Changing the Landscape of FM Broadcast Antenna Technology

BEITC Proceedings John L. Schadler
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Abstract – It has been many years since a new game changing technology in FM broadcast antenna design has been introduced to the market. The many advantages of slotted coaxial pylon antenna technology that have benefitted the UHF and high band VHF broadcast community for decades can now be realized in the FM band. Those benefits include smaller size leading to low wind load, less parts and less connections leading to higher reliability and a high degree of both azimuth and elevation pattern flexibility. In most applications, the use of slotted coaxial antennas has been limited to single channel television operation. In this paper, the use of slotted coaxial pylon antenna technology in the FM band is presented. Discussion includes various methods to increase the bandwidth of slotted coaxial antennas. The cumulative effect of the methods can boost the bandwidth to 20% allowing for effective broadband operation at FM frequencies, leading to a new innovative product line of FM broadcast antennas.

Introduction

In 1967 Matti Siukola, RCA Scientist and Unit Manager of Advanced Development for RCA Broadcast Systems, presented his paper “Dual Polarization FM Broadcasting with a Single Antenna” at the NAB symposium (see Figure 1). The concept of radiating circular polarization from a single element revolutionized the FM broadcast industry and is still the basic premise for antenna design today.

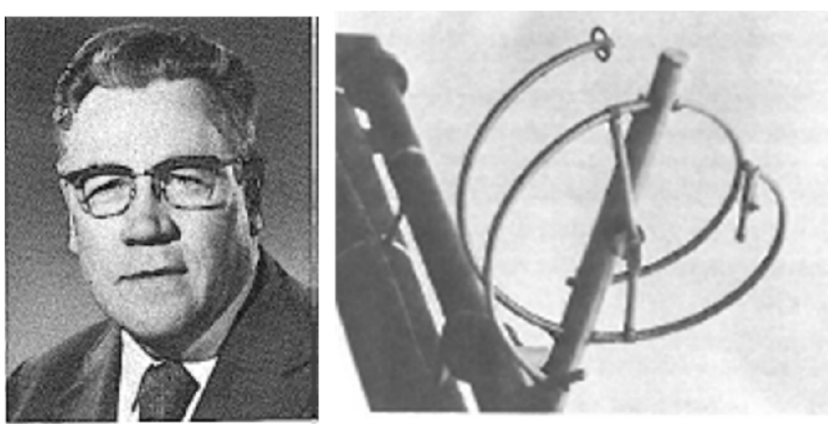

FIGURE 1: MATTI SIUKOLA – RCA’S BFC - FIRST DUAL POLARIZED FM ELEMENT.

The BFC was both bandwidth and power limited due to its size. The quality factor (Q) of a circularly polarized antenna element is directly related to the element’s volume by equation (1) [1] [8].

This paper is excerpted from the Proceedings of the 2022 NAB Broadcast Engineering and Information Technology (BEIT) Conference, © 2022, National Association of Broadcasters, 1 M Street S.E., Washington, DC 20003 USA.

$$Q = \frac{1}{2}\left[\frac{1}{(\beta a)^3} + \frac{2}{\beta a}\right] \qquad (1)$$

Where (a) is the occupied volume radius and β=2π/λ. The fundamental maximum bandwidth bounds of an antenna is given by equation (2) [3].

$$bw = \frac{\pi}{Q ln\left(\frac{VSWR+1}{VSWR-1}\right)} \qquad (2)$$

Where the VSWR is the maximum allowable within the passband [1]. It was clear that the one way to increase the bandwidth of the BFC would be to make it larger. Simply making it bigger degraded the circularity, making the azimuth pattern resemble more of a peanut shape then an omni. In 1978, Don Hymas, RCA Unit Manager Antenna Engineering, presented his work at the 1978 IEEE Broadcast Symposium “A New High Power Circularly Polarized FM Antenna”, which introduced the industry to the RCA-BFM (see Figure 2).

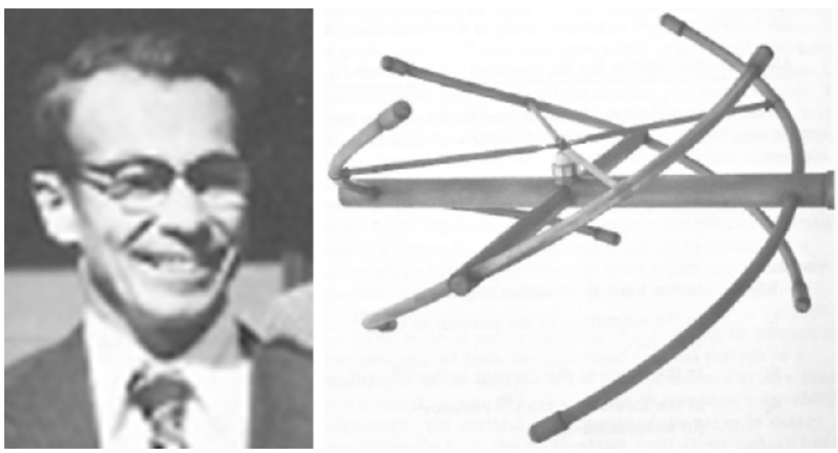

FIGURE 2: DON HYMAS – RCA’S BFM – HIGH POWER BROADBAND CIRCULARLY POLARIZED FM ELEMENT.

