Broadband Slotted Coaxial Broadcast Antenna Technology

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Summary

Slotted coaxial antennas have many advantages over traditional broadband panel antennas including much smaller size and wind load, higher reliability and a greater degree of azimuth and elevation pattern flexibility. The one disadvantage of slotted coaxial antennas is their inherently narrow bandwidth. In most applications their usage is only considered for single channel operation, approximately 1% bandwidth for UHF. This paper deals with various methods to increase the bandwidth of slotted coaxial antennas. The cumulative effect can boost the bandwidth to over 10% allowing for broadband operation of at least 10 channels in the UHF band.

Introduction

In the communication industry, what is acceptable VSWR varies widely depending on the application. In some cases such as broadcast, the VSWR must be close to unity where in other cases it can be as high as 10:1. The frequency bandwidth can be expressed as the ratio of the band of operation to the center frequency as a per cent:

$$\%bw = \frac{f_h - f_l}{f_0} x100 \quad (1)$$

The natural bandwidth of a coaxial slot radiator is typically on the order of .5% to 1%. 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 1. It should be noted that by removing this length dependence, a slot can become a broadband device such as the one shown in Figure 2. One could argue that this would be simply removing the “coaxial” from the slotted coaxial antenna.

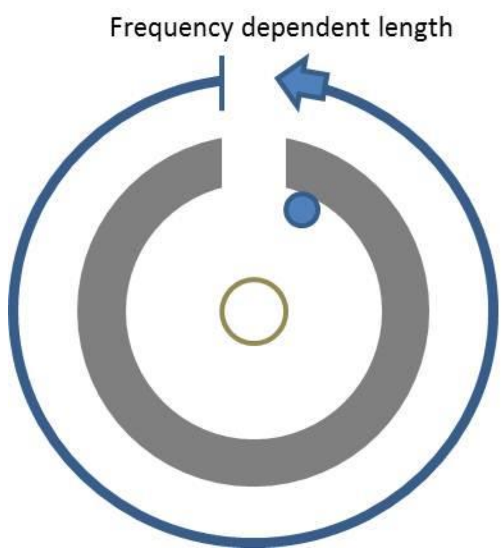


Figure 1: Cylinder creates a frequency dependence causing narrow band operation.

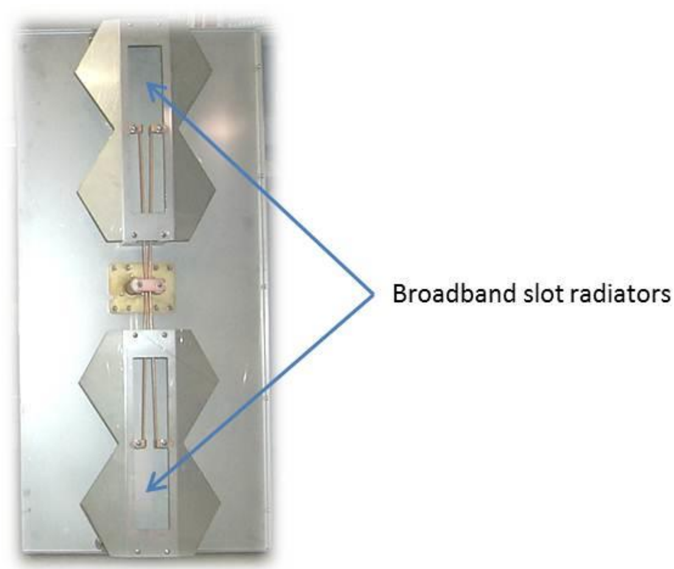


Figure 2: Slot radiator used in a broadband panel configuration.

