Expansion of combined systems has not been limited to small and medium markets. Large metropolitan combined stations that rarely exceeded 10 stations in the 1990s are now routinely being replaced by systems with room for 20 stations or more.

At the same time that changes in the FM spectrum made combining attractive and increased filtration a necessity, the FM channel itself became increasingly complicated. In the 1980's, the 67 KHz SCA (Subsidiary Communications Authorization) became more widely used. This was quickly followed by the 93 KHz SCA, pushing critical information to the ± 100 KHz fringe of the FM channel and closer to potentially interfering signals. With the introduction of IBOC in the early 2000's, the channel has increased in size to ± 200 KHz from center frequency, and its full width is being utilized. Even this enhanced channel is becoming more crowded as digital multicasting becomes commonplace.

The net result is that as the FM channel becomes larger and more complex, filters and combiners have had to evolve to provide enhanced isolation between closer-spaced signals at the same time that their own passbands need to be more tightly controlled to pass the enhanced channel. Today's combiners are even being used to isolate separate signals on the same frequency, in order to facilitate the combining of analog and digital signals.

Why combiners are used

Shortage of prime locations

As populations migrate to the suburbs, it has become more desirable to construct large broadcasting facilities which can reach these heavily populated areas from more central locations. Of course, these prime locations have become more valuable, so it makes sense to use each location to its fullest potential. This can best be done by sharing a transmitter site and a common antenna among several users. To accomplish this, the broadcast industry uses combiners of various types and sizes. For example, in San Francisco (Mt. Sutro), Toronto (CN Tower), Montreal (Mt. Royal), New York City (Empire State Building), and Chicago (John Hancock and Sears Buildings), tall towers or towers on skyscrapers have been used to consolidate as many broadcasting facilities as possible, including VHF-TV, UHF-TV, FM and land mobile communications services. This approach has proven very effective, not only using real estate economically, but also spreading the tower costs over many users.

Group ownership of FM stations in a market has led to proliferation of combined stations. And with the implementation of DTV systems, FM stations are being forced off existing towers, making it even more imperative that they share tower space, which increases the demand for combined systems.

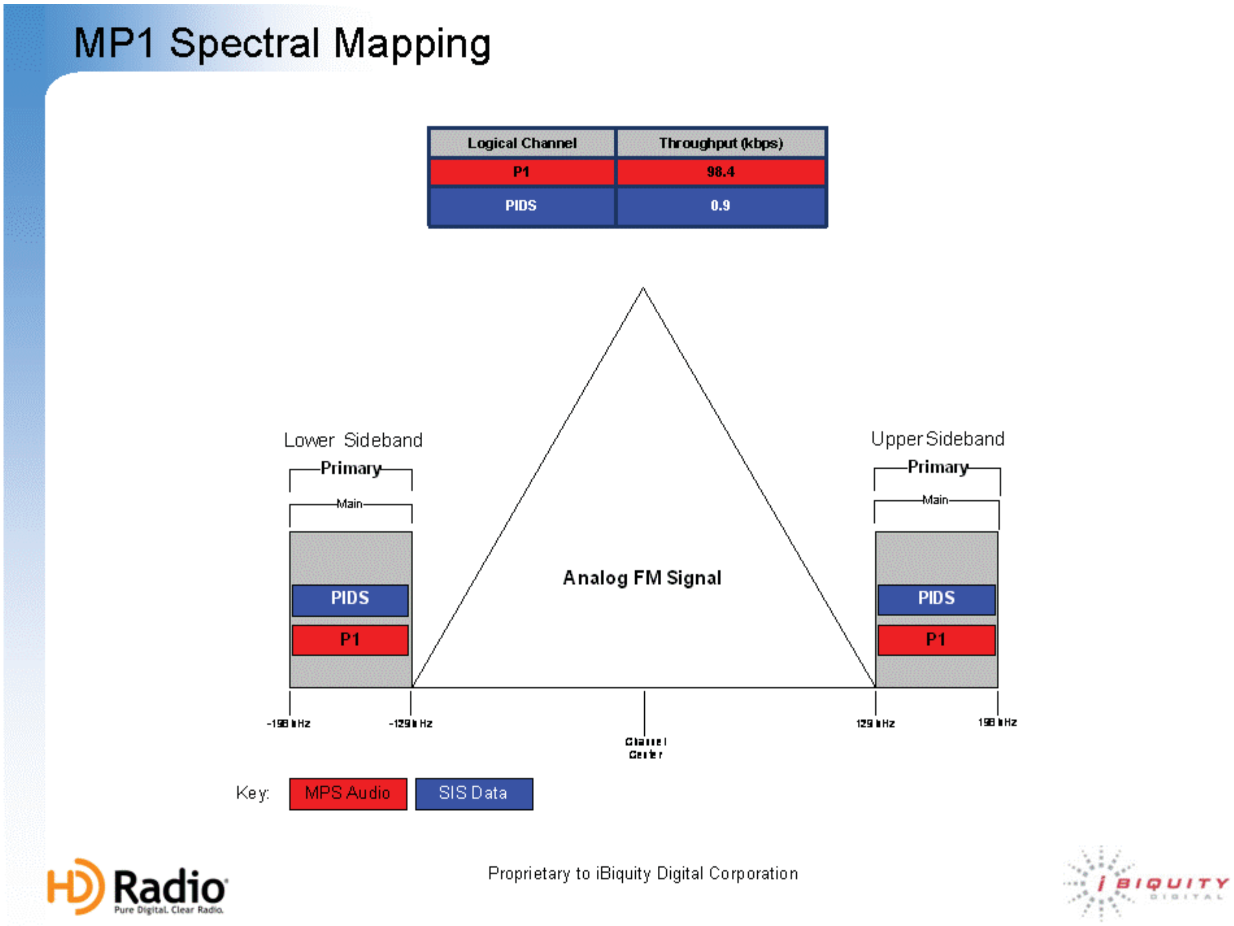
FCC isolation requirements

When more than one signal is broadcast over a single antenna, the signals must be combined in such a way that no chance exists for the signals to feed back into each other's transmitter. Failure to do so would allow intermodulation products to be generated within the final amplifier stages of the transmitters and broadcast over the antenna. These intermodulation products are generally referred to as "spurs." Spurs created between FM stations can occur not only in the FM band, but also within the low band VHF channels and above the FM band causing interference to the aviation band. In addition, FCC Rule 73.317(d) specifies that spurs more than 600 kHz removed from the carrier must be attenuated below the carrier frequency by 80 dB or by 43 + 10log10 (power in watts) dB, whichever is less. In practice, stations operating transmitter output powers of 5 kW or greater must usually meet the 80 dB requirement, while stations running lower TPOs (transmitter power outputs) fall under the computational method.

Experience has shown that to prevent spurs, each transmitter must be isolated from all others in the system by a minimum of 40 dB, with 46 to 50 dB ensuring regulatory compliance. Spur attenuation is accomplished by a combination of transmitter turn-around loss and filtering. Turn-around losses are inherent to the way spurs are created in the transmitter. These losses typically run in the 6-13 dB range for tube-type transmitters, while 15-25 dB is typical for solid-state units. An off-frequency signal is attenuated 40 dB as it passes through the bandpass filters of the combiner module toward the transmitter with the spur it creates exiting the transmitter an additional 6-25 dB below the level the signal entered. This spur is then attenuated 40 dB as it passes back through the bandpass filters. The result is spur attenuation of at least 80 dB, with 100 dB or more possible.

In-band-on-channel (IBOC) combining

The IBOC signal is transmitted above and below the standard FM analog signal (Figure 1) and is discussed in the IBOC chapter of this handbook. This IBOC signal can be combined in a modified analog transmitter. This is called low-level combining and is covered in the transmitter chapter. The IBOC signal can also be combined by using a dual input antenna or separate antennas; this is discussed in the antenna chapter. The section entitled "Combining Digital and Analog Signals" on page 19 discusses combining the digital and analog signals from separate transmitters into a common transmission line before sending them to the antenna.



MP1 Spectral Mapping

Logical Channel	Throughput (kbps)
P1	98.4
PIDS	0.9

Proprietary to iBiquity Digital Corporation

Figure 1. Spectral Mapping of an FM Channel (from iBiquity)

Considerations in combining

Frequency response

Energy transfer through the bandpass filter is highest, or least attenuated, at the resonant frequency, and drops off at frequencies above and below that frequency. This frequency response is the fundamental property that enables a filter cavity to 'sort' frequencies.

If it were possible to design an ideal filter, its frequency response plot would be as shown in Figure 2. Response would be flat within the pass band, with a vertical "roll-off" at the edges of that band.

Figure 3 shows the frequency response of a real-world single-cavity bandpass filter. Note that the energy transfer is highest at the resonant frequency (f0) and drops off gradually away from f0.

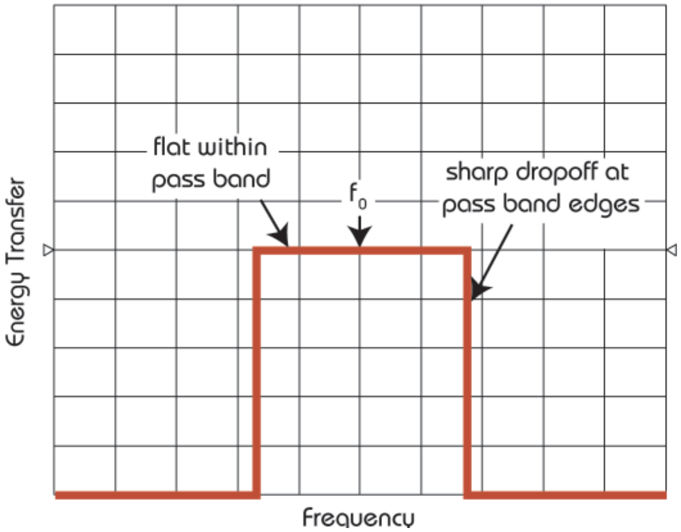


Figure 2. "Ideal" Filter Frequency Response

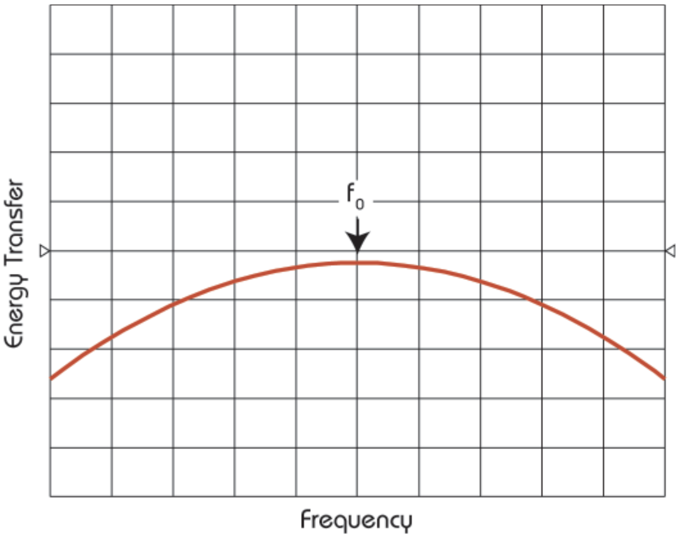


Figure 3. Frequency Response, Single-Cavity Filter

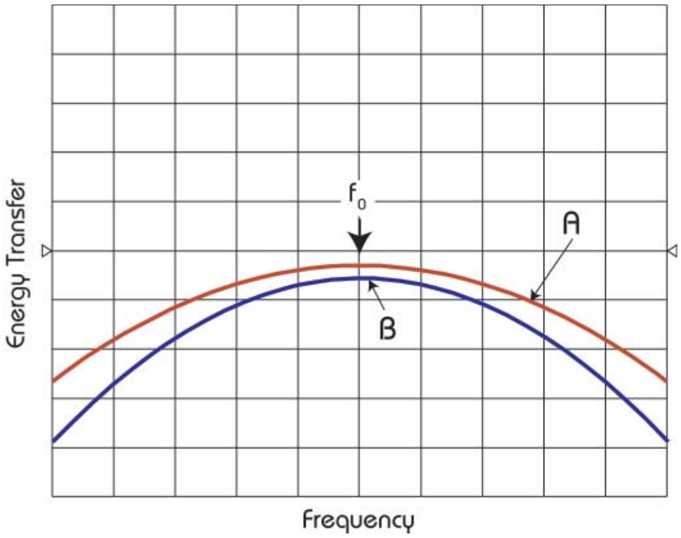


Figure 4. Insertion Loss, Single-Cavity Filter

Insertion loss

Even at the resonant frequency f_0, energy transfer is not perfect; some energy is lost along the way. The efficiency of a filter at the resonant frequency is expressed as insertion loss; that is, the loss of energy at the resonant frequency. The lost energy is converted to heat and dissipated in the metal surfaces of the cavity. A cavity that is larger in size is more efficient than a smaller sized cavity, in that it will provide a lower insertion loss at the resonant frequency with comparable frequency response. Coupling efficiency also affects insertion loss; curve B of Figure 4 shows the effects of coupling adjustment.

Our theoretical ideal filter would show no insertion loss in the pass band.

Group delay

The signal takes a finite amount of time to pass through the cavity, and just as more energy is lost, more time is taken at non-resonant frequencies. Figure 5 is a plot of time vs. frequency and shows that as the frequency changes further away from f_0, the signal takes more time to pass through the cavity. This is termed group delay difference, or group delay for short. Excessive group delay within the pass band results in signal distortion.

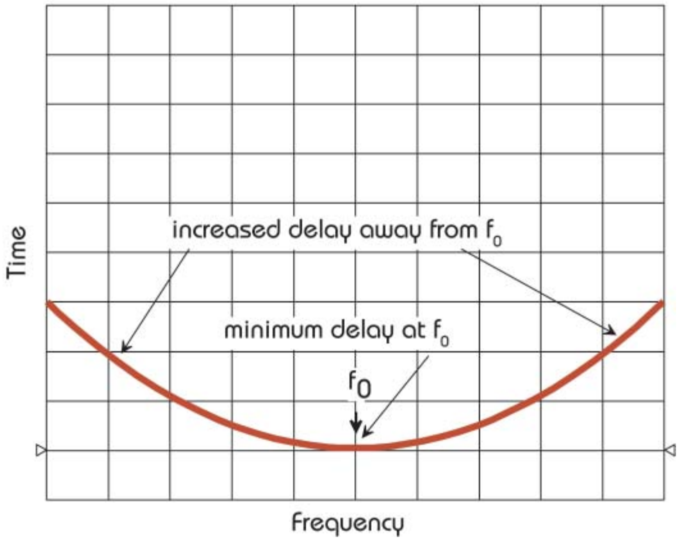


Figure 5. Group Delay, Single-Cavity Filter

Our "ideal filter" would have no group delay difference; that is, the curve would be a horizontal line, at least across the pass band.