The BFM’s quadrupole design was larger for higher bandwidth and filled in the azimuth pattern with its two extra radiators to produce omni directional coverage. This again was a leap in FM technology and is the basis for most FM ring-style antennas today.

The vast majority of UHF broadcast antennas used in the US are slotted cylinder “pylon” designs. Their advantages have been presented and marketed for more than 50 years. It is their simplicity, versatility and low wind load that have made them the antenna of choice. The simplicity was depicted in a witty RCA ad in 1966 shown in Figure 3. The pylon concept has been restricted to the TV bands primarily due to general size and bandwidth limitations. It will be shown in this paper that these limitations can be overcome resulting in a truly innovative game changing antenna design for FM.

FIGURE 3: RCA 1966 AD – JUST NEED A LITTLE PAINT.

Increasing the Bandwidth of a Slotted Coaxial Antenna

The natural bandwidth of a coaxial slot radiator is typically on the order 1% for VSWR operation less than 1.1:1 and is defined as:

$$\%bw = \frac{f_h - f_l}{f_0}(100) \tag{3}$$

The fundamental limitation of a coaxial slot stems from the frequency dependence imposed on the structure by connecting the two sides of the slot together by wrapping the outer conductor to form a cylinder as shown in Figure 4. Even though this fundamental limitation exists, other methods that increase the bandwidth can be applied.

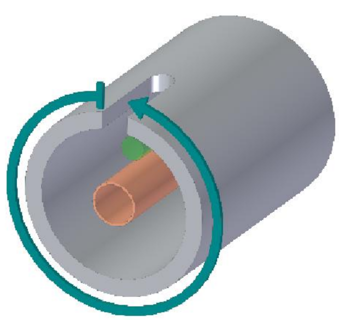

FIGURE 4: CYLINDER CREATES A FREQUENCY DEPENDENCE RESULTING IN NARROW BANDWIDTH.

Techniques to improve bandwidth of an antenna can be classified into two categories: those that lower the quality factor (Q), as seen in equation (2), and those that provide additional phase cancelation outside of the radiating elements. The percent bandwidth needed in order to achieve full band FM operation will need to be on the order of 19%. It must be noted that typical Q values for single slot coaxial antennas range from 30 to 40. In order to achieve 19% bandwidth and considering a maximum allowable VSWR of 1.2:1, the Q must be substantially reduced to approximately 5 to 10, (refer to equation 2). The new pylon design will incorporate two techniques to help achieve the required Q to make full FM band operation achievable.

Reducing the Circuit Capacitance

The Q of a parallel resonant circuit can be expressed as: [5]

$$Q = \omega_0 RC \tag{4}$$

The expression shows direct proportionality between the capacitance C and Q. Reducing the capacitance reduces the Q and in turn will increase the bandwidth as depicted by equation (2). The capacitance of the slot network can be greatly reduced by changing the coaxial inner to a microstrip. The microstrip can be placed near the bottom of the coax outer shell with the slot directly fed with a feed strap. Refer to Figure 5. To quantify the reduction in Q this technique provides, the capacitance of the coaxial line and the capacitance of the microstrip line can be compared. The capacitance of a coaxial line can be calculated using equation 5 [6].

$$C_c = \frac{2\pi\epsilon_0\epsilon_r}{ln\left(\frac{D}{d}\right)} \tag{5}$$

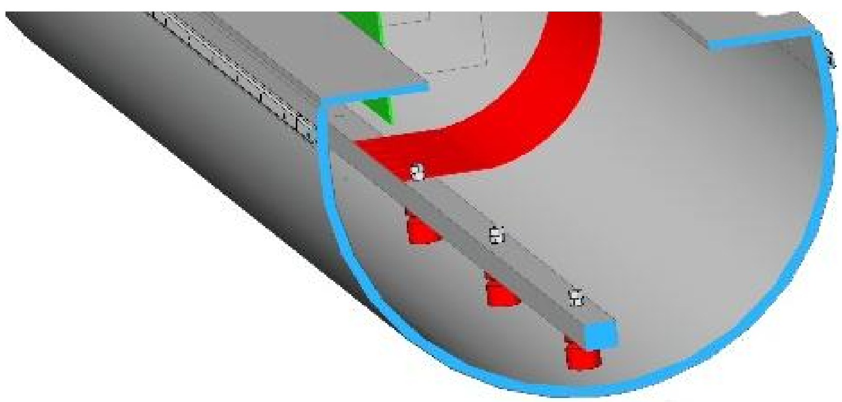

FIGURE 5: MICROSTRIP FED SLOTTED CAVITY.

Where $\epsilon_0 = 8.854X10^{-12}\ F/m$, (D) is the diameter of the inside of the outer and (d) is the diameter of the inner conductor [5]. The capacitance of microstrip can be found using equation 6 [7].

$$C_m = \frac{\epsilon_r L}{60 v_0 ln\left[\frac{8h}{w}+\frac{w}{4h}\right]} \quad for\ \frac{w}{h} < 1 \tag{6}$$

Where $v_0 = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 299792548\, m/s$, w is width and h the height of the microstrip off the backplane. For a typical coaxial design of near 70 ohms, such as the example shown in Figure 4, compared to a similarly dimensioned microstrip feed design shown in Figure 5, we can see that:

$$C_c \approx 2C_m$$

Since the capacitance and Q are directly related, this means the Q has also been reduced by a factor of 2 when converting the coaxial design to a microstrip fed slot.

