Economical High-Power Broadband Circularly Polarized FM Broadcast Panel Antenna

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Abstract – *Historically, broadband circularly polarized multi-station FM panel broadcast antennas have been limited to crossed dipole or quad dipole designs with two or more inputs per panel. These designs require a significant number of radiator parts and elaborate external feed systems with many cables, power dividers and/or 90-degree hybrids. In all of the current designs, the number of stations and the maximum total power that the master FM antenna can accommodate is usually limited by the size of the input balun of each radiator. This paper will discuss a new approach to a broadband, circularly polarized FM broadcast antenna panel with a reduced number of parts in each radiator as well as having only a single input to each panel. The single input considerably reduces the amount of required external feed system which in turn reduces cost and improves reliability. This new design also incorporates a single large balun tube allowing for high power operation.*

INTRODUCTION

All broadband circularly polarized FM broadcast panel antennas on the market today are variations of three basic dipole designs.

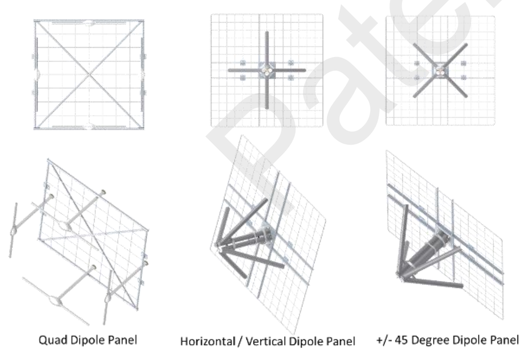


Figure 1: The three basic dipole designs used in FM broadcast panels. Quad dipole, horizontal / vertical crossed dipole pair and +/-45 degree crossed dipole pair.

In all cases, these panel designs have either two or four inputs per panel or a hybrid attached to the back of each panel converting the inputs into a single feed. Hybrids simplify the external feed system but add both cost and complexity to the panel. For simplicity of comparison, assume a panel array of a single layer of three panels around without the use of hybrids attached to the panel inputs. The feed system for the quad design array would typically consist of a two-way power divider feeding two six-way power dividers feeding twelve cables as shown in Figure 2.

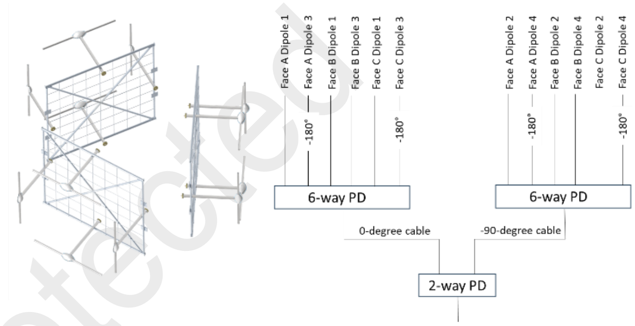


Figure 2: Single layer panel array and feed system layout for a quad dipole configuration.

For the same simple single layer array case, both the horizontal / vertical crossed dipole pair and the +/-45 degree crossed dipole pair would typically utilize a single six-way power divider feeding six cables as shown in Figure 3.

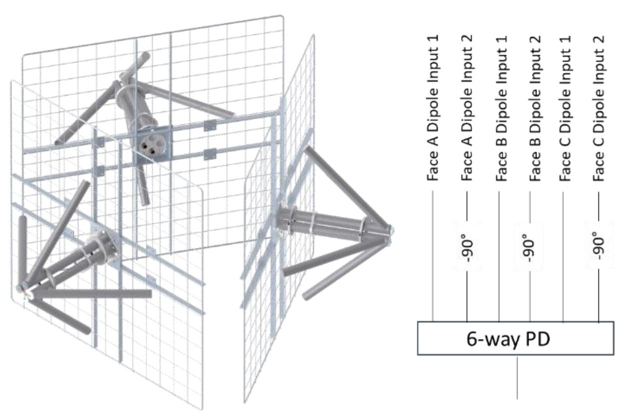


Figure 3: Single layer panel array and feed system layout for a horizontal / vertical dipole, or a +/- 45 degree dipole configuration.