IBOC requires the full channel bandwidth, so it is important to limit group delay across the full channel.

Impedance

Current flow in any RF circuit must overcome resistance, capacitive reactance, and inductive reactance. The vector sum of these is termed impedance. Because this is a complex function, it may only be fully represented on a complex diagram known as a Smith chart. A full discussion of Smith charts is beyond the scope of this chapter (see "Books on Related Topics" at the end of this chapter for more information on Smith charts), but a few features will aid in the understanding of filter performance and tuning.

Figure 6 shows an expanded Smith chart. The center horizontal axis (A) represents a state of pure resistance. In a properly tuned system, this state exists at f_0, the resonant frequency, where the inductive and capacitive components cancel each other out. The center point on line A represents a resistive value of 50 ohms (50 Ω); to the left, the resistive value decreases, approaching a short circuit (0 Ω); to the right, it increases, ap-

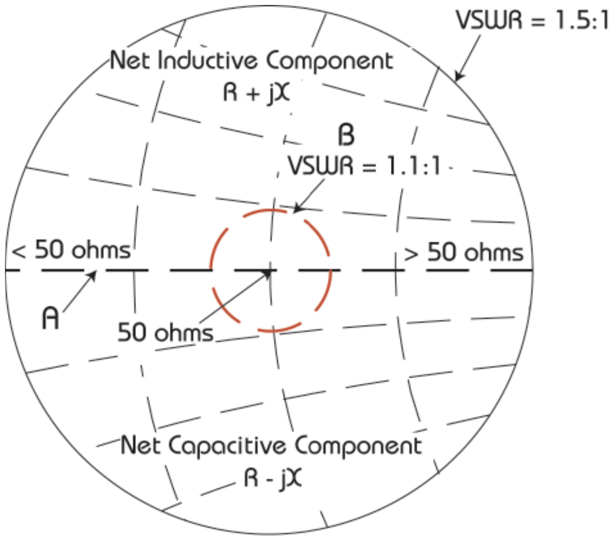


Figure 6. Smith Chart Components

proaching an open circuit (infinite Ω).

The region above the horizontal axis represents a state when the vector sum of the circuit is inductive in nature. Conversely, below the axis, the circuit is capacitive. Any point on the chart may be expressed as R ± jX, where R is the resistive component, j is a constant, and X represents the magnitude of the net inductive or capacitive component of the circuit.

A circle drawn around the center point would be a locus of points of equal VSWR; for example, circle B in Figure 6 represents a VSWR of 1.1: 1. Points within the circle then represent conditions of VSWR less than 1.1:1.

Our "ideal filter" would be plotted as a dot at the center of the chart, representing a pure 50-ohm resistance throughout the pass band, with no capacitive or inductive components.

Figure 7 shows the Smith chart of a single-cavity bandpass filter. At the resonant frequency f_0, the impedance is pure resistance and 50 ohms, at chart center. As the frequency changes away from f_0, the inductive and capacitive components grow, forming a vertical arc. The slight offset to the right of chart center represents insertion loss.

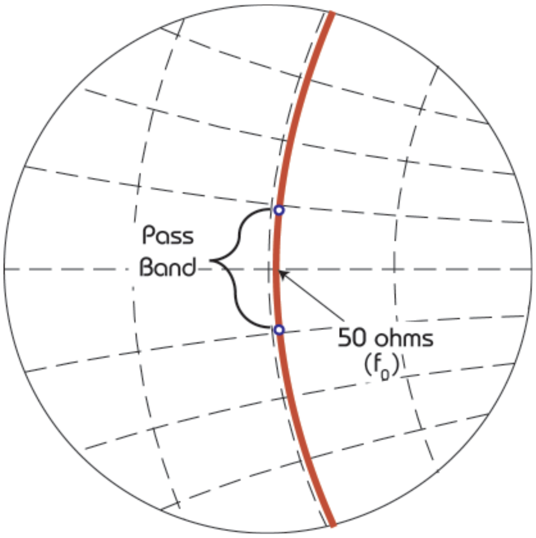


Figure 7. Smith Chart, Single-Cavity Filter

The small circles (beads) on the curve indicate the pass band. Usually, a range of ± 200 kHz is considered an acceptable pass band for a filter system.

Figure 8 is an impedance diagram showing manipulation of the coupling through the cavity. Curve A (truncated for emphasis) is a cavity with the loops adjusted for maximum coupling. This curve almost passes through the center of the chart (R = 50 Ω) due to insertion loss, and the entire 200 kHz pass band (between the beads) is within the circle representing VSWR = 1.1:1.

As the coupling is adjusted to achieve increased isolation (curve B), and still more isolation (curve C), the center of the curve moves into the R > 50 Ω area to the right of chart center, an indication of greater insertion loss. In addition, the beads representing ± 200 kHz move outward, well outside the 1.1:1 VSWR area. Again this illustrates the tradeoff between increased isolation and increased insertion loss.

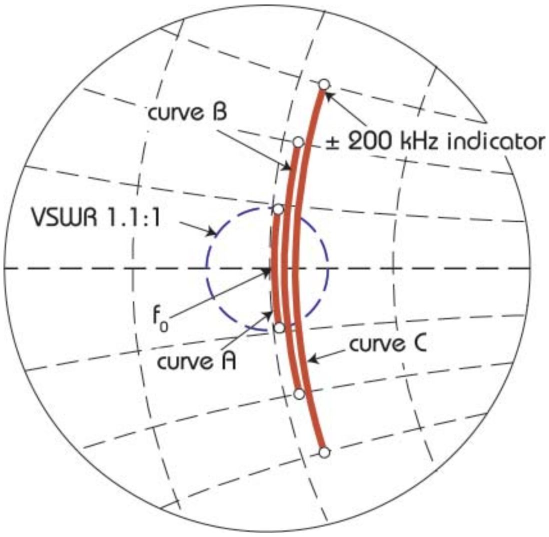


Figure 8. Tuning of Single Bandpass Cavity

Physical size

The physical size of the cavity is established for the purpose of power capacity and electrical performance. Then the cavity is tuned to optimize the performance for a given application.

Tuning compromises

Note that an ideal filter would have a 50-ohm impedance (unity VSWR), no insertion loss, no group delay, and flat frequency response within the pass band. As Figures 3, 4, and 5 show, actual cavities do not meet these ideals. It is important to remember that filters are always designed for best real-world overall performance, and that at times, a little performance must be sacrificed in each parameter to improve overall performance.

In order to obtain increased isolation to meet today's standards, the number of cavities in a filter system must be increased - but this occurs at the cost of increasing group delay and insertion loss. In a four-cavity system, the group delay curve becomes so steep as to be unacceptable (Figure 9).

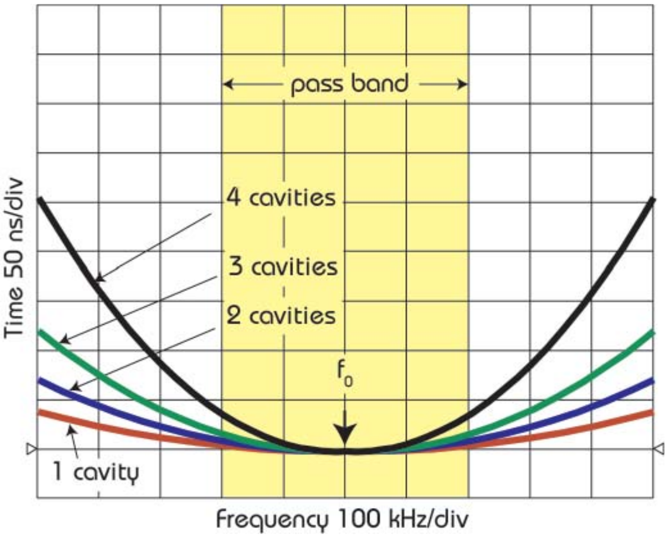


Figure 9. Group Delay, 1-, 2-, 3-, and 4-Cavity Filters

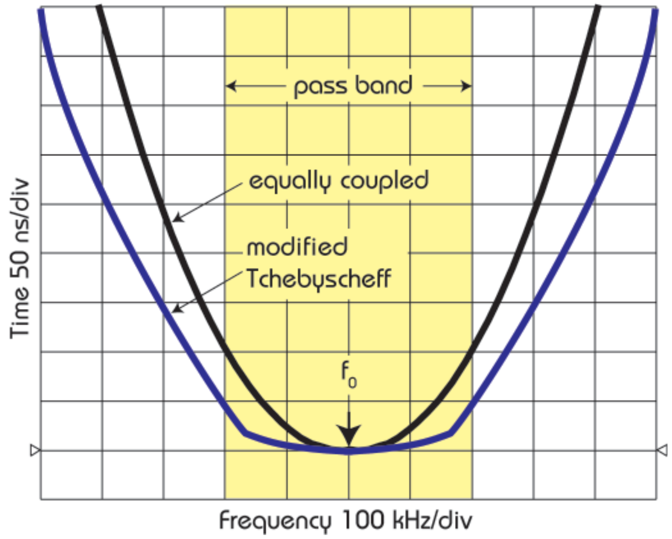


Figure 10. Group Delay, 4-Cavity Filter Tuned for Group Delay

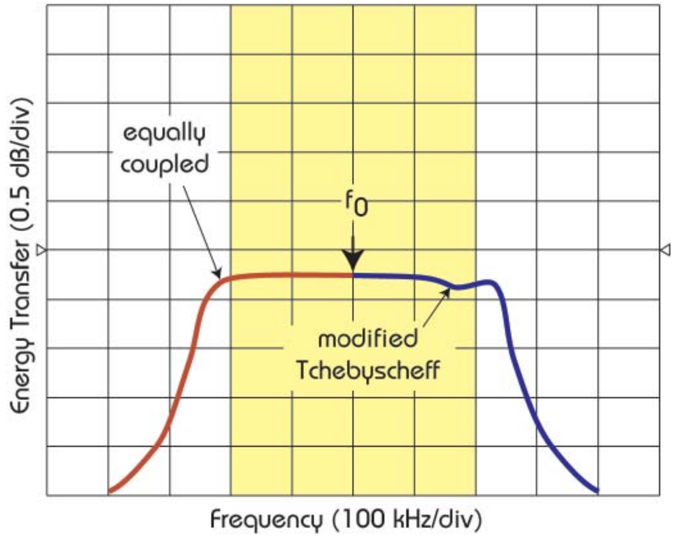


Figure 11. Frequency Response, 4-Cavity Filter Tuned for Group Delay

Therefore, the tuning is modified to decrease group delay to an acceptable level, as shown in Figure 10.

This adds some minor distortion to the frequency response (Figure 11).

Although none of the individual parameters is optimized by itself, the overall performance of the filter is optimized and acceptable.

A four-cavity bandpass filter is as large a filter system as is needed for most high isolation applications.

Components of combiners

Tee or star-point junction

A tee junction, shown in Figure 12, is a coaxial component that provides for two RF signals to flow into a common path; a star-point junction is a tee with more than two input paths. This basic coaxial component is one of the building blocks of a branched combiner.

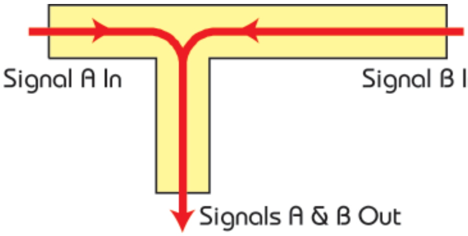


Figure 12. Tee Junction

Resistive load

Resistive loads, often called "dummy" loads, are used in many applications and can be manufactured in many sizes depending on the power requirement. In a dummy load, incoming power is absorbed and converted to heat. The heat must then be dissipated to the surrounding air, so the power rating of a dummy load is determined by the size of the resistor and the amount of heat that can be dissipated before the resistor overheats and fails. If enough resistors can be chained together with enough cooling, they can dissipate almost an unlimited amount of RF energy.

Quadrature hybrid

The heart of the modern balanced combiner system is the quadrature hybrid (usually just called hybrid). A hybrid is a complex broadband device that has the ability to operate in various modes either singly or simultaneously. The detailed mathematical explanation of a hybrid is beyond the scope of this work (see "Books on Related Topics" at the end of this chapter for more information on hybrids); this chapter covers only the use of hybrids in combining systems.

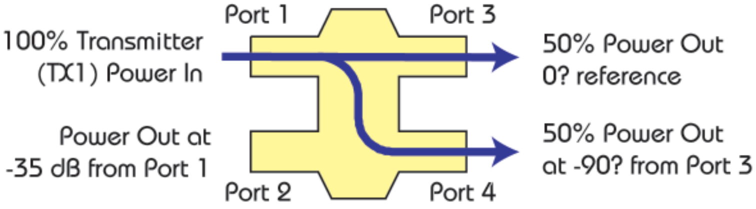


Figure 13. Hybrid as Signal Splitter

Hybrid as signal splitter

In Figure 13, the hybrid is acting as a power splitter and phase shifter. When an RF signal is applied to port 1 (TX1), the hybrid splits the signal in half, and the phase of port 4's output is delayed with respect to port 3's output by 90 degrees. Port 2 is called the isolated port, because the isolation between ports 1 and 2 is approximately -35 dB, and is usually terminated with a 50-ohm resistive load.

If two inputs are required, Port 2 can be used as an additional transmitter input (TX2). In this configuration, the output power levels are the same as above, but the phases are reversed (Figure 14).

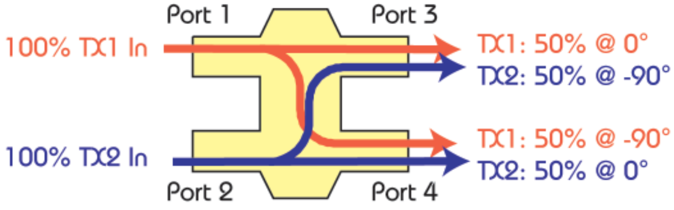


Figure 14. Hybrid Splitting Two Input Signals

Hybrid as signal combiner

Use of a hybrid in reverse, for combining, is shown in Figure 15. If two equal RF signals, with the proper phasing, are introduced at ports 1 and 2, the combined signal exits the hybrid through port 4. If the phase of the two input signals is reversed, the signal will exit the hybrid through port 3. Again the isolated port is usually terminated with a resistive load.