Babinet's Principle

Another technique that can be used to provide broadband impedance cancellation and lower the Q of a slot radiator is to place a complementary impedance in the same circuit as the slot. Babinet's principle, put into antenna terms by H.G. Booker in 1946, relates the fields and impedance of an aperture antenna to its dual [4]. The dual of a slot would be a dipole as shown in Figure 6.

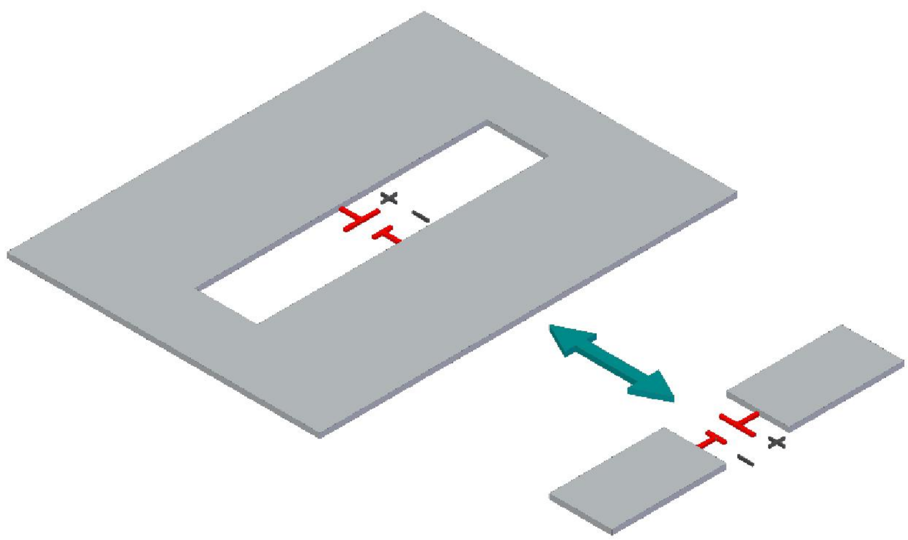

FIGURE 6: DUAL ANTENNAS, (LEFT) SLOT ANTENNA AND (RIGHT) THE DIPOLE ANTENNA.

Babinet's principle relates the impedance of a slot (Z_S) to the impedance of its complementary dipole (Z_D) by the relation:

$$Z_S = \frac{\eta^2}{4Z_D} \tag{7}$$

Where η is the intrinsic impedance of free space and has the value of 377Ω. Since:

$$Z_S Z_D = \frac{1}{4}\eta^2 \; represents\ a\ real\ number,$$

$$(R_D + jX_D)(R_S + jX_S) \; is\ real$$

$$\Rightarrow R_S X_D = -R_D X_S$$

This implies an inverse relationship and will provide a level of cancelation if the slot and dipole are used in the same circuit. Using a parasitic dipole, which was developed and patented by Dielectric, to add a vertical component to the horizontally polarized signal emanating from the slot as shown in Figure 7, places them in the same circuit. This technique not only provides elliptical or circular polarization, but it also reduces the Q of the radiating combination which provides an overall increase in the operating bandwidth.

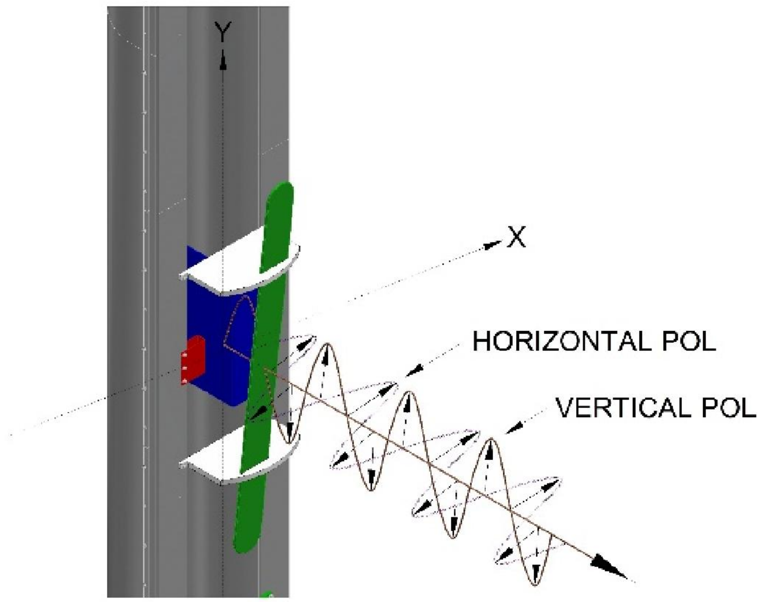

FIGURE 7: PARASITIC DIPOLE PLACED OVER THE SLOT. THE COMBINATION PRODUCES ELLIPTICAL OR CIRCULAR POLARIZATION.

It has been shown that the loaded Q of a coupled slot decrease on the order of 30% to 40% with the complementary addition of a parasitic dipole over the slot. [2].