Note that the horizontal / vertical or the +/-45 degree dipole pairs require only half of the external feed system compared to the quad dipole design, thus reducing the number of cables and connections.

IMPEDANCE OF A DIPOLE

The input impedance of a dipole is given by [1]:

$$Z_{in} = R_{in} + jX_{in}\Omega \quad (1)$$

Where R_{in} is the input resistance and X_{in} is the input reactance.

$$R_{in} = \frac{\eta}{2\pi}\Big\{\Big[C + ln(kl) - C_i(kl) + \frac{1}{2}\sin(kl)\,[S_i(2kl) - 2S_i(kl)] + \frac{1}{2}\cos(kl)\Big[C + \ln\Big(\frac{kl}{2}\Big) + C_i(2kl) - 2C_i(kl)\Big]\Big\} \Big/ \Big(\sin\Big(\frac{kl}{2}\Big)\Big)^2 \quad (2)$$

$$X_{in} = \frac{\eta}{4\pi}\Big\{\Big[2S_i(kl) + \cos(kl)\,[2S_i(kl) - S_i(2kl)] - sin\,(kl)\Big[2C_i(kl) - C_i(2kl) - C_i\Big(\frac{2ka^2}{l}\Big)\Big]\Big]\Big\} \quad (3)$$

Where:

C = .5772 (Euler's constant)

$\eta = \sqrt{\frac{\mu}{\varepsilon}}$ (Intrinsic Impedance)

$$S_i(x) = \int_0^x \frac{siny}{y}dy$$

$$C_i(x) = \int_\infty^x \frac{cos\,y}{y}dy$$

a = Dipole radius

$$k = \frac{2\pi}{\lambda}$$

l = Dipole length

The Sine and Cosine integrals ($S_i(x)$ *and* $C_i(x)$) can be approximated using series expansions:

$$S_i(x) \approx \sum_{n=1}^{\infty}(-1)^{n-1}\frac{(x)^{2n-1}}{(2n-1)(2n-1)!} \quad (4)$$

$$C_i(x) \approx C + \ln(x) + \sum_{n=1}^{\infty}\frac{(-1)^n x^{2n}}{(2n)(2n)!} \quad (5)$$

To understand how the radiated amplitude and phase of a dipole changes versus its length, the dipoles input impedance can be plotted using equations 2 and 3 as shown in Figure 4.

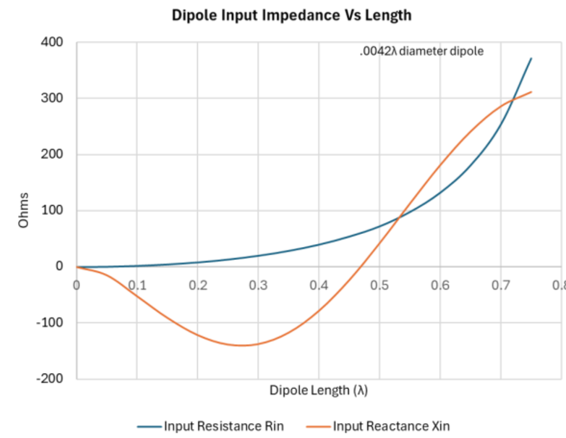


Figure 4: Input impedance vs. length of a .0042λ diameter dipole

The input impedance is the ratio of voltage to current at the feed point location which is directly related to the feed point phase. The resonance of a center fed dipole is where the reactance is zero and the dipole impedance is purely real. This occurs at a length that is slightly less than half of a wavelength. At this point the feed point phase is zero. Using the real and imaginary parts of Zin, (Rin and Xin), the feed point phase can be calculated and plotted as shown in Figure 5.