The hybrid can be used to combine two incoming signals in the exact reverse of Figure 14. If two incoming signals with the correct phasing are present at Port 1 and two at Port 2, as shown in Figure 16, then port 4 is an output for one combined signal TX1 and port 3 is the output for the other combined signal TX2.

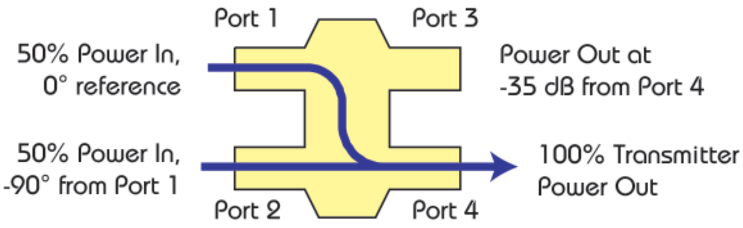


Figure 15. Hybrid as Signal Combiner

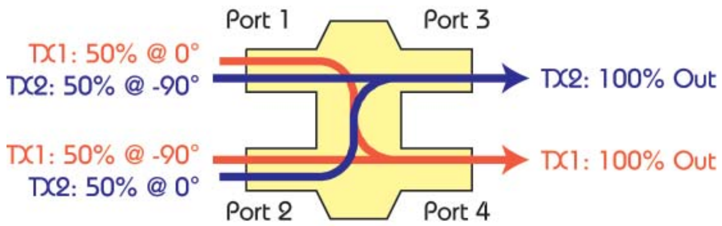


Figure 16. Hybrid Combining Two Signals

Hybrid as signal reflector

The hybrid's third mode of operation is called the reflected mode (Figure 17). When two identical devices with high impedance, such as bandpass filters tuned to another frequency, or band-reject filters tuned to the incoming frequency, are attached to ports 3 and 4 of the hybrid, the signal entering at port 1 is reflected and exits the hybrid through port 2. Again the hybrid is symmetrical; if a second signal enters port 2 it will be reflected and exit port 1. The characteristics of this third mode make the hybrid useful in conjunction with other hybrids and cavities in combining systems.

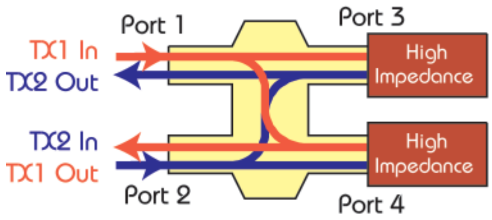


Figure 17. Hybrid as Signal Reflector

A hybrid can operate in all three modes simultaneously. With power moving in so many different directions at once, it is imperative that it have good electrical characteristics, and that it be as balanced and symmetrical as possible, both mechanically and electrically. Balanced and symmetrical hybrids show the same electrical characteristics through each port. The more identical the electrical paths through these ports are, the greater the isolation that can be achieved, and the lower the VSWR at each port. Figure 18 shows the performance curve of a well-balanced and symmetrical hybrid.

Hybrid ring

When two hybrids are used in a ring configuration (Figure 19) to both split and combine a single input signal, virtually 100% of the signal exits the ring through the hybrid leg opposite the input.

In a balanced and symmetrical hybrid ring, if the signal is introduced at Port 2, the outgoing signal will be at Port 7, with isolation at Ports 1 and 8. Likewise, if the signal is introduced at Port 7, it will emerge at Port 2, with isolation at Ports 1 and 8, and if it is introduced at Port 8, it will emerge at Port 1, with isolation at Ports 2 and 7.

Energy can flow in all four directions at the same time without the signals mixing (Figure 20).

The multiple flow paths of the hybrid ring make it the backbone of the balanced combiner.

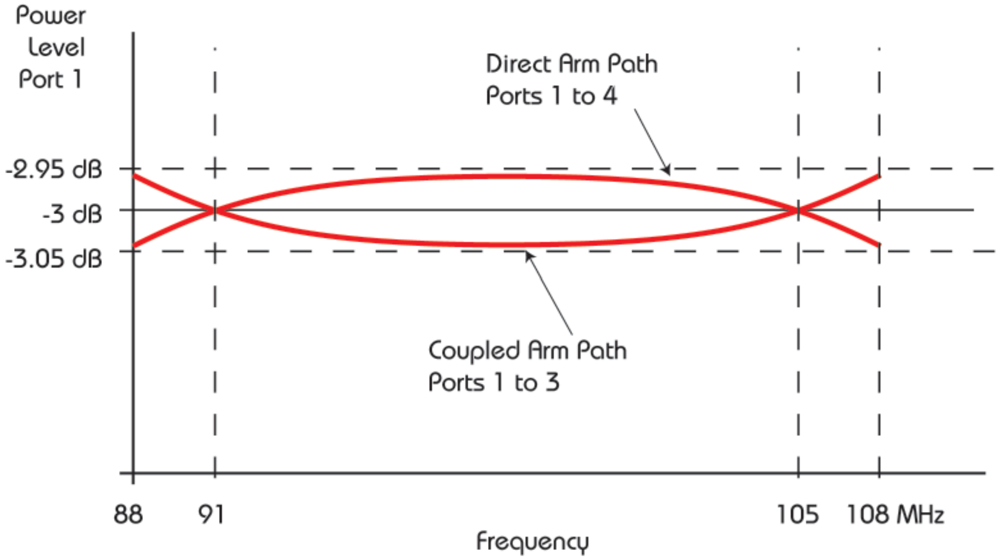


Figure 18. Hybrid Frequency Response

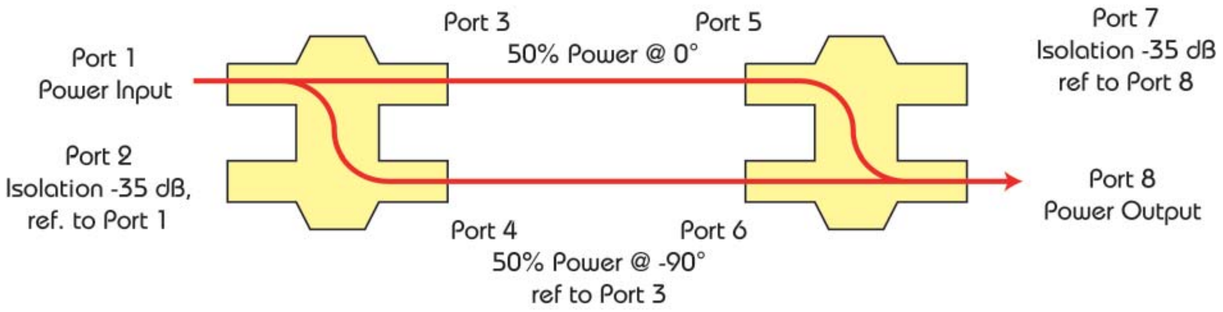


Figure 19. Hybrid Ring

Filter

Filters sort RF frequencies, attenuating some while allowing others to pass readily. Depending on the design, a filter may either attenuate (band-reject type) or pass (bandpass type) a relatively narrow bandwidth.

Band-reject or notch filter

There are several ways to design a band-reject or notch filter (Figure 21), but they all accomplish the same purpose. In one form, a cavity, with only an input coupling loop, is mounted off the transmission line by means of a matched tee. This provides a path which removes the tuned frequency from the system, allowing other frequencies to pass with minimum loss. Other designs employ some form of capacitive coupling into the cavity.

Multiple notch cavities

The frequency response of a typical notch cavity is shown in Figure 22.

When more isolation is needed, two notch cavities are coupled in sequence. The resonant frequencies of the cavities may be identical, yielding a response curve with a very deep narrowband notch, as shown in Figure 23 ...

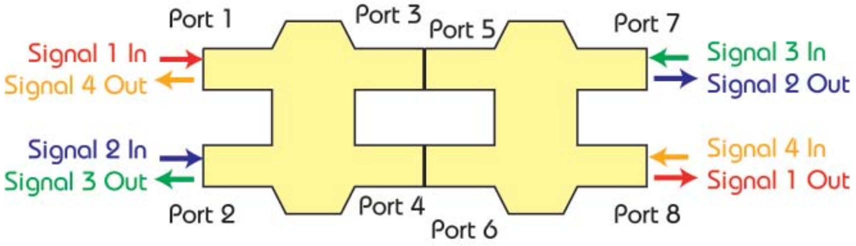


Figure 20. Hybrid Ring Multiple Flow Paths

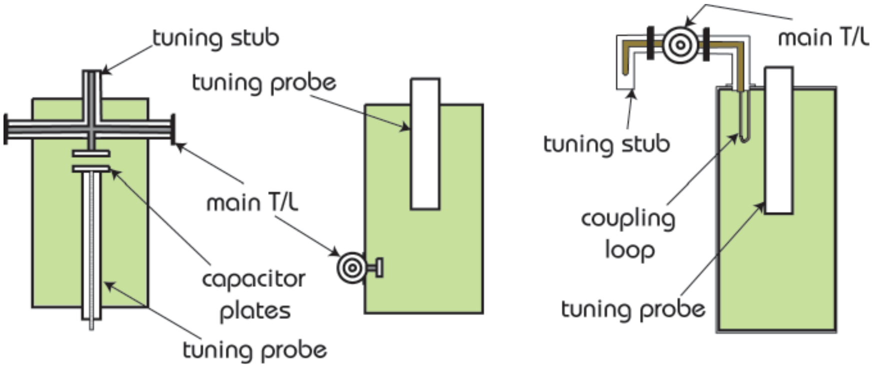


Figure 21. Notch Filter Configurations

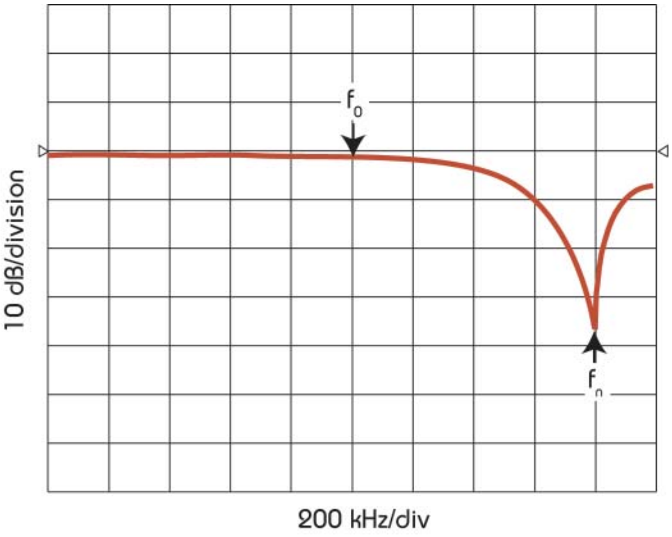


Figure 22. Frequency Response, Single Notch Cavity

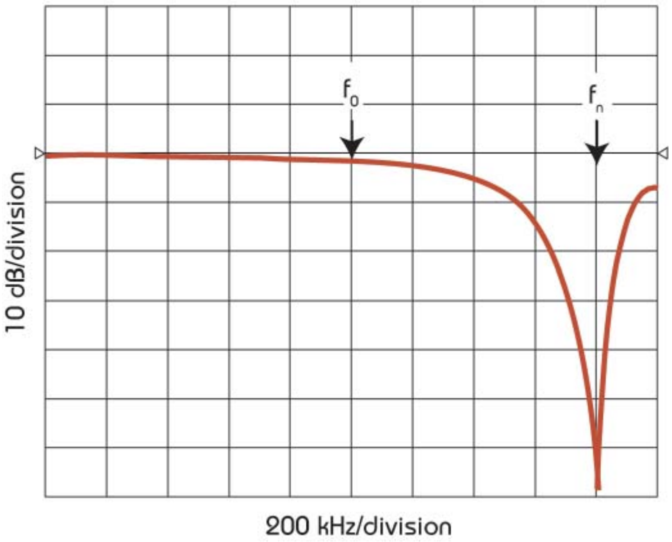


Figure 23. Frequency Response, Dual Notch Cavities

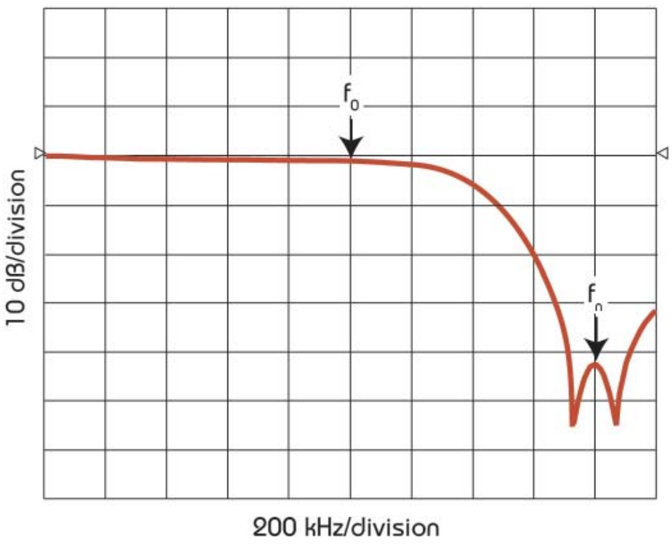


Figure 24. Frequency Response, Staggered Dual Notch Cavities

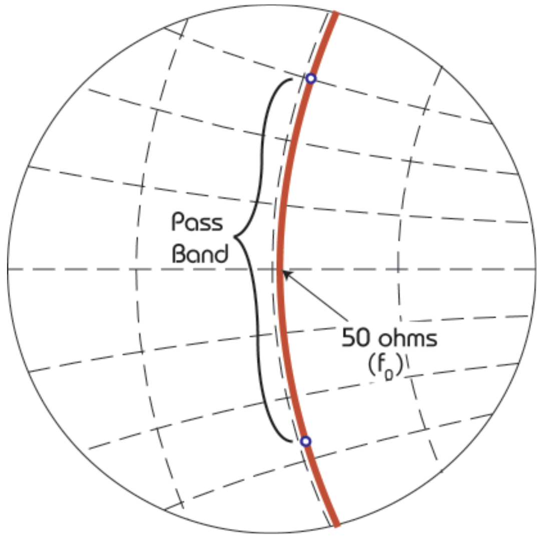


Figure 25. Impedance Plot, Single Notch Cavity

... or they may intentionally be staggered, to give a broader notch response, as shown in Figure 24.

Performance and limitations

The impedance plot of a typical notch cavity is shown in Figure 25. When a single notch cavity is used, an impedance matching network is added to the filter to improve the impedance bandwidth.

The group delay plot of a notch cavity (Figure 26) distorts signal quality. No practical device has been marketed to equalize the group delay of a notch-cavity system. However, this has not been a major issue, since at about the same time (mid-1980s) that group delay was recognized as an issue, the industry was turning towards bandpass filtering anyway.