Simplicity Equals Reliability

As mentioned earlier, an advantage of a slotted pylon antenna is its simplicity. Failure rate is defined as:

$$\lambda = \sum_{i=1}^{n} N_i \lambda_i \pi_{Qi} \tag{8}$$

Where n is the number of part categories, N_i is the quantity of the ith part, λ_i is the failure rate of the ith part and π_{Qi} is the quality factor of ith part [9]. From equation 8, one can conclude that reliability is directly proportional to parts count. The total number of parts in the FM pylon antenna is over 60% less than an equivalent ring style antenna and over 90% less than an equivalent cavity backed panel type antenna used today (see Figure 8).

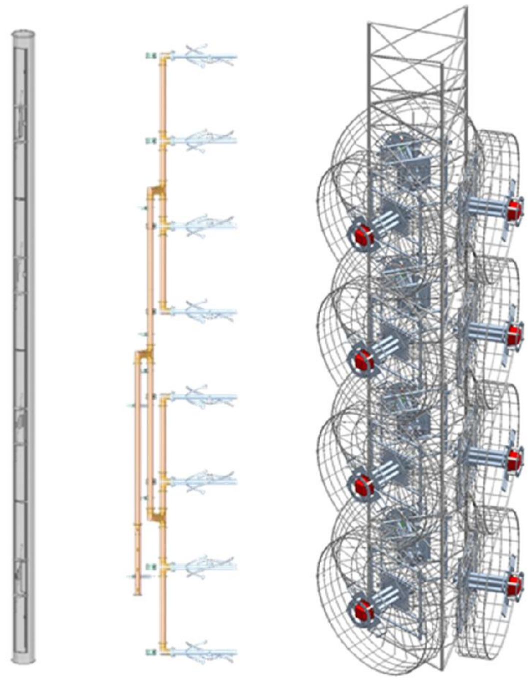

FIGURE 8: FM PYLON ANTENNA (LEFT) COMPARED TO EQUIVALENT RING STYLE (CENTER) AND PANEL (RIGHT) ANTENNAS.

The simplicity of the FM pylon inherently makes it significantly more reliable than any equivalent FM broadcast antenna on the market today.

Improving Polarization Stability

Frequency independence and log periodic theory can be applied to produce a more stable polarization ratio across the FM band. The slot is considered the driven element, but instead of using a single parasitic dipole element to re-radiate the vertical component as shown in Figure 7, multiple elements can be used as shown in Figure 9. Each element is designed uniquely in order to resonate at different frequency slices within the FM band by applying different angles and lengths. A level of frequency independence is achieved by structures which are entirely specified by angles [10]. In doing so, this geometry provides a stable polarization ratio performance across the entire FM band.

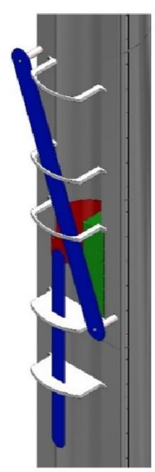

FIGURE 9: FM PYLON USING BROADBAND PARASITIC DIPOLE COMBINATIONS TO IMPROVE THE POLARIZATION STABILITY.

The resulting pattern performance is shown in Figure 10.

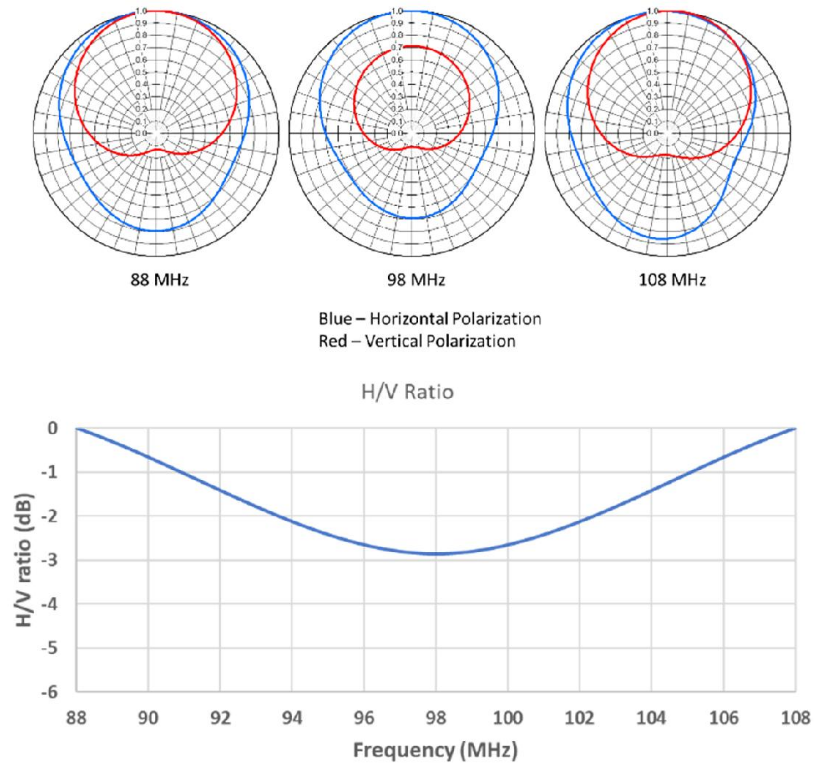

FIGURE 10: FM PYLON PATTERN PERFORMANCE AND POLARIZATION RATIO.