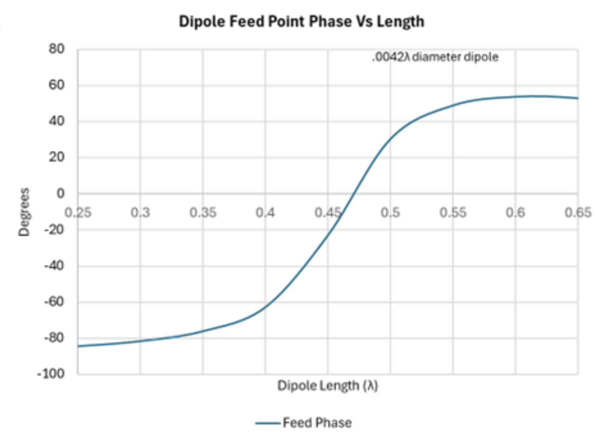


Figure 5: Feed point phase of Zin vs. length of a .0042λ diameter dipole

It is apparent that a 90-degree phase differential can be obtained between two dipoles with a small length difference between them. This occurs between approximately .4 and .5 wavelengths.

SINGLE INPUT CIRCULARLY POLARIZED PANEL ANTENNA

The concept of a single input circularly polarized FM broadcast panel antenna without the use of a hybrid was first demonstrated in Oakley Woodward and Matti Siukola's patent 4,062019 in 1977. The product that was born from the RCA's inventor's innovation came to be known as the DCPJ and is still a popular product today. The panel's premise is based on creating the circularly polarized signal by feeding a pair of dipoles each having two arms of differential length. Since the balun feed creates a 180-phase shift and the differential dipole lengths create a 90-degree offset as shown in Figure 5, the four dipoles are then fed by phases of 0,90,180, and 270 degrees respectively, forming the circularly polarized signal. This technique simplifies the design by eliminating the need to have two inputs, 4 balun tubes, or possibly a hybrid. The single input design requires only half the number of necessary cables in the external feed system compared to the horizontal / vertical or +/- 45 degree dipole pair designs and only one quarter of the cables compared to the quad dipole design. Refer to Figure 7 and compare to Figure 2 and 3.

Figure 6: DCPJ FM broadcast panel antenna.

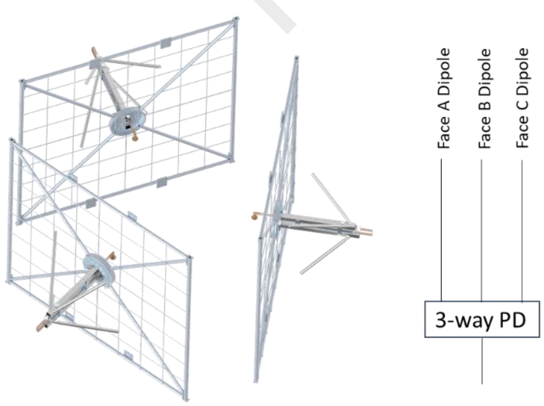


Figure 7: Single layer panel array and feed system layout for a DCPJ panel configuration.

The DCPJ provides an economical solution to expensive cavity backed radiator designs, but due to its limited impedance bandwidth, it has been confined to single channel operation.

INCREASING BANDWIDTH

There are several techniques that are commonly used to expand the bandwidth of dipoles. The combination of the following is implemented and proves the bandwidth of the traditional DCPJ can be increased from 3 MHz to 20 MHz in the FM band.