Techniques to improve bandwidth of an antenna can be classified into two categories, those that lower the quality factor (Q) and those that provide broadband cancelation. Quality factor in its most fundamental form is:

$$Q = w\frac{energy\ stored}{average\ power\ disipated} \qquad (2)$$

Low Q circuits are wideband and high Q circuits are narrow band. Q is the inverse of the fractional bandwidth given by the well-known expression:

$$bw = \frac{VSWR-1}{Q\sqrt{VSWR}} \qquad (3)$$

R.M. Fano derived the fundamental bounds on lossless passive matching networks for narrowband antennas to be:

$$bw = \frac{\pi}{Qln\left\{\frac{VSWR+1}{VSWR-1}\right\}} \qquad (4)$$

where the VSWR is the maximum allowable in the passband [1]. Since equation (3) represents the normally obtained bandwidth where equation (4) expresses the maximum realizable bandwidth that is theoretically achievable using matching techniques, a maximum bandwidth enlargement factor can be found by dividing the two quantities [2].

$$F = \frac{\pi\sqrt{VSWR}}{(VSWR-1)ln\left\{\frac{VSWR+1}{VSWR-1}\right\}} \qquad (5)$$

The expected increase in bandwidth by reducing the Q can be found by a differential given in equation (4).

$$\%bw = \frac{\pi}{ln\left\{\frac{VSWR+1}{VSWR-1}\right\}}\left[\frac{1}{Q_2}-\frac{1}{Q_1}\right] \qquad (6)$$

As can be seen from these relationships, the only way to improve the bandwidth beyond the use of standard matching techniques is to reduce the Q or provide additional cancellation outside of the matching network.

The use of a parasitic dipole over a slot radiator – Babinet's Principle

One technique that can be used to provide broadband impedance cancellation to a slot radiator is by placing 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 [3]. The dual of a slot would be a dipole as shown in Figure 3.

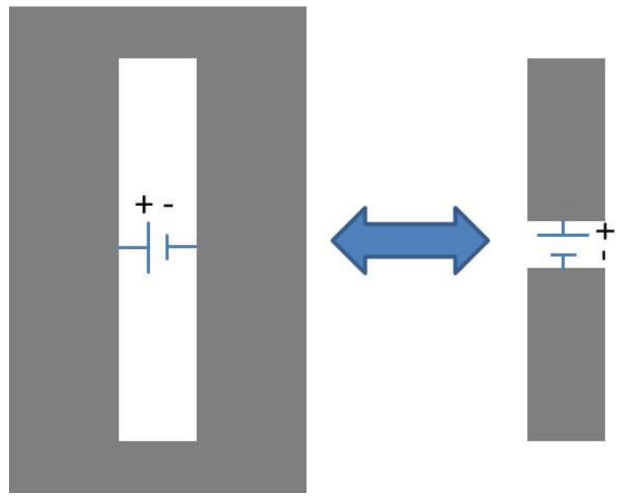


Figure3: Dual antennas, (left) slot antenna and (right) the dipole antenna.

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

$$Z_S = \frac{\eta^2}{4Z_D} \qquad (7)$$

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

$$Z_S Z_D = \frac{1}{4}\eta^2\ represents\ a\ real\ nuber,$$
$$(R_D + jX_D)(R_S + jX_S)\ is\ real$$

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

Note that equation (7) implies an inverse relationship between the slot and dipole and thus would provide a level of impedance cancellation if a dipole and slot radiator can be added together in the same circuit. The use of a parasitic dipole, developed and patented by Dielectric, is used to add a vertical component to the horizontally polarized signal emanating from the slot as shown in Figure 4. This technique not only provides elliptical or circular polarization, it also provides an overall increase in the operating bandwidth.

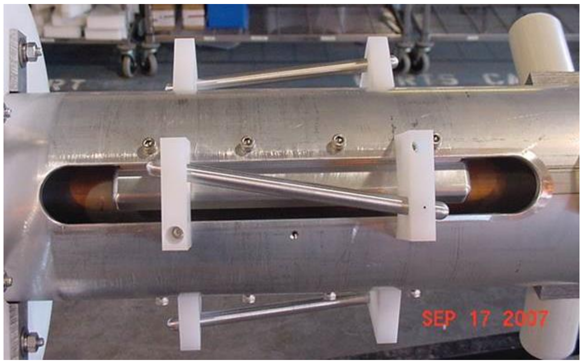


Figure 4: The use of a parasitic dipole placed over the slot provides elliptical polarization and improves the operating bandwidth.