Testing Results

By applying many of the same computer simulation techniques that were developed and refined for TV slot antennas to the new FM pylon, most notably HFSS (High Frequency Structure Simulator), the skills and experience led to the rapid development of a full antenna design. After transferring the virtual design to a final product, testing of a single four bay section of the new FM pylon antenna on a 25-foot trestle proved the performance (see Figure 11).

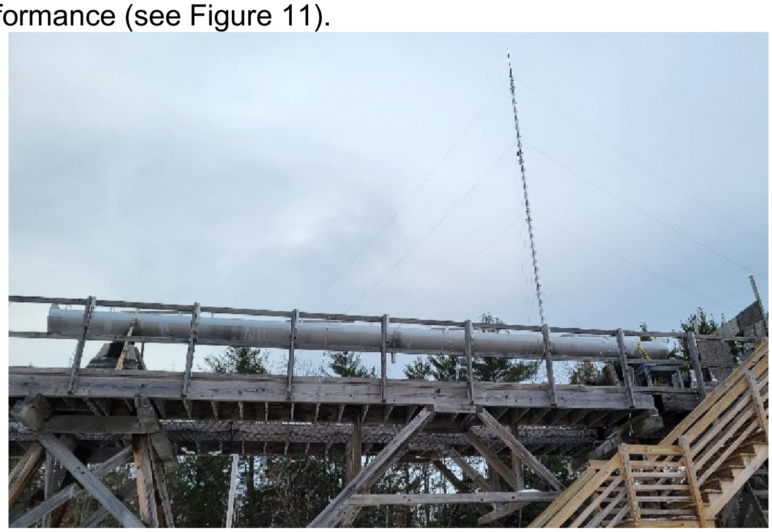

FIGURE 11: FM PYLON ANTENNA IN TEST ON 25' TRESTLE.

The initial impedance and VSWR vs. frequency are shown in Figure 12 with further improvement expected.

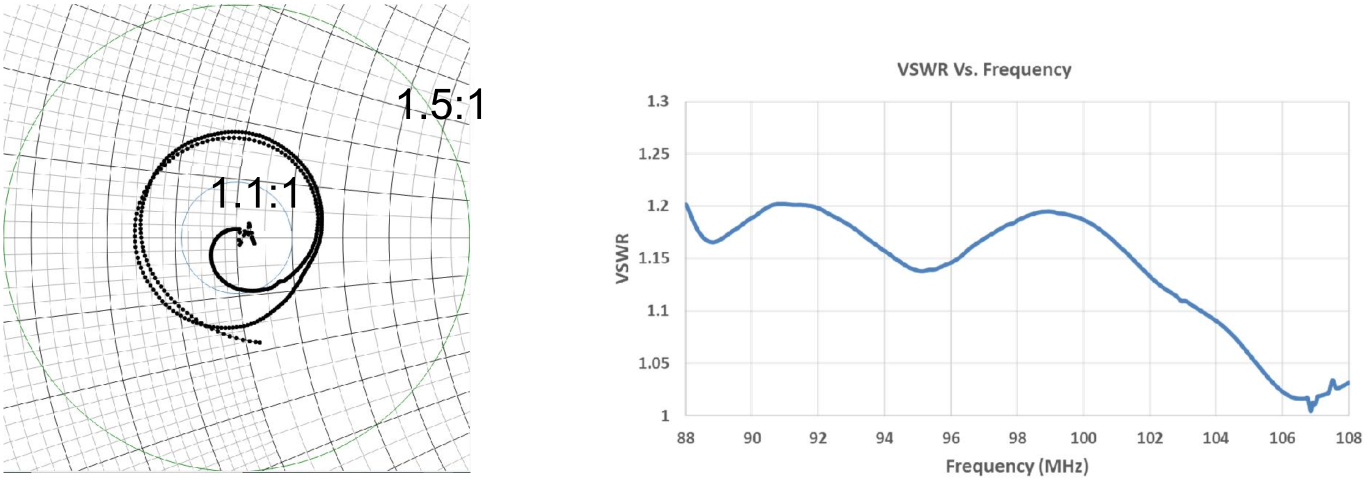

FIGURE 12: FM PYLON PERFORMANCE. IMPEDANCE MEASUREMENT TAKEN 25' ABOVE GROUND ON A WOODEN TRESTLE.

Azimuthal Pattern Flexibility

As seen in the patterns shown in Figure 10, there is a lack of pattern congruency between the horizontal and vertical polarizations of a single FM pylon section in free space. This issue is of little concern since a single section bay will most likely always be side mounted on the tower structure. It is normal for the tower structure to directionalize the patterns with the vertical polarization being affected more than the horizontal polarization. This is due to the tower itself being in the vertical plane. For example, a typical ring style antenna bay will be omni directional in free space for both the horizontal and vertical polarizations. Refer to Figure 13. When adding the transmission line required to feed power into the bay, the vertical polarization begins to directionalize.