Increase dipole diameter:

The Q or quality factor is defined by the ratio of the reactance to the resistance and is inversely proportional to bandwidth.

$$Q = \frac{|X_{in}|}{|R_{in}|} = \frac{f_c}{f_2 - f_1} = \frac{1}{BW} \quad (6)$$

From equations 2 and 3, the dipole radius (a) only shows up in the reactance (X_{IN}). This leads to thicker dipoles having broader bandwidth. This is because they exhibit a smaller reactance change with frequency. Historically, the DCPJ dipole utilized 1" diameter tubes as the radiating elements. This corresponds to .0042λ at the center of the FM band and the resulting reactance was shown in Figure 4. Using equation 3, Figure 8 shows the comparison, at FM frequencies, in reactance between a 1" (.0042λ) and a 3" (.0125λ) diameter dipole.

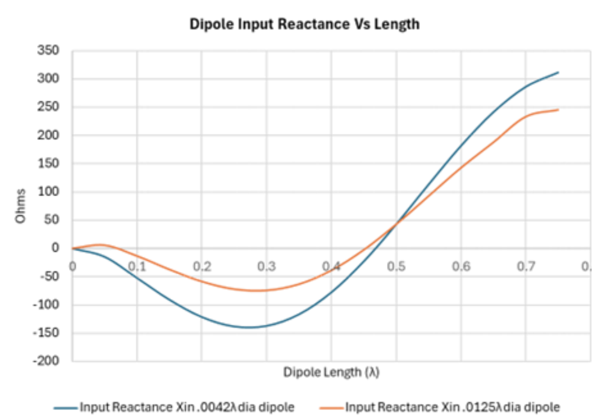


Figure 8: Input reactance vs. length of a .0042λ diameter dipole compared to a .0125λ dipole.

The increase in diameter shows the rate of change of the reactance is significantly reduced which translates to a broader bandwidth. This affects the phase change vs. length differential, which is necessary to produce circular polarization, but with this diameter, a 90-degree difference near response is still attainable as shown in Figure 9.

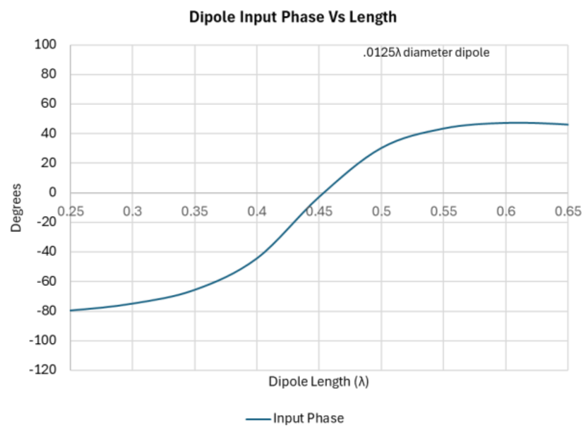


Figure 9: Feed point phase of Zin vs. length of a .0125λ diameter dipole

Add a short circuit stub:

A short circuit stub when positioned and sized on a transmission line acts as a reactive element that will cancel out the reactive component of a load impedance and effectively broaden the usable bandwidth. Keeping the short circuit stub as close to the load as possible provides the best bandwidth to the match.

Add a parasitic element:

Parasitic elements are passive elements that are coupled to a main driven antenna element. They are not fed with power, but they resonate at frequencies slightly different from the driven element. Adding parasitic elements to an antenna such as discs, rods or rings above a dipole can significantly increase its bandwidth by leveraging the combined frequency responses of the driven and the parasitic element. This practice is commonly seen in the use of log periodic antennas designed to operate over a wide band of frequencies.

MATCHING NETWORKS

A matching network is used to match the impedance of a source to a load.

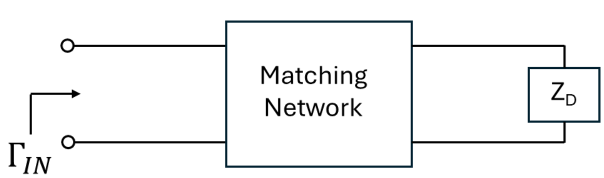


Figure 10: Matching network

This is done by using capacitors and inductors which can be either lumped elements or in the case of high-power RF, distributed elements. The addition of more elements in a matching network can allow for a wider range of impedance transformations resulting in broader band operation. The traditional DCPJ panel has only one matching element, a transformer in the balun, designated here as Z_B to match the load of the dipole Z_D. This limits the usable bandwidth to centering a frequency of interest.