The bandwidth improvement through the complementary addition of the dipole and slot can be shown by comparing the loaded Q of a coupled slot with and without the presence of the dipole. Refer to Figure 5. A comparison of bandwidth through the use of equation (6) assuming the maximum allowable VSWR in the passband after matching is a 1.1:1 confirms a bandwidth improvement of approximately 3.8%.

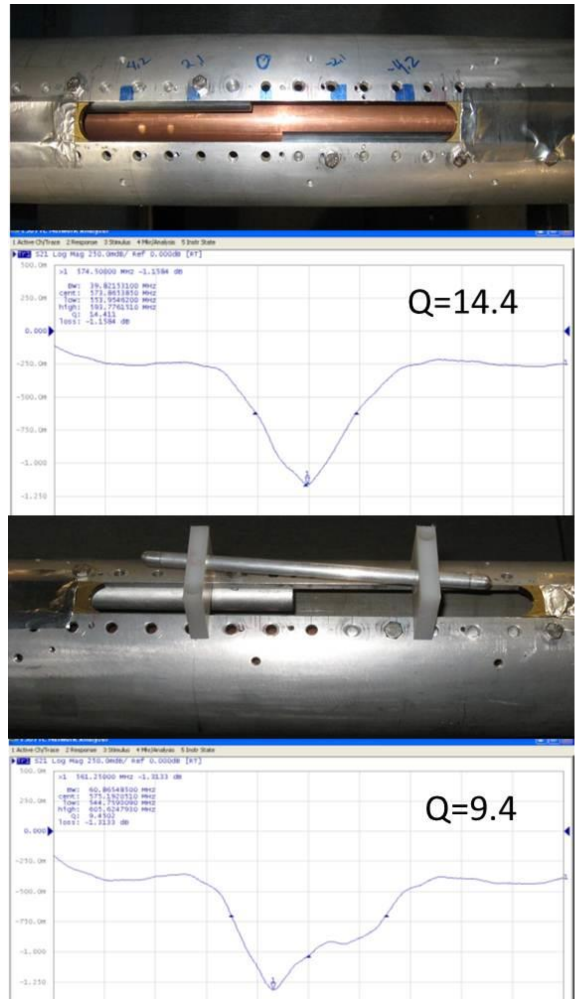


Figure5: Q tests with and without the presence of a parasitic dipole placed over the slot.

Relationship between coaxial pipe thickness and Q

An axial slot cut into the wall of a coaxial line will not affect the internal fields and thus does not act as a radiator, but the placement of a coupling structure on one side of the interior wall of the slot will unbalance the fields and act as a voltage generator across the slot as shown in Figure 6. This can be viewed as a potential difference created across two parallel plates and thus generates a capacitance between the slot walls.

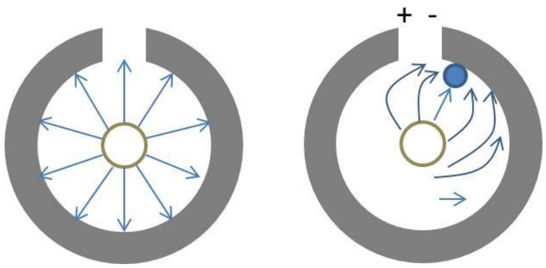


Figure 6: Coupled slot in a coaxial line. Fields alien to internal coupling device.