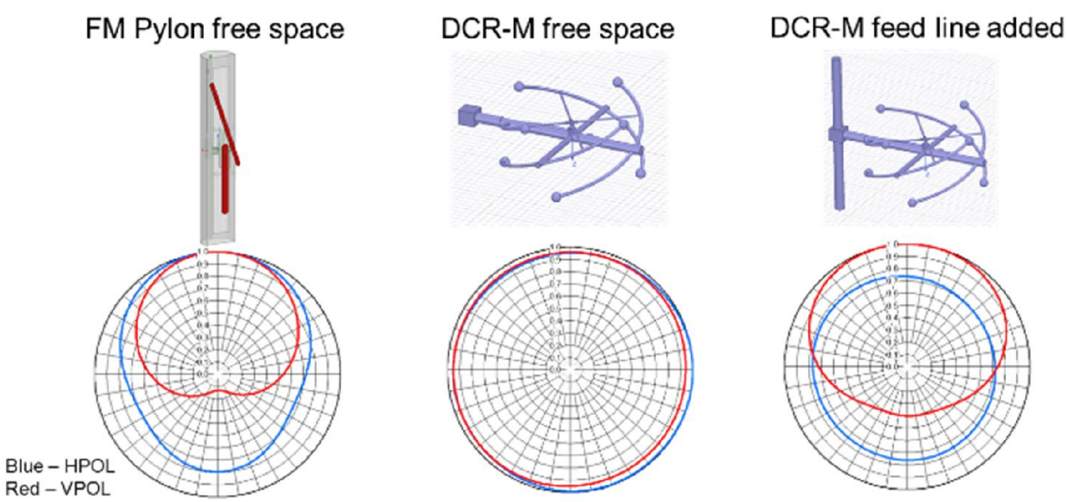

FIGURE 13: COMPARING THE FM PYLON ANTENNA TO A TYPICAL RING STYLE FM BAY IN FREE SPACE AND ALSO WITH THE ADDITION OF A FEEDLINE BEHIND THE BAY USED TO SUPPLY RF POWER.

When including the tower, it can be shown that the resulting patterns of the FM pylon and that of a typical ring style antenna become very similar in nature as shown in Figure 14.

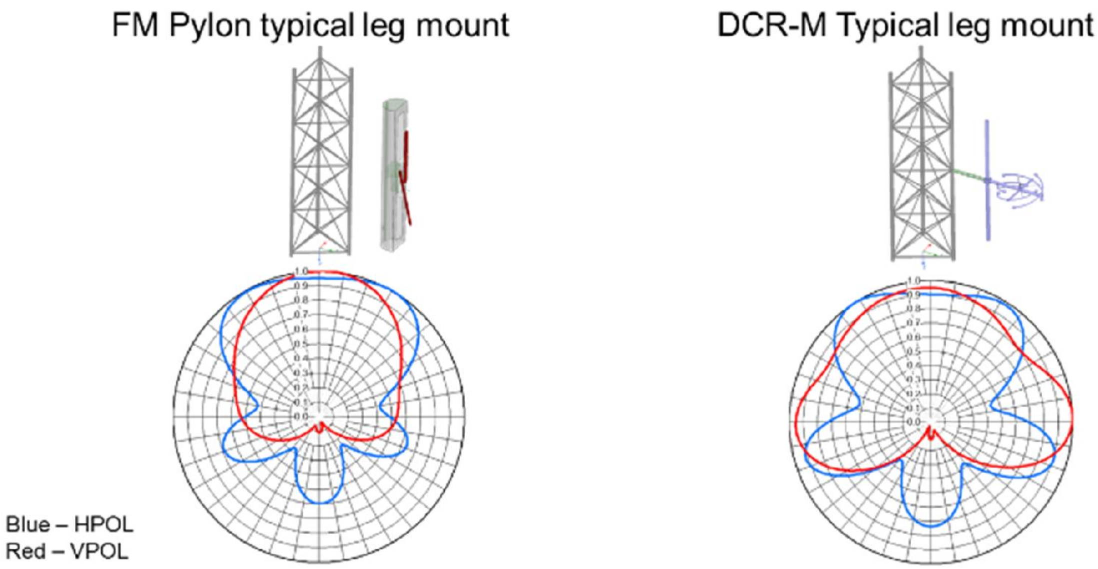

FIGURE 14: COMPARING AZIMUTH PATTERNS OF A FM PYLON ANTENNA SINGLE BAY AND A TYPICAL RING STYLE BAY SIDE MOUNTED ON A TYPICAL TOWER.

Since the single section of the FM pylon can be used as an array element in both the azimuth and elevation planes, it has the same pattern flexibility as complicated panel antennas. The azimuth pattern can be shaped and optimized to provide desired coverage by placing multiple modules into a support structure. The number of modules around can be 2 to 4 and placed at any orientation with each fed with different amplitudes and phases resulting in a variety of standard pattern shapes as well as an infinite number of unique solutions that can be used for directional applications. The support structure can be either side mounted or top mounted on the tower. Refer to Figure 15.