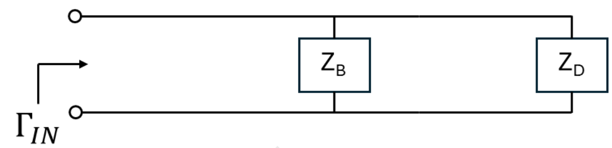


Figure 11: Matching network of a traditional DCPJ FM broadcast panel

The matched impedance at 98 MHz using a transformer in the balun (Z_B) on a typical DPCJ panel is shown in Figure 12.

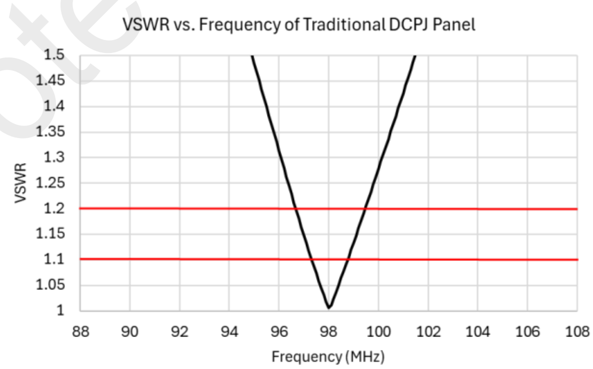


Figure 12: VSWR vs. Frequency of a traditional DCPJ panel antenna matched at 98 MHz using a transformer in the balun.

Note the bandwidth that is under a 1.2:1 VSWR is 3MHz.

NEXT GENERATION - DCPC

By implementing the methods described above to expand the operating bandwidth, DCPC becomes a full band product. The design starts with increasing the diameter of the dipole from 1” to 3”. The basic design is shown in Figure 13. Note the balun has been made into a single tube for simplicity and reduction of parts.

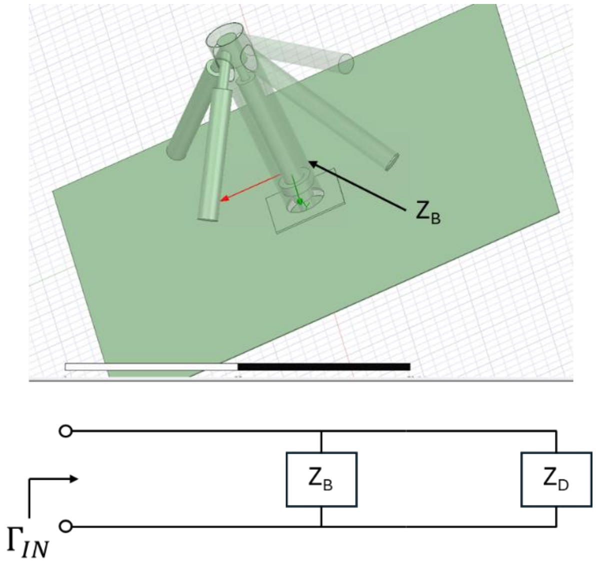


Figure 13: Basic design of the new DCPC.

The balun matched VSWR of the basic design with 3” diameter dipole arms is shown in Figure 14.

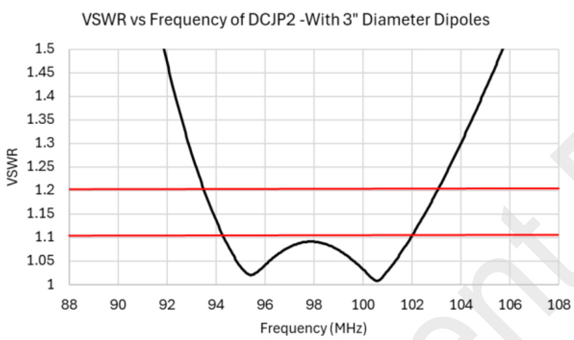


Figure 14: VSWR vs Frequency of the basic design of the new DCPC with 3” diameter dipole arms.