When a resonate circuit is loaded, the loaded Q is given by:

$$Q_L = \frac{\omega_0 C}{G_{Total}} \quad (8)$$

making the capacitance and Q directly proportional. Larger C will increase the Q at the resonate frequency which in turn reduces the bandwidth as depicted by equations 3 and 4. For a parallel plate capacitor, the amount of capacitance is directly proportional the area of the plates.

$$C = \frac{\epsilon A}{d} \quad (9)$$

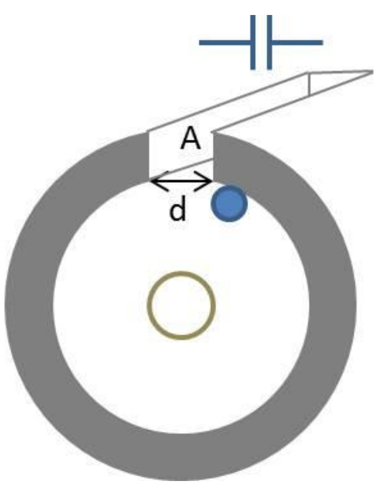


Figure 7: Capacitance between slot walls

Figure 7 suggests that thicker wall slotted coaxial antennas will have high Q's and smaller bandwidths compared to the same geometry using a thinner wall outer conductor. Using equations 8, 9 and 4 imply a directly proportional relationship of the area the slot wall to amount of achievable bandwidth. For example, a 10" long slot with a ¼" wall would have 4X less capacitance as a 10" slot with a 1" wall and thus 4X the bandwidth. This is not true in practice since the field inside the slot is not evenly distributed, but concentrated at the top edge of the slot and near the coupler or interior wall. Figure 8 shows evidence of this phenomenon when analyzing the fields within a slot radiator using high frequency simulation. Through experimentation, the relationship between Q and slot thickness is shown in Figure 9. As can be seen from this chart, using equation 6 and a VSWR max of 1.1:1, the expected bandwidth of a slotted coaxial antenna can be increased approximately 1.5% thought the use of thin wall structures.

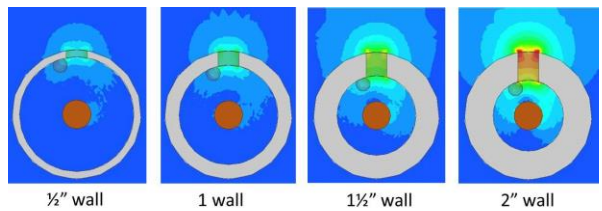
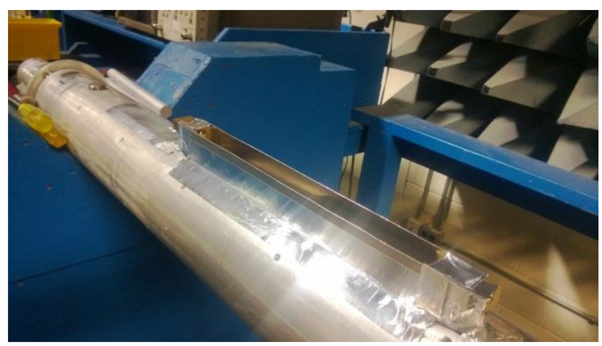


Figure 8: HFSS simulation of the fields produced inside a coaxial slot radiator.



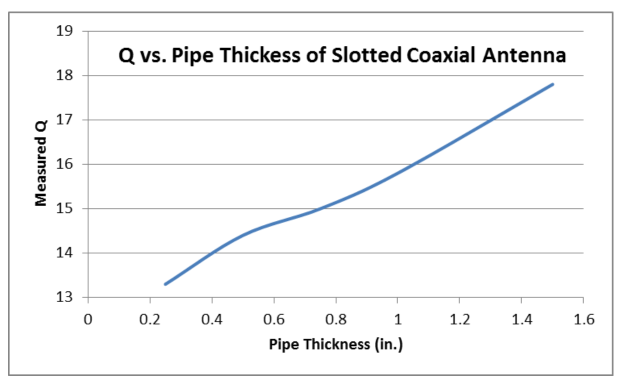


Figure 9: Q of single slot antennas of the same diameter with various wall thickness.

Multi-sectional phase cancellation

Feeding broadband panel antennas by a corporate feed network is common practice. It provides a stable elevation pattern frequency response and can provide a level of impedance cancellation if phased correctly. The feed system makes use of the fact that multiple voltage reflections from similar unmatched loads can be made to arrive at a common point in the system, in the proper phase relation, causing a net cancellation to occur.