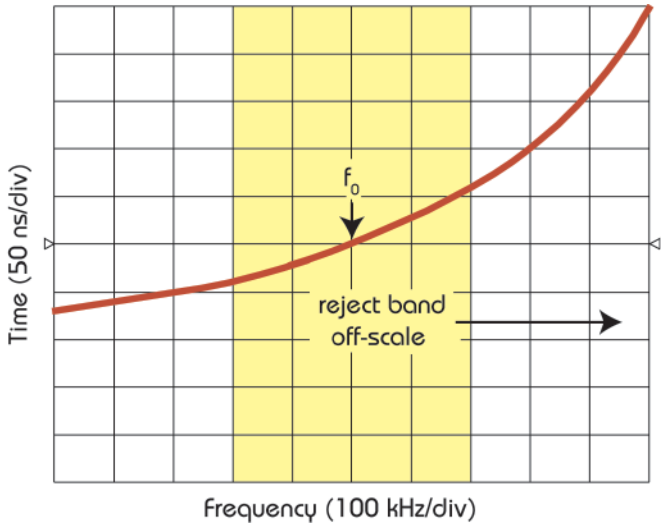


Figure 26. Group Delay, Single Notch Cavity

Bandpass filter

Figure 27 shows the basic mechanical configuration of a bandpass filter cavity. When RF energy is applied to the input coupling loop, the loop inductively couples the energy into the cavity. Energy is transferred through the cavity and inductively coupled to the output coupling loop.

The resonant frequency of the cavity is tuned by adjusting the tuning probe. The transfer of energy is maximized at the resonant frequency. Therefore, a filter of one or more identical cavities can be used to attenuate frequencies other than the resonant frequency.

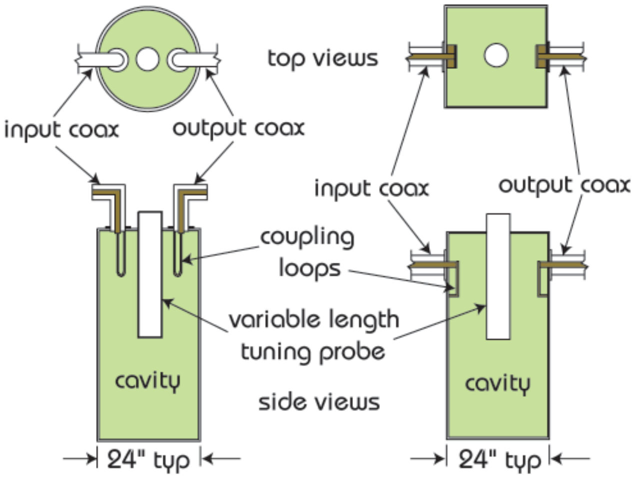


Figure 27. Bandpass Cavity Configurations

Multiple bandpass cavities

Generally, a filter system is considered adequate if it provides a VSWR of 1.1:1 over a frequency range of ± 200 kHz. This is termed the bandwidth of the filter system. In most cases, a single bandpass cavity will not yield this much bandwidth. To increase the isolation and increase VSWR bandwidth, a second cavity may be added to the first, as shown in Figure 28.

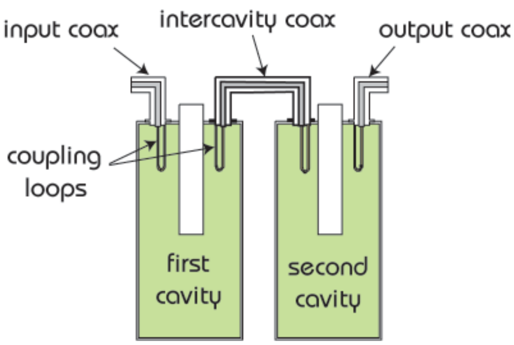


Figure 28. Two-Cavity Bandpass Filter

When two identical cavities are coupled 1/4-wave apart, the impedances superimpose themselves as shown in Figure 29. Note that Figure 29 shows two Smith charts superimposed 180° apart. The small circles (beads) representing the ± 200 kHz bandwidth fall on a VSWR circle of about 1.3:1.

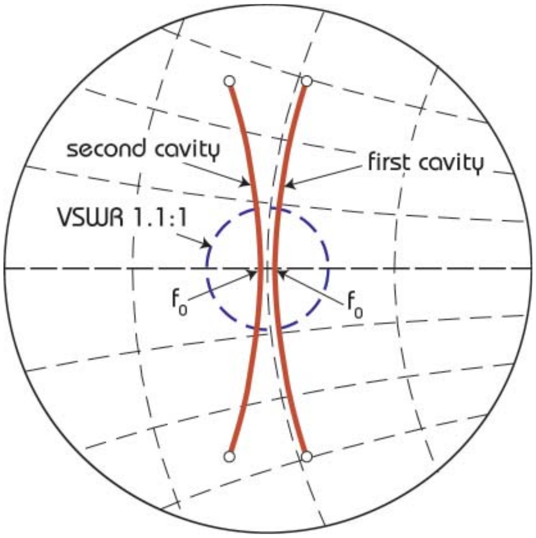


Figure 29. Superimposed Impedance Curves of a 2-Cavity Bandpass Filter

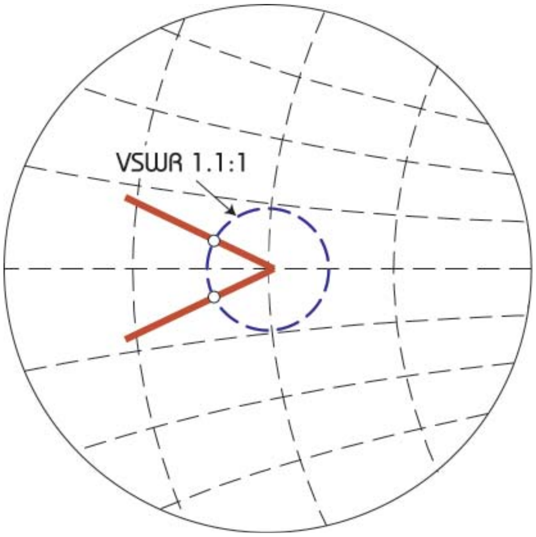


Figure 30. Impedance Plot, 2-Cavity Bandpass Filter

When their impedances are added together mathematically, due to phase cancellation, the VSWR bandwidth improves to about 1.1:1 (Figure 30).

Curve A of Figure 31 shows the frequency response of the two cavity filter.

When still more isolation is required, more cavities can be added. Figure 31 shows the frequency responses of three-, four-, and five-cavity systems, respectively. As more cavities are added, the curve becomes squarer - flatter across the pass band, with a sharper roll-off; that is, it starts to approach our "ideal" filter, shown in Figure 2. Consider, however, that the five-cavity filter does not show a great improvement over the four-cavity filter, and in fact, the four-cavity filter represents the best compromise among isolation, insertion loss and physical size for close-spaced stations transmitted through a combining system.

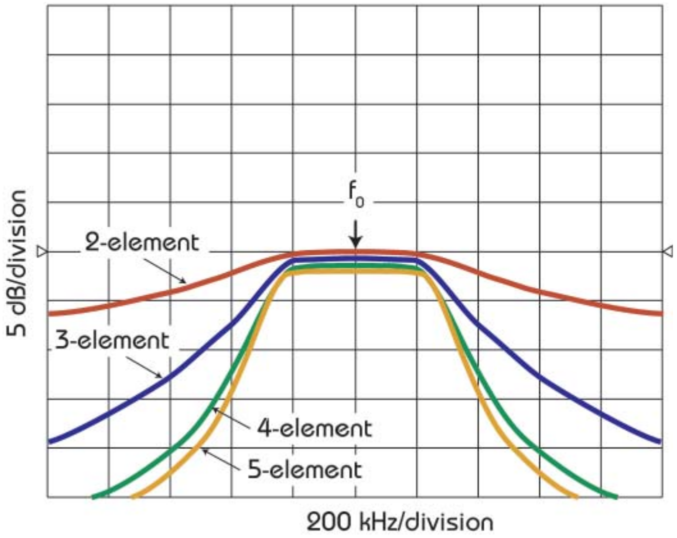


Figure 31. Frequency Response, 2-, 3-, 4- and 5-Cavity Bandpass Filters

Figure 32 shows Smith charts for a three-cavity system and a four-cavity system. Note that the beads indicating the ± 200 kHz points are well within the 1.1:1 VSWR circle.

Mechanical constraints

In order to obtain the optimum mathematical cancellation shown in Figure 30, the cavities must be spaced at 1/4 electrical wavelength. As the frequency increases, the electrical wavelength decreases - therefore, the physical length of the intercavity coax must be shortened. At the higher frequencies of the FM band, the large cavities used for high-power applications are difficult to link together, because the cavities themselves approach 1/4 electrical wavelength. As a result, when the intercavity coax is added, the electrical spacing is longer than 1/4 wavelength. In this case, the coupling loops must be manipulated to compensate for the extra length, so that the impedance bandwidth of the cavities is maintained.

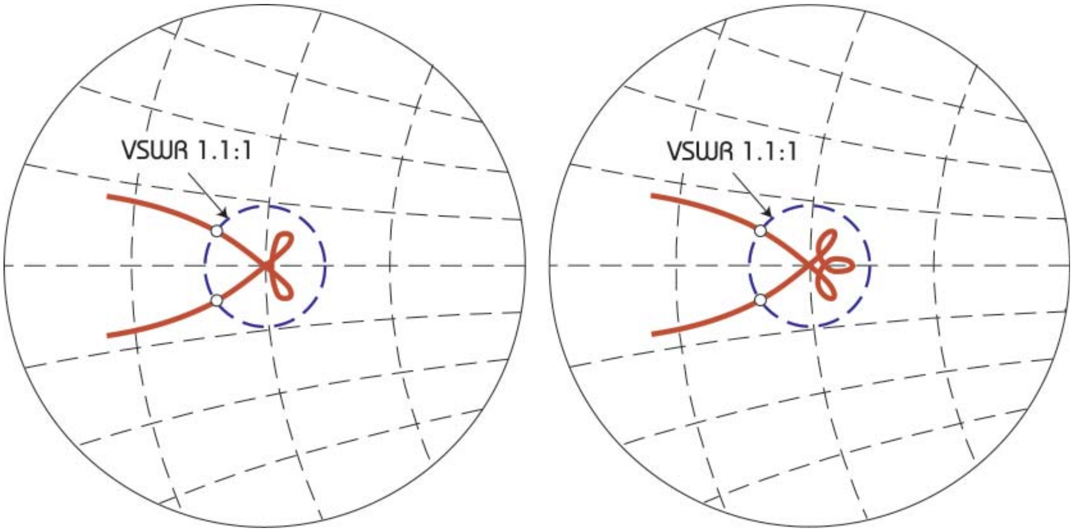


Figure 32. Impedance Plots for 3- and 4-Cavity Equally-Coupled Bandpass Filters

Common-wall coupling

The spacing problem can be prevented by building the cavities contiguous to each other and coupling them through a tuned opening in the wall between them, as shown in Figures 33 and 34. The 1/4-electrical-wavelength spacing is maintained by the coupled fields between the cavities.

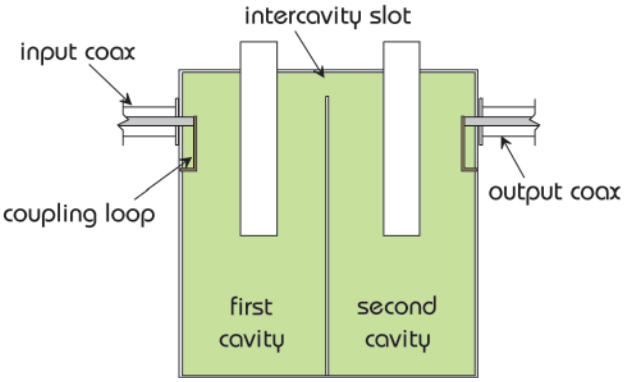


Figure 33. Slot-Coupled Cavities

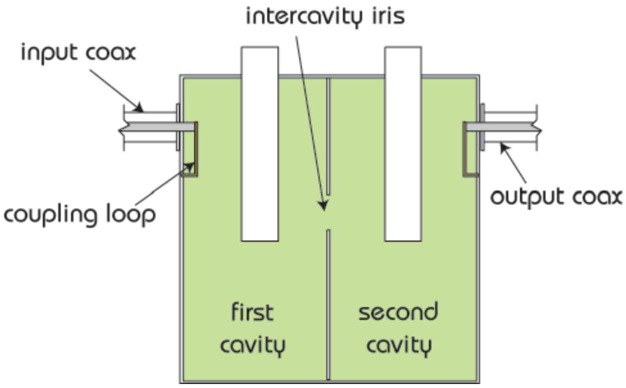


Figure 34. Iris-Coupled Cavities

Coupling options

Although common-wall coupling can be accomplished using a true iris placed away from the top of the cavity (Figure 34), the size of the iris is difficult to control and adjust.

Another method, shown in Figure 35, of coupling energy from one cavity to the next is neither an iris nor a slot, but a trapezoidal opening designed so that no adjustments are needed to couple the energy from one filter to the next across the FM band. Like most broadband-tuned networks, however, it is difficult to optimize a filter set at any one particular frequency.

Perhaps the best configuration, shown in Figures 33 and 36, is a slot at the very top end of the cavities where the magnetic fields are at their strongest point and the size and shape of the slot can be manipulated externally for ease of adjustment in tuning the filters.