The bandwidth that is under 1.2:1 VSWR has now increased to 9.5 MHz but rises sharply outside of the matched region. Utilizing one of the empty dipole arms, the next step is to add a short circuit stub denoted as Z_{SS} from the feed point down through the arm as shown in Figure 15.

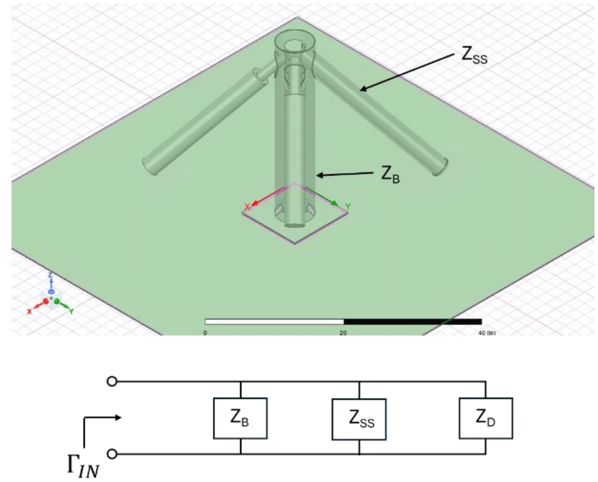


Figure 15: Adding a short circuit stub inside a dipole arm and connected to the feed point.

The bandwidth with the addition of the stub has now increased to 10 MHz under a 1.2:1 VSWR as seen in Figure 16. More importantly, the band edges have flattened out considerably and the design is approaching a full band solution.

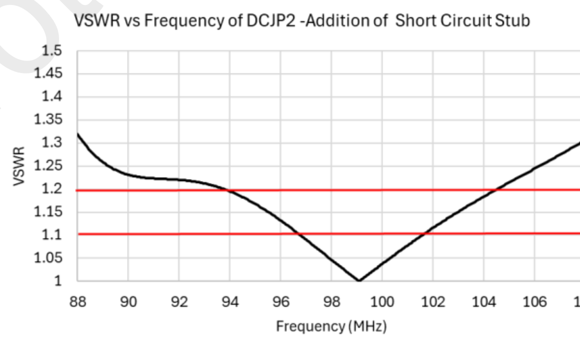


Figure 16: VSWR vs Frequency of the new DCPC with the addition of a short circuit stub in one of the dipole arms.

The final step is to add a floating parasitic ring denoted as Z_P above the dipoles as shown in Figure 17.

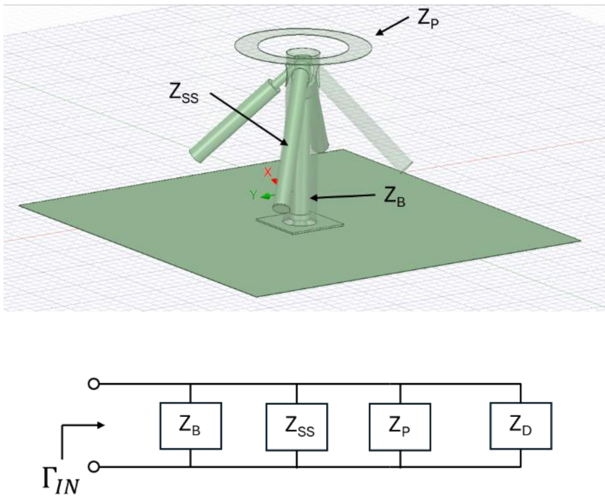


Figure 17: Adding a floating parasitic ring above the dipoles.