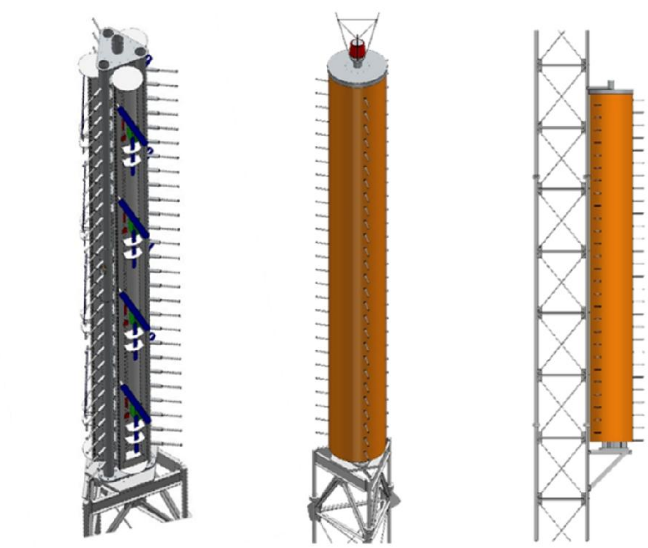

FIGURE 15: FM PYLON ANTENNA MODULES PLACED IN A SUPPORT STRUCTURE TO PROVIDE AZIMUTH PATTERN AND MOUNTING FLEXIBILITY.

Examples of azimuth patterns generated by FM pylon configurations are shown in Figure 16.

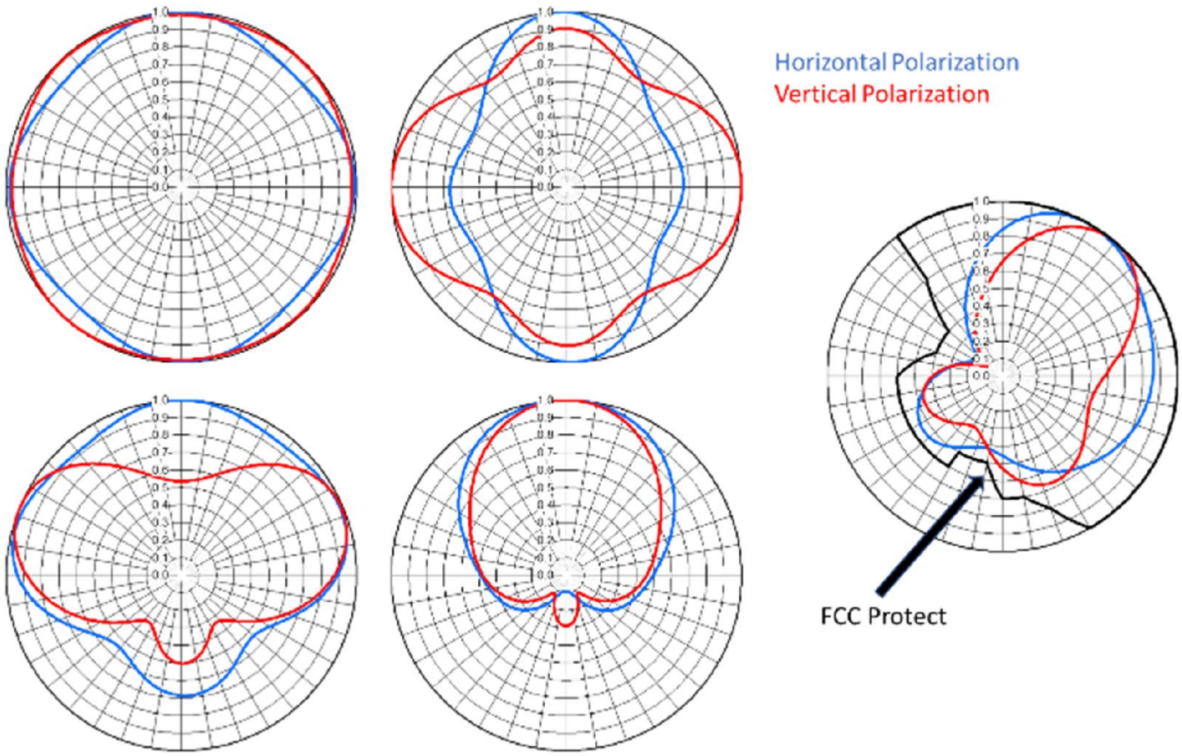

FIGURE 16: EXAMPLES OF AZIMUTH PATTERN FLEXIBILITY BY VARYING THE NUMBER OF BAYS AROUND AND THEIR FEED AMPLITUDES AND PHASES.

Elevation Pattern and Gain Flexibility

The elevation gain can be increased by stacking multiple 4 bay modules into an 8 or 12 bay configuration.