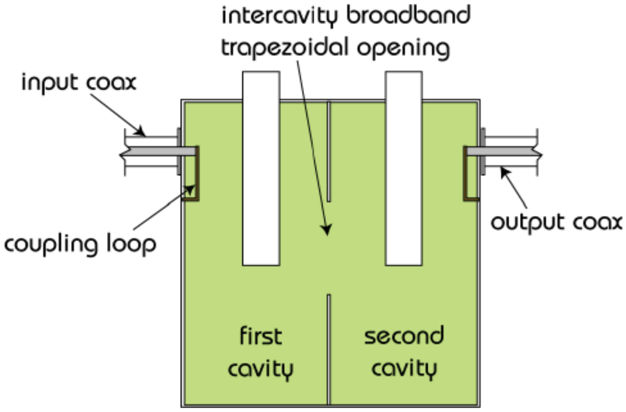


Figure 35. Cavities Coupled by Broadband Trapezoidal Opening

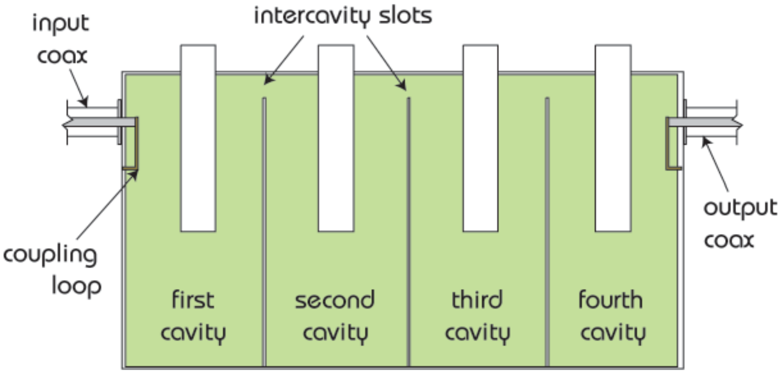


Figure 36. Four-Cavity Slot-Coupled Filter

Interdigital filters

Interdigital filters have only recently been introduced as an alternative to loop- and iris-coupled filters at FM frequencies. Interdigital filters do not employ individual cavities that must be coupled together. As shown in Figure 37, the energy is directly coupled to the input and output tuning probes. Parts counts are minimized and interdigital filters are significantly smaller than even iris-coupled filters. Because of their smaller size, interdigital filters have higher insertion losses than either loop- or iris-coupled filters of the same power rating, and careful attention must be paid to the thermal properties of the filter. Interdigital filters have better out-of-band isolation than cavity-style systems and are ideal for balanced combiners because of the ease of maintaining identical tuning across the channel.

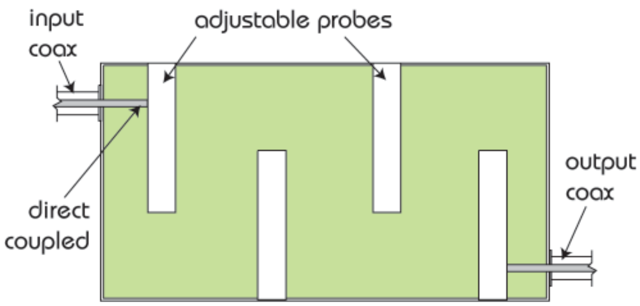


Figure 37. Four-Pole Interdigital Filter

Cross coupling

If a transmission line segment is added between the first and last bandpass sections (Figure 38), a parallel transmission channel is created.

This line segment is then tuned to achieve specific phase and amplitude characteristics, so that unwanted frequencies at both ends of the filter cancel each other out. It therefore acts as a band-reject component, creating notches at the edges of the pass band (Figure 39).

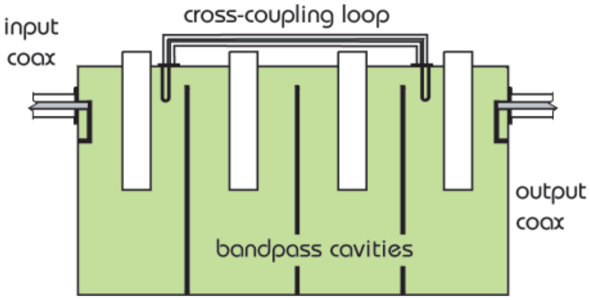


Figure 38. Filter with Cross-Coupling

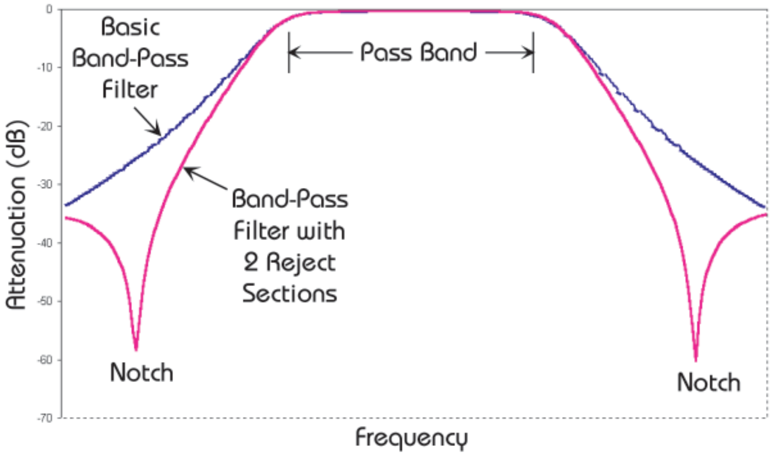


Figure 39. Frequency Response, Filter with Cross-Coupling Loops

Isolator

An isolator is comprised of a circulator and a load. Signals move between legs in only one circular direction, giving the device its name. While it is theoretically possible for the signal originating at any given leg to reach any other leg, this is prevented by the existence of one high-impedance leg, which traps energy trying to move across it and shunts it off to a dummy load. Thus it is possible to configure the circulator to allow the signal from the transmitter to flow freely out the adjacent antenna leg, but energy returning through the antenna leg is interrupted before it can reach the transmitter leg.

This is shown in Figure 40. The signal from the transmitter is fed into the isolator at Leg 1. It flows out Leg 2 on the transmission line toward the antenna. At the same time, any signal from the antenna enters the circulator at Leg 2 and is directed to the dummy load at Leg 3. The actual isolation value is a function of the match of the dummy load and is typically -26 dB.

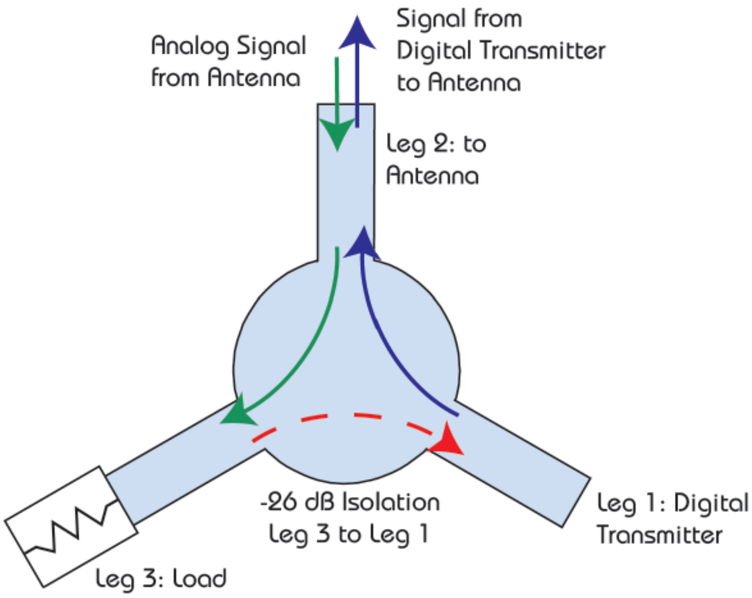


Figure 40. Isolator

This ability of isolators to divert on-frequency signals headed in the wrong direction is key to a number of modern combining strategies which employ separate digital and analog transmission paths, and where the combining method does not afford at least 35 dB of isolation between the digital and analog transmitters.

Directional couplers

Precision directional couplers are commonly found on each broadband output of a combiner system. This directional coupler is a convenient port for taking FCC-required test measurements, enabling diagnostics, and as a port for any protection and monitoring system the combiner may employ. Its versatility is further enhanced when it is used with directional couplers located on the inputs to each module.

Group delay equalizer

A group delay equalizer consists of a quadrature hybrid and two identical bandpass filters that have only one coupling loop, so that the energy is coupled in and out of the cavity by the same loop (Figure 41).

The tuned frequency is delayed for longer than the off-resonant frequencies (Figure 42).

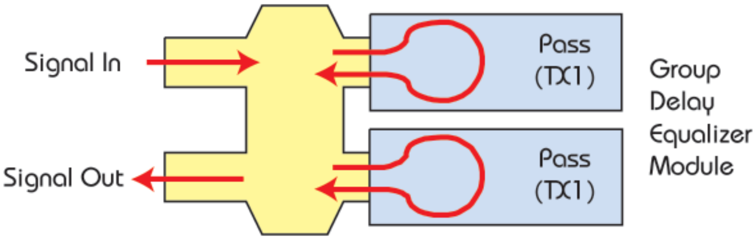


Figure 41. Group Delay Equalizer

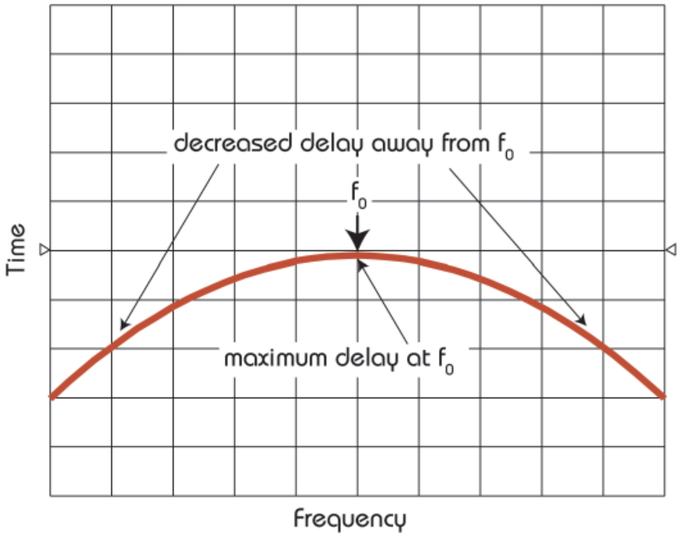


Figure 42. Group Delay of Group Delay Equalizer

Types of combiners

Branched or star point combiners

A branched combiner is a simple combination of a tee junction and the required number of filters to ensure a sufficient amount of isolation to prevent spurs. For example, an FM branched combiner consisting of a three-cavity bandpass filter in series with two band-reject cavities (Figure 43) may be used to provide the isolation required for two close-spaced frequencies 0.8 MHz apart.

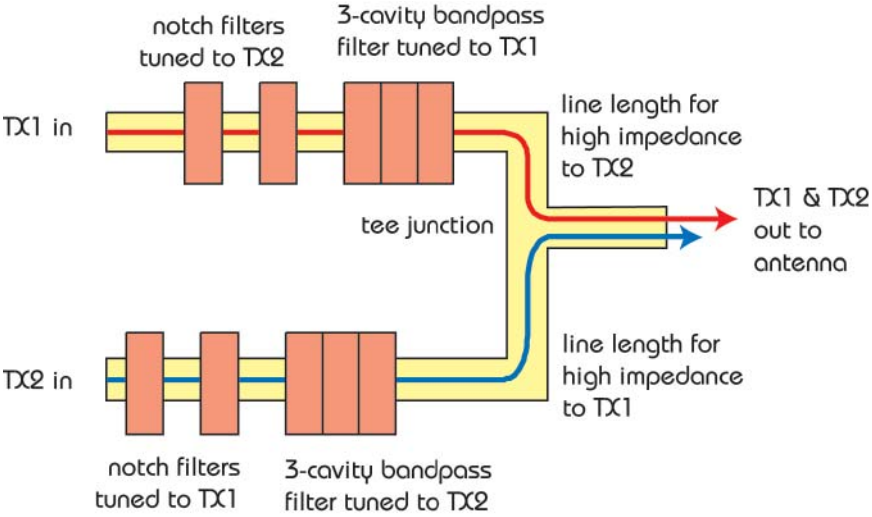


Figure 43. Branched Combiner with Notch Cavities

TX1 and TX2 are the signals from transmitters 1 and 2 as they enter the combiner. The signals pass through the notch and bandpass filters and arrive at the tee junction. The length of the coaxial line between each set of filters and the tee junction is adjusted to provide a very high impedance (approaching an open circuit) to the other frequency, so that the power flow of each signal is through its own filter, out of the tee junction, and up to the antenna.

Performance

Refer again to Figure 30, the frequency response curve for a three-cavity bandpass filter, and Figure 23, the frequency response curve for a two-cavity staggered-frequency band-reject filter. When these filters are used in combination, the resulting curve is shown in Figure 44.

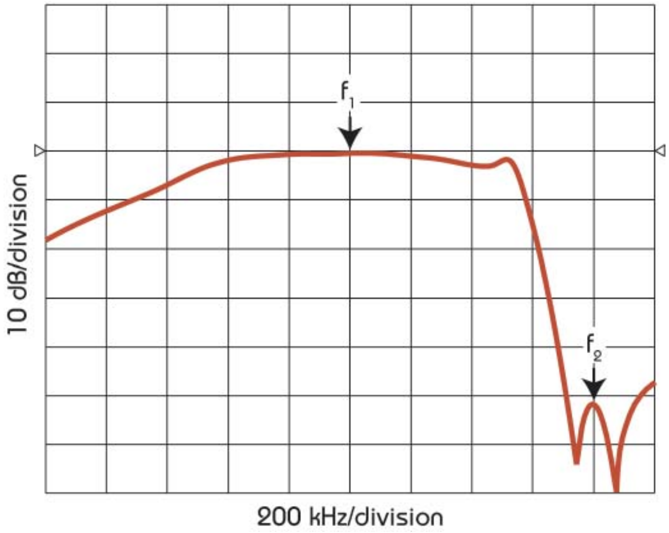


Figure 44. Frequency Response of a 3-Cavity Bandpass Filter in Series with Two Notch Cavities

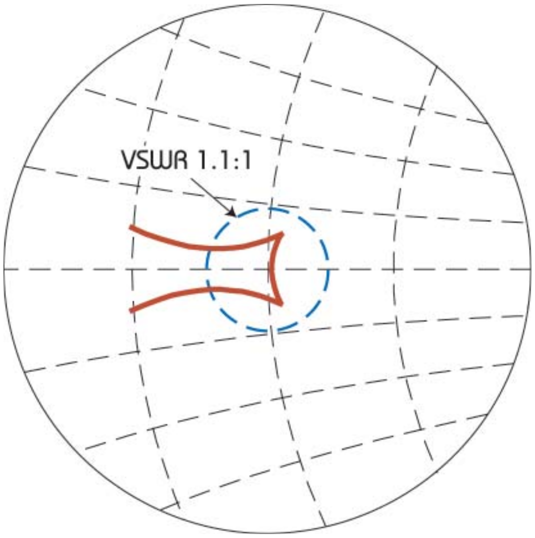


Figure 45. Impedance of a 3-Cavity Bandpass Filter in Series with Two Notch Cavities

Note that the insertion loss for the pass frequency f_1 is only about 0.25 dB and the isolation at the reject frequency f_2 is greater than 50 dB across the channel.

The impedance plot, Figure 45, is likewise the combination of impedance plots for the same filter combination.