The bandwidth with the addition of the stub and the parasitic ring has now increased to 19 MHz under a 1.2:1 VSWR as seen in Figure 18.

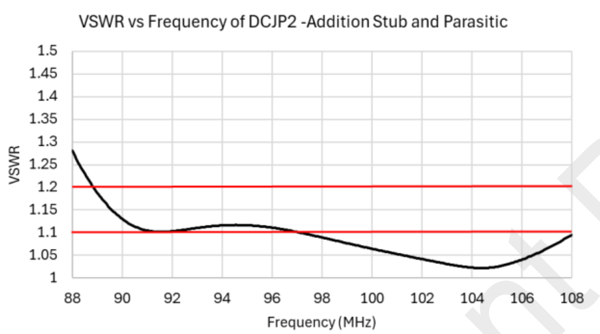


Figure 18: VSWR vs Frequency of the new DCPC with the addition of a short circuit stub in one of the dipole arms and the addition of a parasitic ring.

POWER HANDLING

Typically, broadband master FM broadcast antennas are designed to handle high power to accommodate the total required energy of all the stations combined. In many cases, the limiting factor is the balun tube itself or the flat feed strap that is used to jumper the inner conductor in the balun to the other half of each dipole.

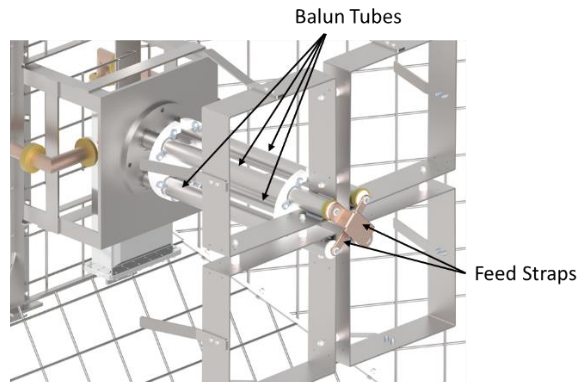


Figure 19: Typical power limiting area of a broadband master FM panel antenna.

The new DCPC utilizes a single balun tube that is 6” in diameter and does not require any feed straps. Refer to figures 13, 15 and 17. This is a vast improvement over existing designs which have multiple smaller size balun tubes and feed straps that are subject to breakdown. Field analysis of a single bay with 10kW power applied to the input reveals a peak voltage of 4.11 kV/cm. Comparing this value to the E-field breakdown in air (22.8 kV/cm), [2], the voltage safety factor of the DCPC is 5.5:1. Note that this translates to over a 30:1 safety factor in the peak power.

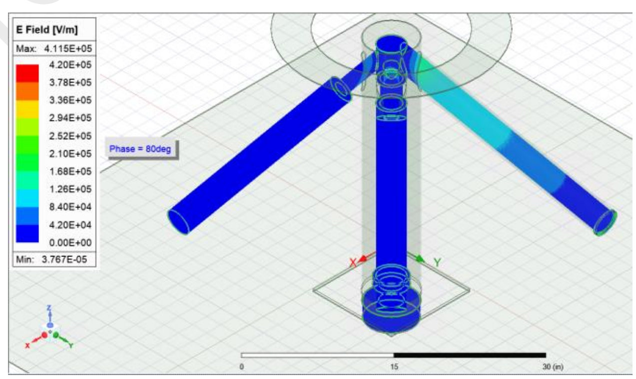


Figure 20: E-field analysis of the DCPC panel antenna.

AZIMUTH PATTERN AND H/V RATIO

Since the horizontal to vertical polarization ratio (H/V ratio) is a function of the differential dipole length on the DCPC as discussed earlier, the ratio will vary with frequency. The H/V ratio on a single panel can be set to near one or equal horizontal and vertical components at the center frequency of 98 MHz. When doing so, the ends of the FM band 88 and 108 MHz have ratios of .67 and .45 respectively as seen in Figure 21.