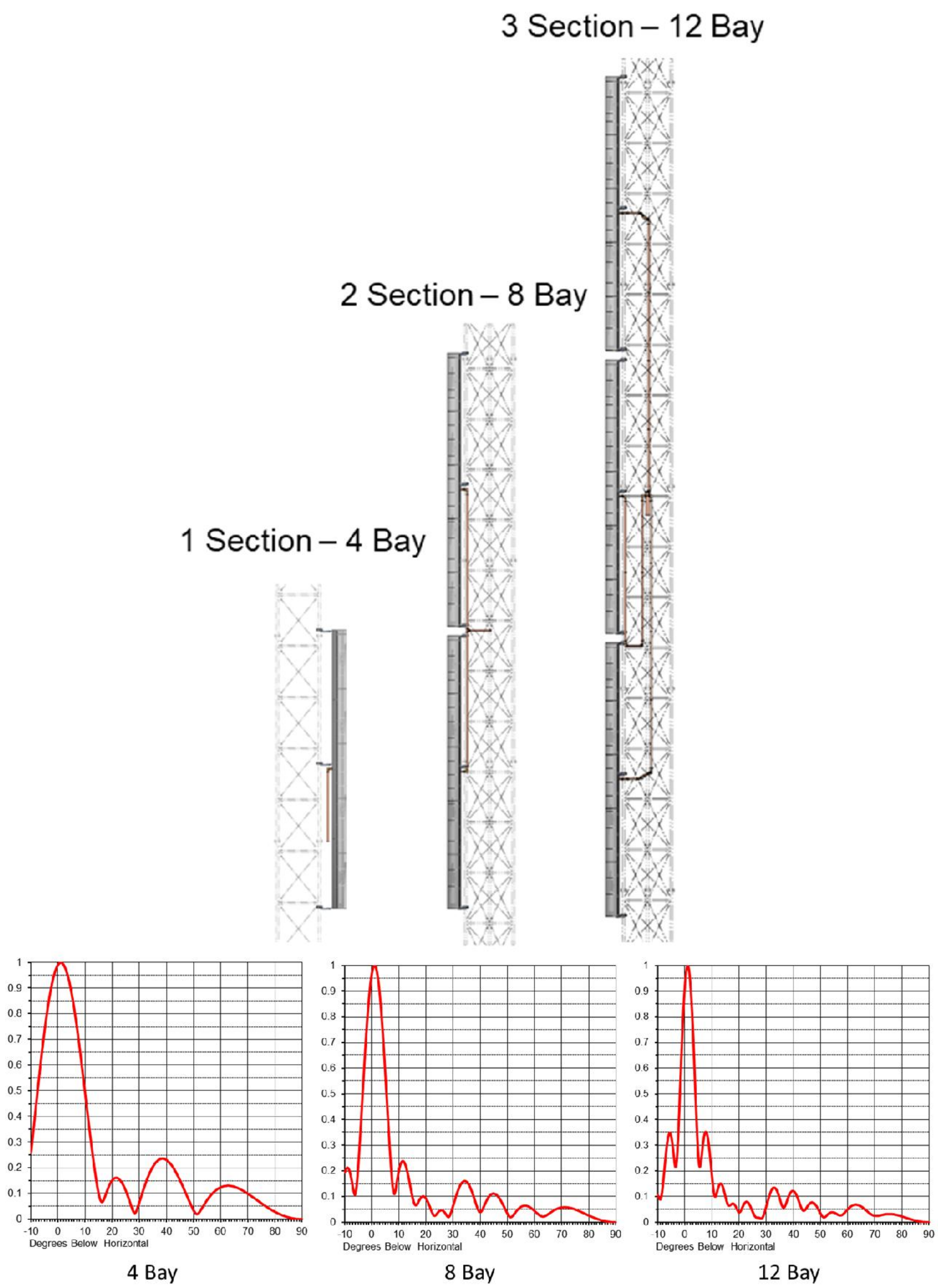

FIGURE 17: FM PYLON 4 BAY ANTENNA MODULES STACKED IN ELEVATION TO INCREASE THE GAIN, CHANGE BEAM TILT AND OPTIMIZE NULL FILL.

Conclusion

The many advantages of slotted coaxial pylon antenna technology that have benefitted the UHF and high band VHF broadcast community for decades can now be realized in the FM band. Those benefits include smaller size leading to low wind load, less parts and less connections leading to higher reliability and a high degree of both azimuth and elevation pattern flexibility. By incorporating techniques to lower the Q of the slot cavity, full FM band VSWR performance can be obtained. The design of a broadband parasitic dipole pair provides a simple, cost-effective solution to stable polarization ratio across the band.

References

[1] Schadler, J. L., “Considerations for -10dBc IBOC Combined Station Side-mount Master FM Antenna Design”, *IEEE Broadcast Symposium*, 2015.

[2] Schadler, J. L., “Broadband Slotted Coaxial Broadcast Antenna Technology”, *White Paper*, Dielectric.com.

[3] Fano, R. M., “Theoretical Limitations on the Broadband Matching of Arbitrary Impedances”, *Journal of the Franklin Institute*, Vol. 249, Jan. 1950

[4] Booker, H. G., “Slot Aerials and Their Relation to Complementary Wire Aerials (Babinet’s Principle)”, *J. IEE, Pt. III-A*, Vol. 93, 1946, pp. 620-626

[5] Pozar, D. M., *Microwave Engineering; 3rd Edition*, 2005.

[6] King, R. W. P., *Transmission-line Theory*, 1955

[7] Paul, C. R., *Analysis of Multiconductor Transmission Lines; 2nd Edition*, 2008

[8] McLean, J. S., “A Re-Examination of the Fundamental Limits on the Radiation Q of Electrically Small Antennas”, *IEEE Transaction on Antennas and Propagation*, VOL 44, No. 5, May 1996, pg.672-675

[9] *MIL-217 Standard*

[10] Rumsey, V., *Frequency Independent Antennas*, 1966