Branched combiners with feedback loops

Although many branched combiners still in operation use notch cavities for enhanced isolation, most modern branched combiners have gone to feedback loop technology (Figure 46) for this purpose.

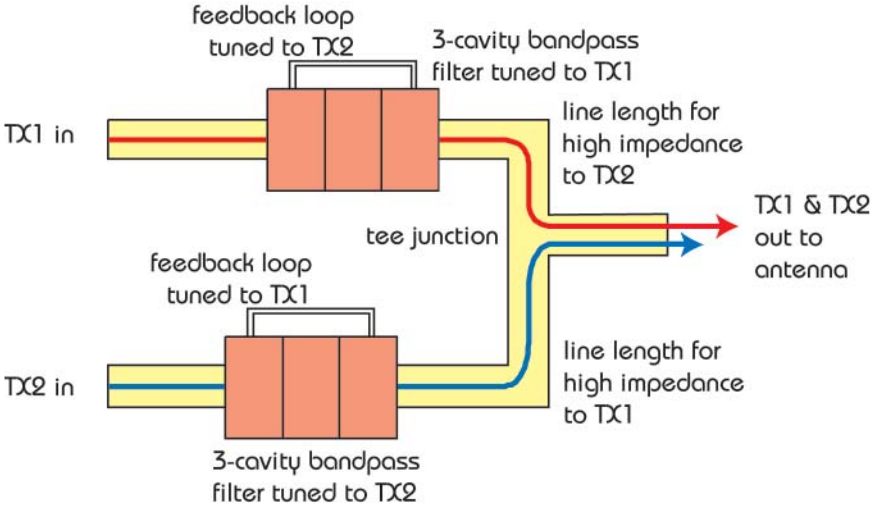


Figure 46. Branched Combiner with Feedback Loops

Figure 47 is the frequency response curve of the three-cavity bandpass filter with feedback loops. Notice that the curve is smoother through the pass band and even though it only has one notch, the isolation at f_2 still exceeds -50 dB.

The impedance plot of a branched combiner with feedback loops is almost identical to that of the combiner with notch filters, Figure 45.

Limitations

A branched combiner is very efficient for a two-station installation, and has been used for as many as four stations, but a tee junction for more stations than that starts to become impractically large, and adjusting the lengths of interconnecting coax becomes prohibitively complex. Also, a branched combiner cannot easily be expanded later to include more stations, although it can be expanded by integrating it with balanced combiner modules. To combine more than four stations, a balanced combiner becomes more practical and cost-effective.

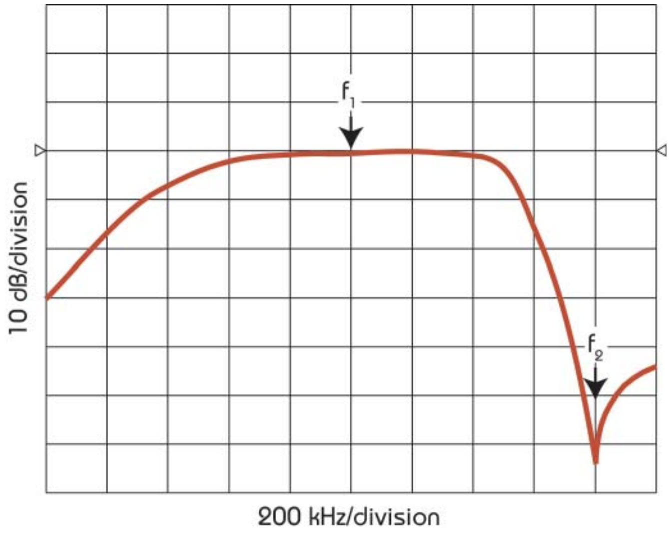


Figure 47. Frequency Response of Branched Combiner with Feedback Loops

Balanced combiners

The balanced combiner is based on a hybrid ring. Each leg of the ring contains an identical set of either bandpass or band-reject filters — hence the term "balanced." It is imperative that the filters of all modules be tuned to have as close to the same response characteristics as possible. The goal is to have the hybrids react identically to the filters. Small differences in electrical length through the hybrids quickly add up to an increased VSWR. For example, a phase difference of ± 2° in the legs of a hybrid produces a VSWR of 1.07:1 (or a return loss of -29 dB). If that phase difference degrades to ± 4°, the VSWR deteriorates to 1.15:1 (-23 dB).

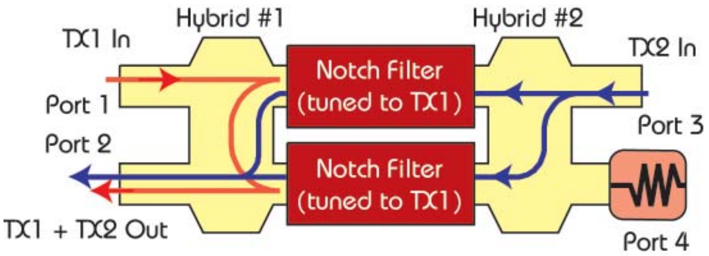


Figure 48. Two-Station, One-Module Notch Filter Balanced Combiner

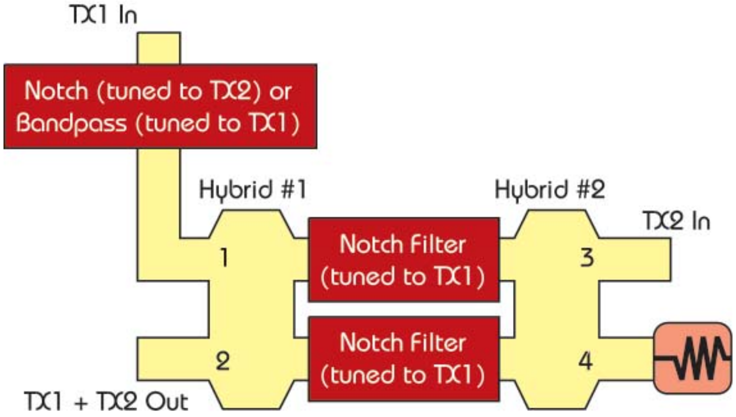


Figure 49. Two-Station, One-Module Notch Filter Balanced Combiner with Input Filter at TX1

Most early balanced combiners used notch filters.

Notch filter balanced combiners

In the notch-filter balanced combiner (Figure 48), both notch filters within the hybrid ring are tuned to reject TX1's frequency, which enters the combiner (red arrows) at port 1. That signal is reflected by the filters, and exits at port 2.

TX2 (blue arrows) enters the broadband input port of the module, port 3, passing through in the diagonal mode shown in Figure 19, with minimal loss in the reject cavities.

Performance

The isolation of transmitter 2 from frequency TX1 is the sum of the hybrid ring isolation of -35 dB and the isolation of the notch cavities, which can approach -35 to -40 dB. However, the isolation of transmitter 1 from frequency TX2 is only that of the hybrid ring; about -35 dB. Therefore, additional filtering, either bandpass or band-reject, is required to ensure that no spurs are generated within transmitter 1. This added filter is shown in figure 49.

External bandpass filtering

A better way to reject multiple unwanted frequencies, of course, is to use a bandpass filter tuned to the desired frequency. For example, Figure 50 shows a five-station, four-module combiner.

In this example, each input filter is a bandpass filter tuned to the frequency of that input. If reject filters were to be used at the various inputs, each input would have to filter all the frequencies previously introduced. Therefore, port 3 of module 2 would have to contain two notch filters; port 1 of module 3, three filters; and port 3 of module 4, four filters. This proliferation is avoided by the use of input bandpass filters.

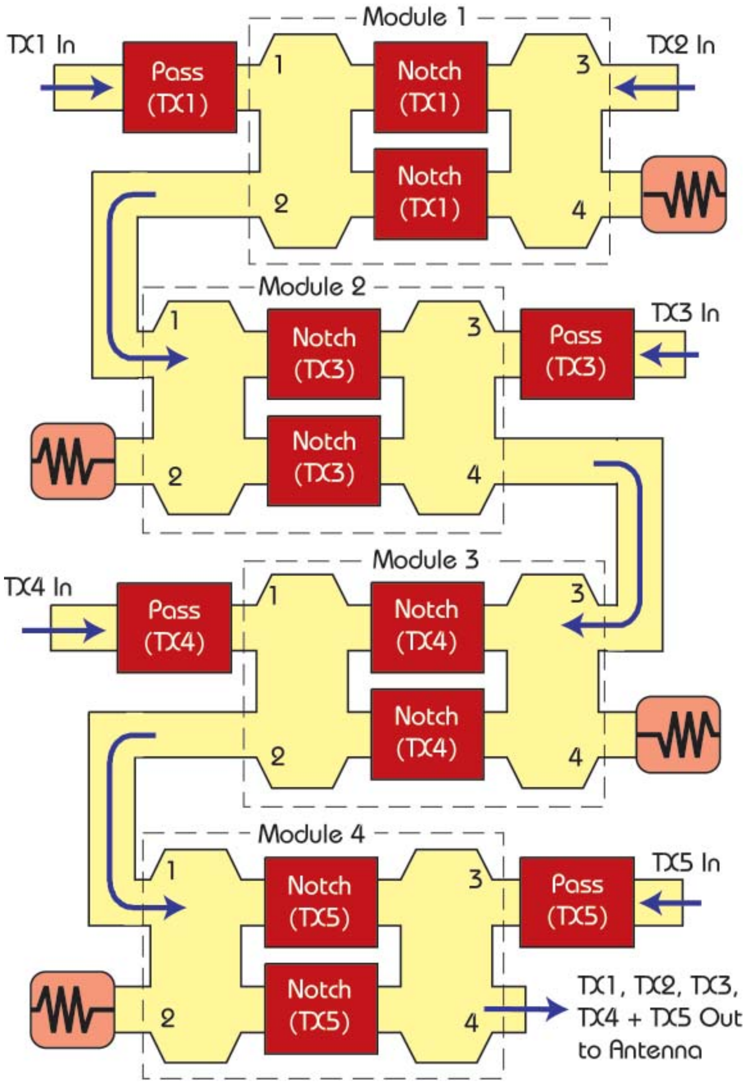


Figure 50. Five-Station Notch Balanced Combiner with Input Bandpass Filters

Emergency input port

In some cases, instead of having a station located at port 3 of module 1, that port is terminated in a 50-ohm load and can be used as an emergency input for any station in the system. Providing an extra port in this way allows a damaged module to be bypassed. Because of the nature of that particular port, as long as the input filter at port 1 of module 1 is a bandpass filter, no further input filtering is necessary.

Limitations of notch filter balanced combiners

A problem with using notch filters within the hybrid rings is that if the two filters in any module are not identically tuned, an imbalance occurs within the hybrid ring, thus reducing the isolation to a point where a spur can be generated within a transmitter. Once a spur has been generated, there are no filters within the system to reject that spur, since the filters are tuned only to the expected frequencies. Therefore, the spur is broadcast.

A second disadvantage of using internal notch filters is that since each module in turn has to conduct the accumulated power of all the previous modules, for a high-powered system each module must be larger than the previous one, and the power rating of the system is limited by the size of the final module.

Third, notch-filter combiners are impractically narrowband in nature for today's wideband IBOC channels, especially when the frequencies combined are close-spaced.

Because of these limitations, notch-filter systems are no longer used. Modern FM combiners use bandpass filters.

Bandpass filter balanced combiners

In a bandpass balanced combiner system, bandpass filters are used within the hybrid ring. The basic system layout is similar to that of a notch combiner.

The power flow is shown in Figure 51 (compare to Figure 48). In the notch system, the filters rejected signal TX1 entering port 1. In the bandpass system TX1 also enters port 1, but passes through the hybrid ring's bandpass filters and out port 4, while signal TX2, entering at port 3, is reflected by the filters and exits at port 4.

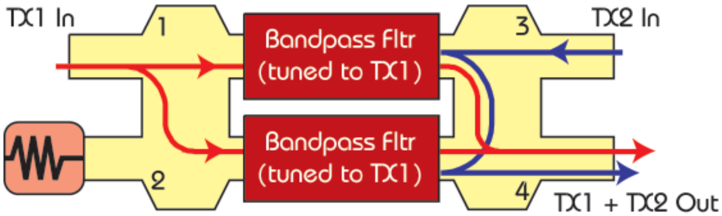


Figure 51. Two-Station, One-Module Bandpass Filter Balanced Combiner

The isolation of transmitter 1 from frequency TX2 is the sum of the hybrid ring isolation (35 dB) and the isolation of the bandpass filter (about 25 dB). However, the isolation of transmitter 2 from frequency TX1 is only the hybrid ring isolation of about 35 dB. Therefore, an additional filter must be added between transmitter 2 and its input port (Figure 52), similarly to the single-module notch filter balanced combiner shown in Figure 49.

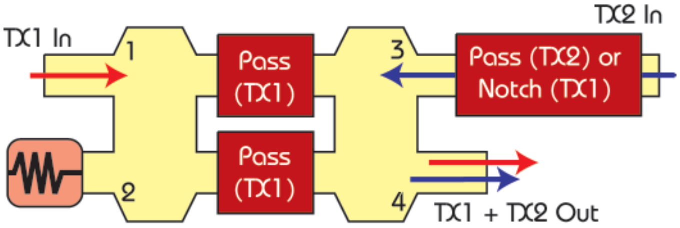


Figure 52. Two-Station, One-Module Bandpass Filter Balanced Combiner with Input Filter at TX2

Alternatively, a second module may be added to port 4 of module 1, and port 3 terminated in 50 ohms (and available as an emergency input port). Signal TX2 is then introduced at port 1 of module 2, as shown in Figure 53.

No input filter is necessary now for TX2, because it is isolated by the bandpass filters in Module 2. The emergency input port now sees both frequencies TX1 and TX2, reduced 35 dB below each transmitter's power level.

A multiple-station bandpass balanced combiner (Figure 54) is an extension of the latter configuration, where each frequency has its own module.

In a bandpass system the accumulated power entering each module flows only through the output hybrid, so the power-handling capacity of the system is limited only by the size of the output hybrids and interconnecting transmission line, not the entire module.

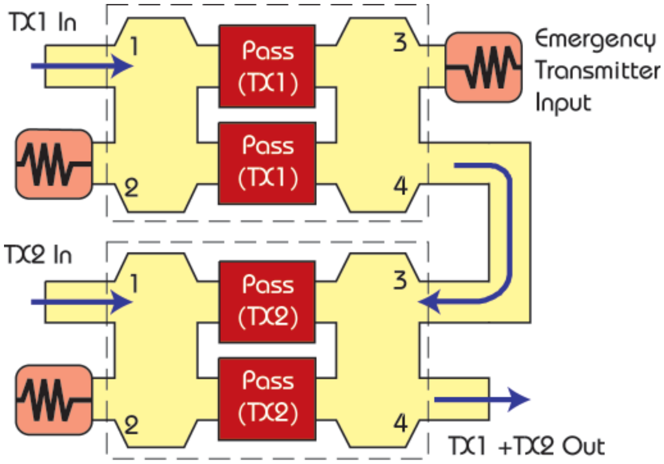


Figure 53. Two-Station, Two-Module Bandpass Filter Balanced Combiner

Performance

The frequency response, the group delay, and the impedance diagram for this combiner are shown in Figures 55, 56 and 57, respectively.