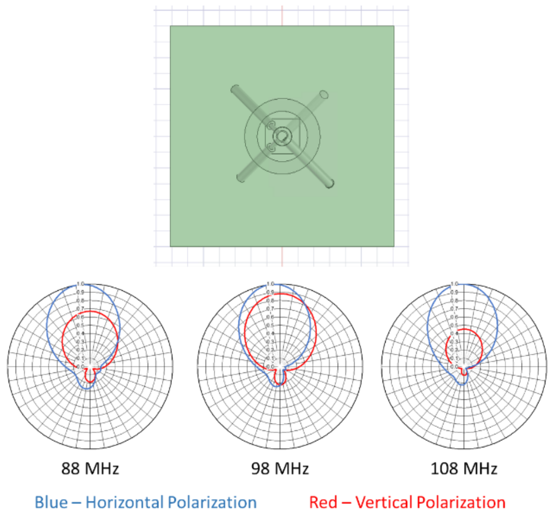
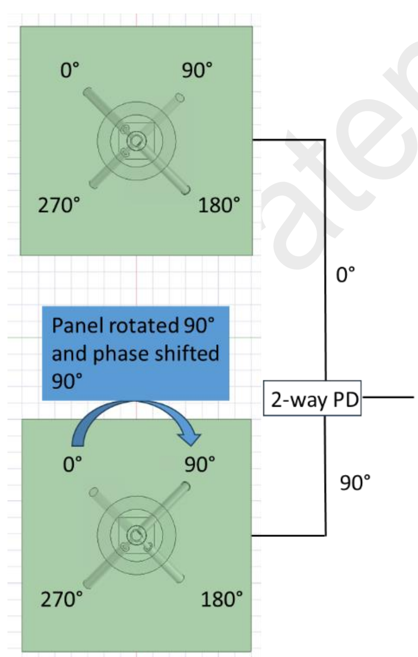


Figure 21: H/V ratio of the DCPC FM panel antenna across the band.

Although not bad, this can be greatly improved to close to a perfect H/V ratio of one across the band. By utilizing the fact that the bays can be rotated to switch the horizontal and vertical components on every other layer in a multilayer system, the mean combined azimuth patterns produce a linear H/V ratio. When rotating the lower bay, the rotating phase (0,90,180,270 degrees) can be brought back into sync by feeding the bay 90 degrees out of phase with respect to the upper bay. This is shown in Figure 22.



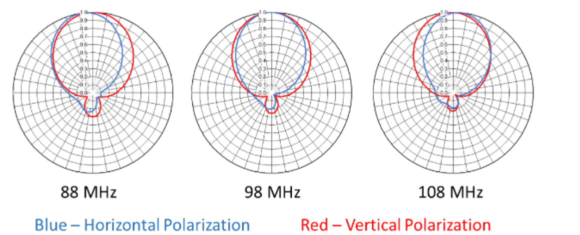


Figure 22: Stabilized H/V ratio of the DCPC FM panel antenna across the band of a two layer array using bay rotation.

Another added benefit of feeding alternating bays 90 degrees out of phase is impedance cancelation. Since the impedance of half the bays will be rotated a quarter wave from the other half, the resulting VSWR will be very low.

CONCLUSIONS

By lowering the Q of the dipole by increasing the diameter as well as adding two more stages to the matching network circuit, the bandwidth of the traditional DCPJ FM broadcast panel antenna can be increased to full band operation. The H/V ratio can be stabilized across the FM band by using a combination of panel rotation and phase shift in a multilayer array. Other benefits of the new DCPC include higher power handling, a single balun tube and no feed straps. The combination of these features provides a superior new product for economical, high power, broadband FM broadcast.

ACKNOWLEDGMENTS

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[2] John L. Schadler "ATSC 3.0 Ready – Designing Antennas for Higher Power OFDM PAPR", NAB BEIT, 2018