Group delay effects

When two stations are 1.2 MHz apart or closer, the bandpass filter will not provide quite enough isolation, allowing a small amount of signal interaction. This affects the group delay curve of the module which is farthest from the antenna, as shown in Figure 58.

A group delay equalizer can be installed either at the combiner input, using high-power components, Figure 59, or between the transmitter's exciter and the IPA, using similar low-power components, Figure 60.

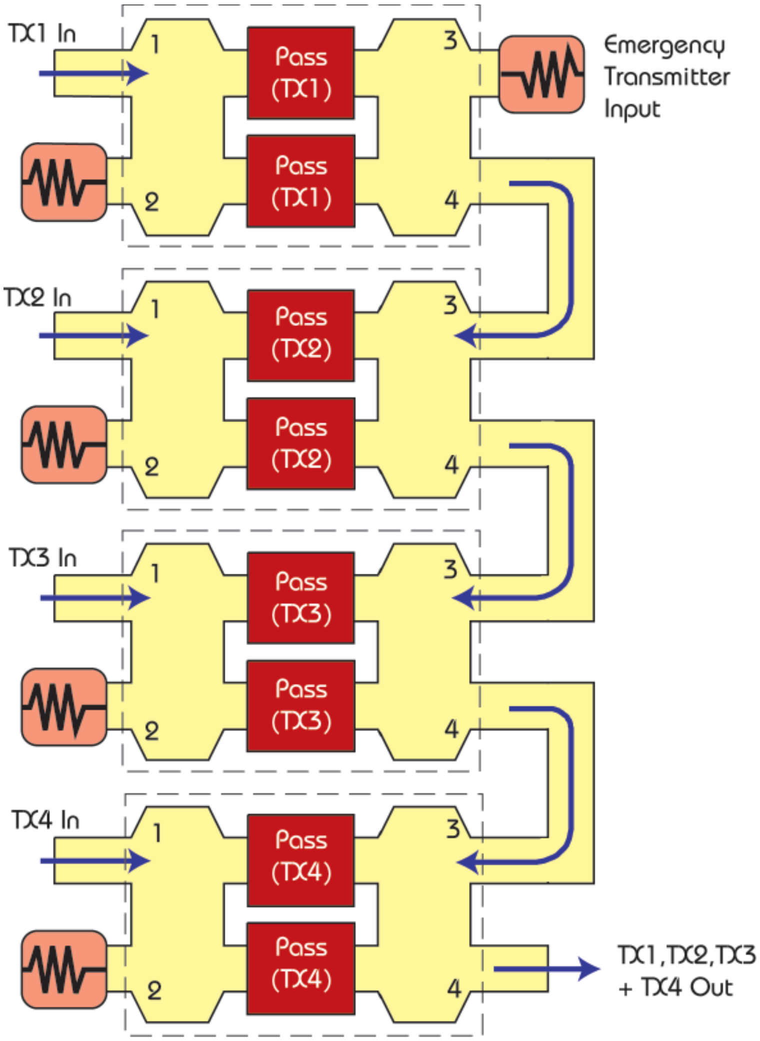


Figure 54. Four-Station Bandpass Filter Balanced Combiner

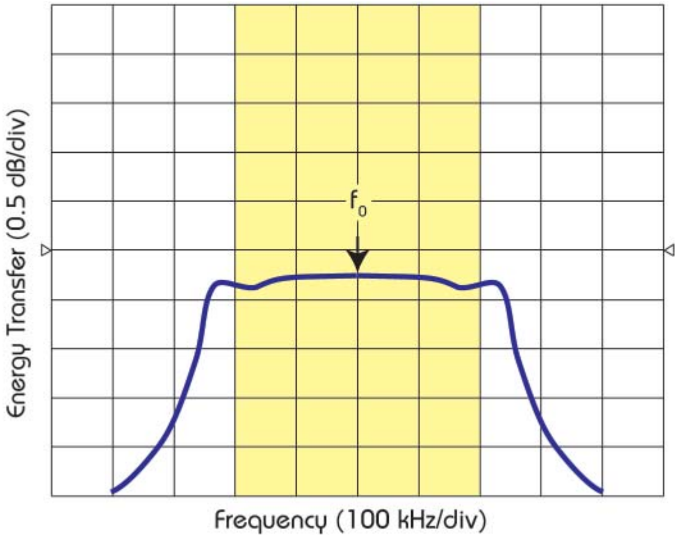


Figure 55. Frequency Response, Bandpass Filter Balanced Combiner

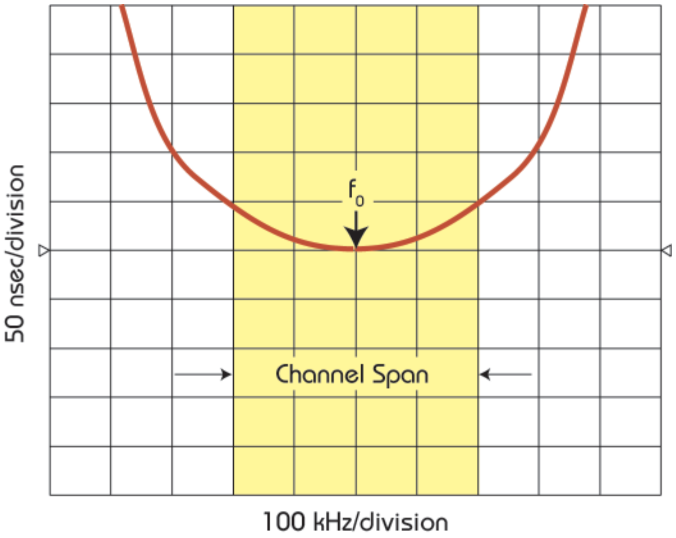


Figure 56. Group Delay, Bandpass Filter Balanced Combiner

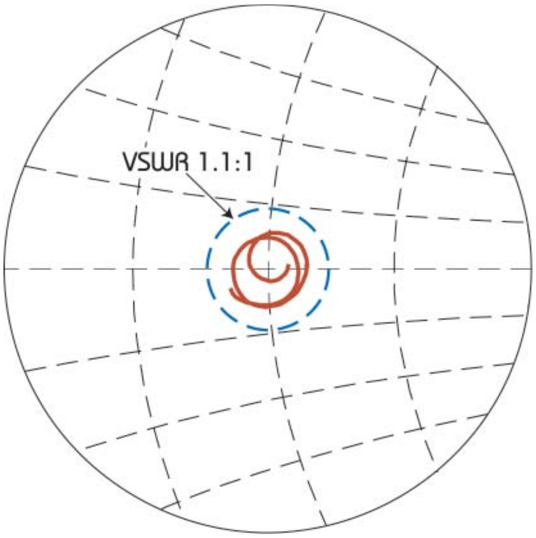


Figure 57. Impedance, Bandpass Filter Balanced Combiner

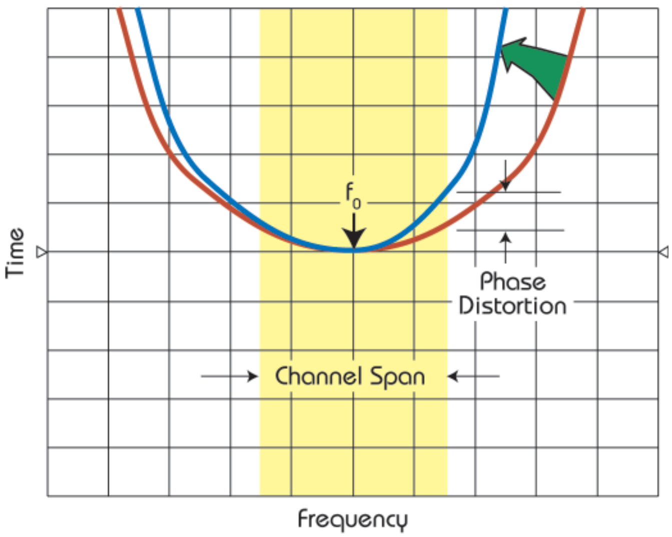


Figure 58. Distorted Group Delay

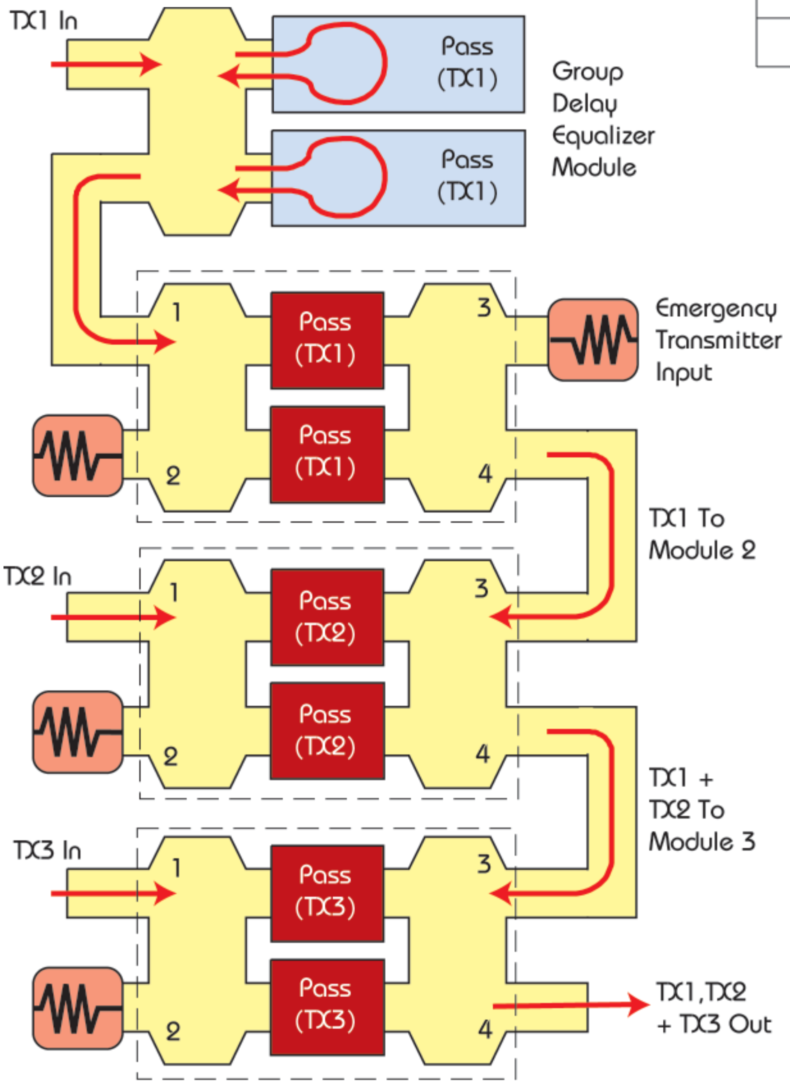


Figure 59. Balanced Combiner with Group Delay Equalizer at Combiner Input

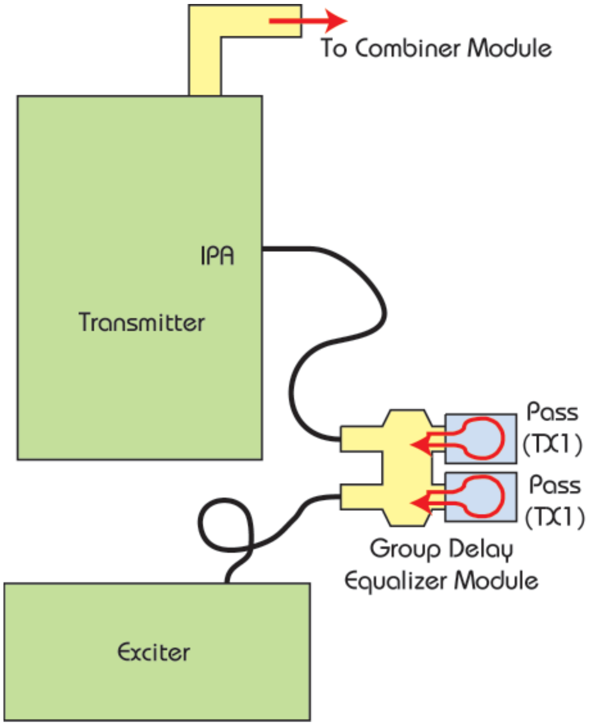


Figure 60. Group Delay Equalizer between Exciter and Transmitter IPA

Combining digital and analog signals

High-level combining

Small probes or small strip lines forming a precision directional coupler have been used to couple a small amount of energy out of the transmission line with coupling factors of anywhere from -40 dB to -60 dB from the RF power level being transmitted within that line. Losses due to this sampling system are insignificant to the analog signal.

High-level combining uses a directional coupler (Figure 61) that has been mechanically enlarged to handle power levels in the kilowatt range, with a nominal coupling factor of -10 dB, to "inject" the digital signal into the analog RF stream.

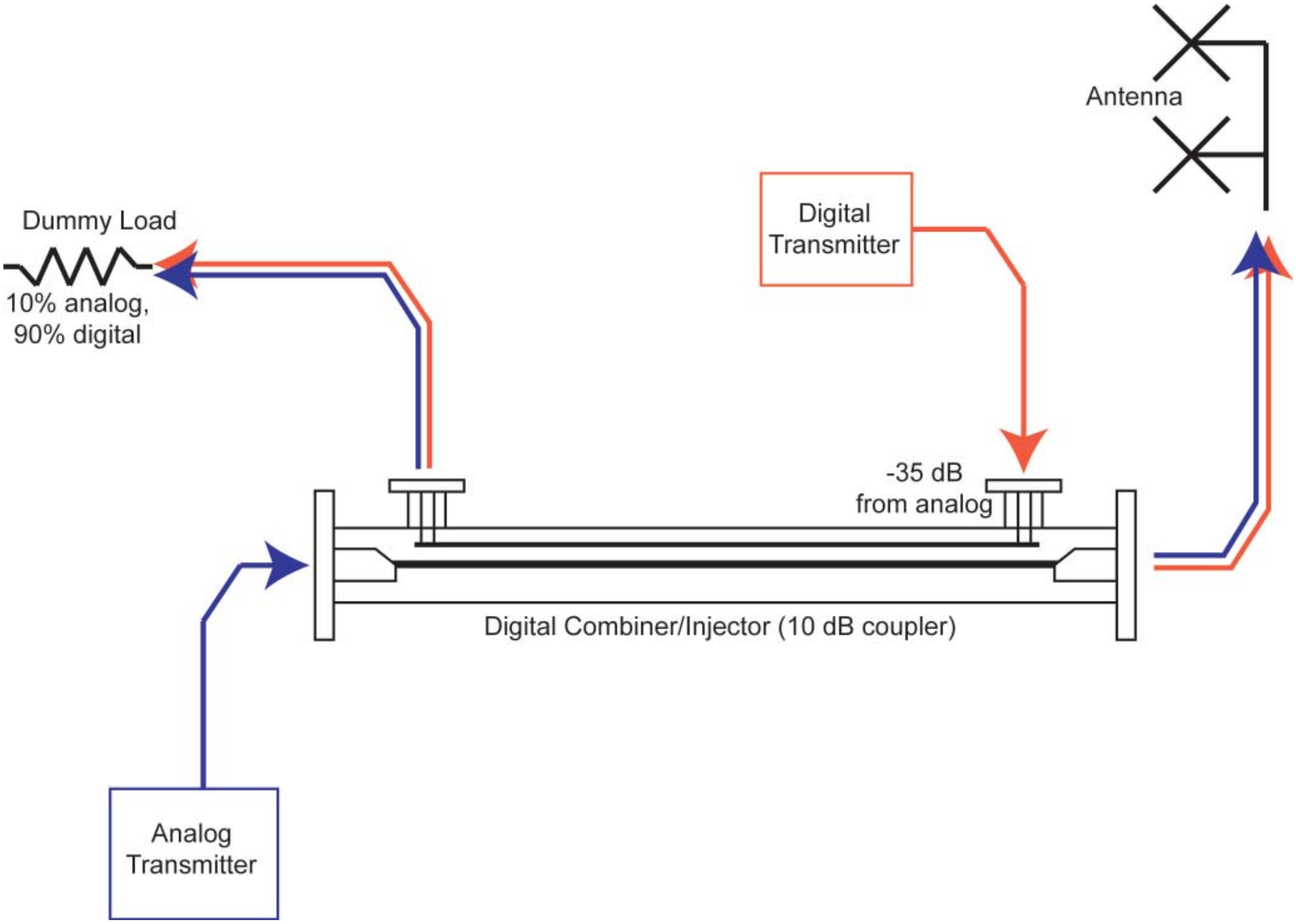


Figure 61. High-Level Combiner/Injector

One strip carries the RF energy from the analog transmitter, which is considered the main line of the transmission system. The other strip is considered the coupling strip. The spacing of the strips determines the amount of coupling between the two signals. Increasing the coupling to only -10 dB introduces a significant loss of a full 10% of the analog power, which is dissipated in a dummy load.

The digital signal enters the directional coupler at the reject port of the coupler, referenced to the analog input. Because it is a -10 dB coupler, only 10% of the digital signal is coupled to the main line. The remaining 90% flows to the dummy load.

Several iterations of a high power combiner/injector were experimented with over the years. The -10 dB value was arrived at as a good compromise for minimizing the loss to the analog transmitter while keeping the size of the digital transmitter to a reasonable level. An injector with a coupling factor smaller than -10 dB will increase analog losses, while a larger coupling factor will require a substantially larger digital transmitter.

This method of combining analog and digital is normally used for stations that only have one single-input antenna and an analog transmitter with the reserve capacity to make up for the 10% loss in power. Depending on the reserve capacity of the analog transmitter and the size of the digital transmitter, the coupling factor can be adjusted to optimize almost any installation.

Mid-level combining

Mid-level combining (Figure 62) was developed by incorporating a standard -3 dB quadrature hybrid and using two analog transmitters; one standard analog transmitter and one linearized transmitter equipped to transmit digital along with the analog. It has been a well-established practice to combine two analog transmitters into a quadrature hybrid so that most of the power goes up to the antenna with minimal loss to the hybrid's dummy load. When the digital component of the linearized transmitter is turned on, the signal enters Port A with its associated analog signal. Because there is no digital signal entering Port B, the digital signal is split in half.

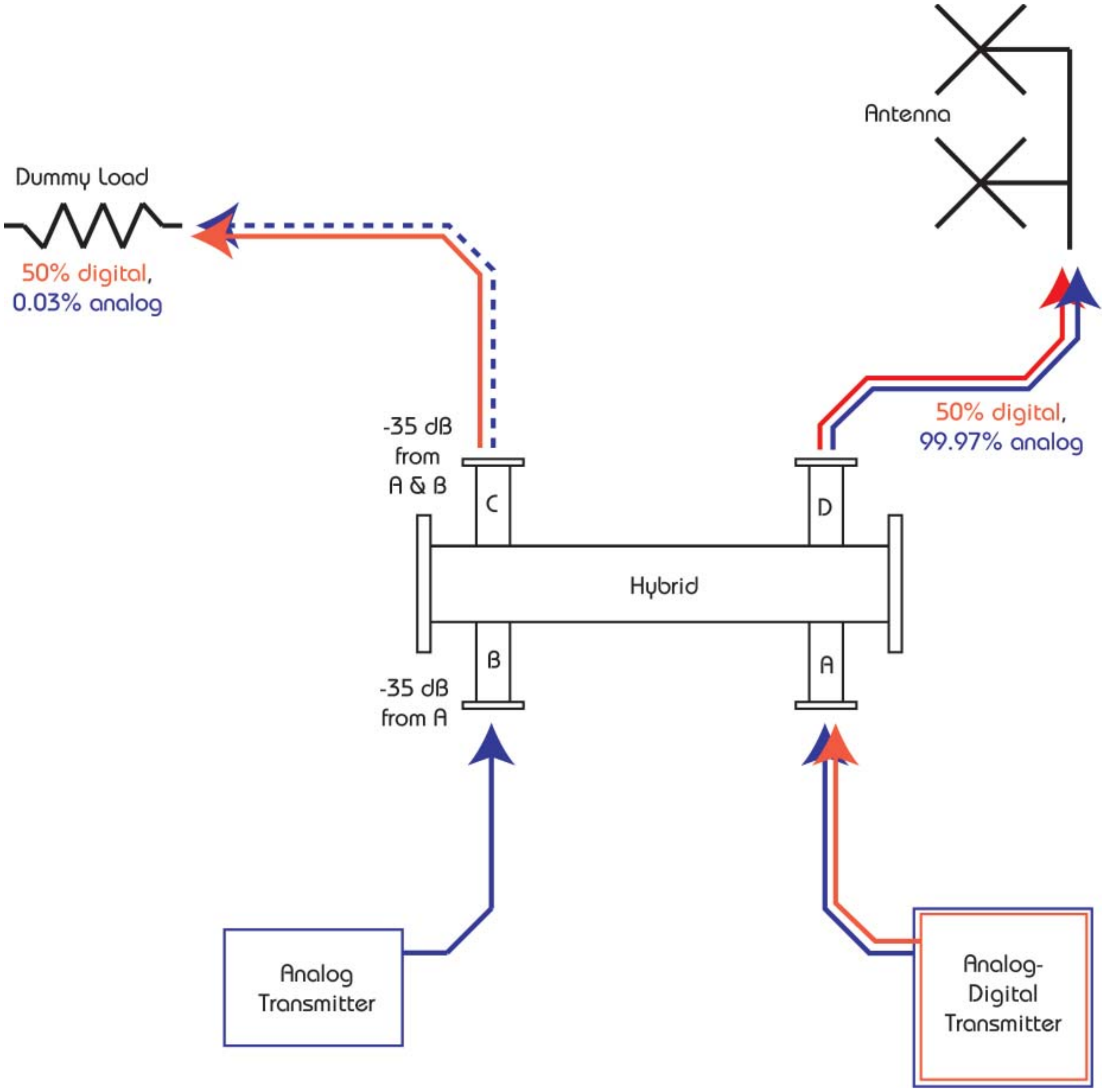


Figure 62. Mid-Level Combining

The benefit of this method over high-level combining/injection is that there is no significant loss to the analog signal and only a 50% loss to the digital signal rather than a 90% loss.

As with the high-level coupler/injector, the power split of the hybrid can be optimized to accommodate different-sized analog transmitters.

Combining using bandpass balanced combiners and antenna systems

Strategies that combine analog and digital signals in antenna radiators, or use separate analog and digital radiators in close proximity, are among the most popular IBOC implementation strategies because they minimize the size and cost of the digital transmitter and reduce the energy wasted.

Back-feeding IBOC into a balanced module

The simple use of balanced combiner modules shown in Figure 54 is termed "single-feeding." A variation on this configuration is called back-feeding (Figure 63), and is used for low-level combining of analog and digital signals with minimal loss.

Digital transmitters are fed through isolators into the hybrid ports opposite the analog transmitter ports and a combined digital signal exits the wideband port (top left) normally occupied by the system reject load in a single-fed combiner. The only added hardware is the isolator in place of the dummy load of the single-feed combiner, to prevent analog on-channel signals from feeding back into the digital transmitter.

Why an isolator?

Transmission systems that do not have enough isolation between the analog and digital components require isolators. When combiners are configured for back-feed operation, on-channel power is coupled from one transmission path into the other via the antenna elements, and feeds back into the module through the opposite leg from which it exited.

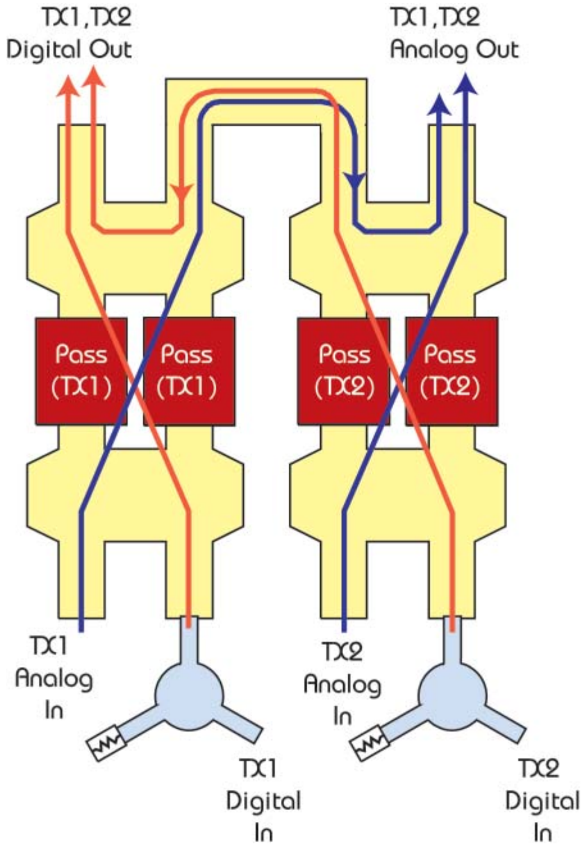


Figure 63. Back-Feed Configuration

While an efficiently operating antenna will minimize the energy coupled between paths, there will still be sufficient energy returned to require a dummy load for the port opposite the analog transmitter input. If a station runs an analog-only or high-level combined analog/digital signal, a stand-alone dummy load is used on this port. When the port is occupied by a digital transmitter, the dummy load becomes part of an isolator assembly.

Isolators are not used where the analog and digital signals are already combined in the transmitter (low level), combined through a hybrid providing at least 35 dB of isolation (mid-level), or combined using a coupler/injector providing at least 35 dB of isolation (high level).

Cross-feeding IBOC into a balanced module

The cross-feed, or split-feed, configuration (Figure 64) is a further extension of back-feeding. Rather than segregating digital and analog signals into separate transmission lines, it combines the analog signals of some stations with the digital signals of others. Again, an isolator is used to provide additional isolation between the analog and digital transmitters.

Usually, the analog power is split as evenly as possible, thus minimizing both the average and peak power any broadband line component carries. Thus 9" components are eliminated in all but the largest systems.

Using equal-sized transmission lines also provides redundancy. A failure in a transmission line or portions of the antenna feed system can be overcome by directing a station's primary transmitter (either analog or digital) over the remaining transmission line.

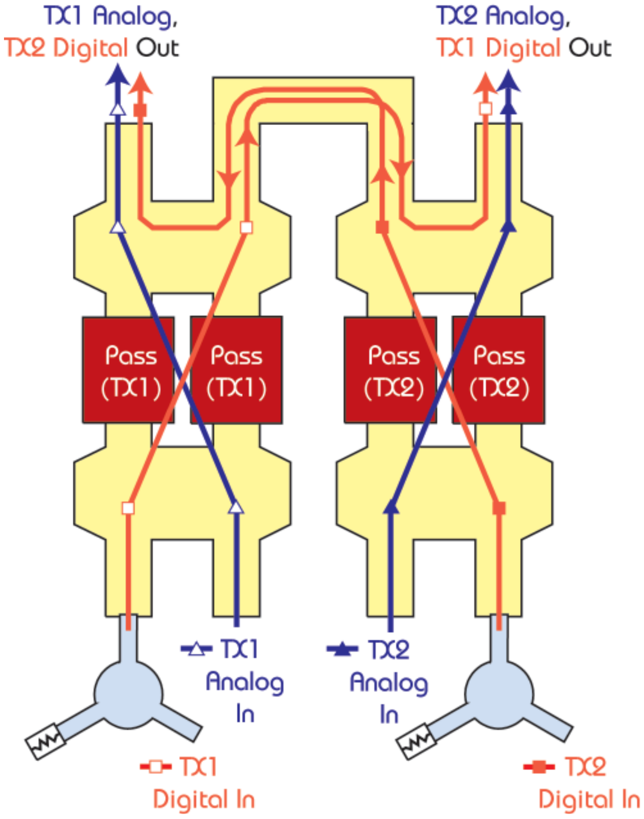


Figure 64. Cross-Feed Configuration

Conclusion

Combiners are required when it is necessary to transmit multiple signals from a single antenna. Without proper combining, signals will interact in each other's transmitters, producing intermodulation products. This section discusses the fundamentals of combining and the use of combiners in FM broadcasting. Several designs and many different components and configurations are described.

The various types of combiners have their own advantages and disadvantages. The system designer must be aware of each so that he can select the appropriate filter system or systems for his own application.

About the contributors.

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Albert G. Friend, Technical Writer/Editor for Shively Labs, edited the text and created the illustrations.

Shively Labs's Web site, containing this and other technical bulletins, is www.shively.com.

Books on related topics.

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