The most cost effective, reliable and lowest wind load method to feed slotted coaxial antennas is to have a single input feeding multiple slots in parallel. This design eliminates feed lines, power dividers and connections, but does not provide broadband performance. In order to take advantage of phase cancellation to extend the impedance bandwidth, the slotted coaxial antenna must be broken down into multiple sections as shown in Figure 10.

Figure 10: Single section vs. multi-section slotted coaxial antenna designs

The question that needs to answered is; "What is the optimum number of sections and what is the phase relationship between them for maximum impedance cancellation?" To analysis this, an arbitrary number of loads are connected in parallel as shown in Figure 11.

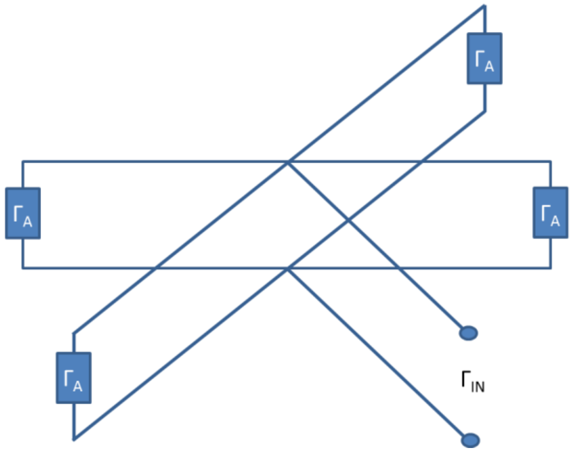


Figure 11: Arbitrary number of loads connected in parallel.

Γ_A represents the complex reflection coefficient of the individual radiators or antenna sections. The total system input refection coefficient is the summation of the individual radiators each with a phase offset φ_l looking into each feed line at the feed point.

$$\Gamma_{IN} = \sum_{p=1}^{n} \Gamma_A \, e^{-j\beta(p-1)\emptyset_l} \qquad \beta = \frac{2\pi}{\lambda} \qquad (10)$$

For the case where Γ_{IN}=0, full cancelation of all the radiators, it can be shown that the phase offset between the radiators must be of the solution:

$$\emptyset_l = \frac{k\lambda}{2n} \quad for\ k = 1,2,3 \ldots.. \qquad (11)$$

Where n is the number of antenna radiators. It should be noted that if the antenna array is broken into sections with each section consisting of more than one radiator layer, then the phase offset per section is simply:

$$\emptyset_{section} = \frac{\#\ of\ layers}{\#\ of\ sections}\emptyset_l \qquad (12)$$

The corresponding beam tilt produced by the phase off per layer can be calculated as follows:

$$BT = sin^{-1}\left(\frac{\emptyset_l}{360}\right) \qquad (13)$$

Figure 12 is a chart of number of layers for optimum k values of 1, 2 and 3 overlaid with various beam tilts for given phase offset. For example if a 16 layer antenna is split into 4 sections, with k=1, this would produce a beam tilt of 1.7 degrees. A phase offset of 12.5 degrees per layer or 50 degrees per section will be required for optimum impedance cancellation.

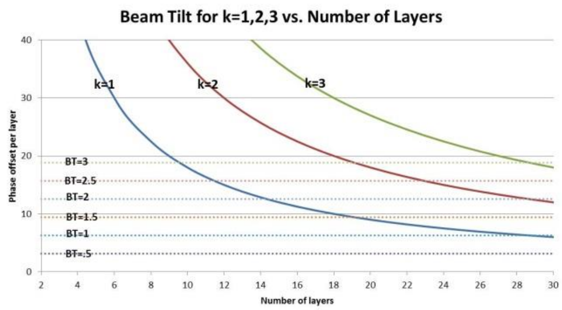


Figure 12: Design parameters for optimum impedance cancellation.

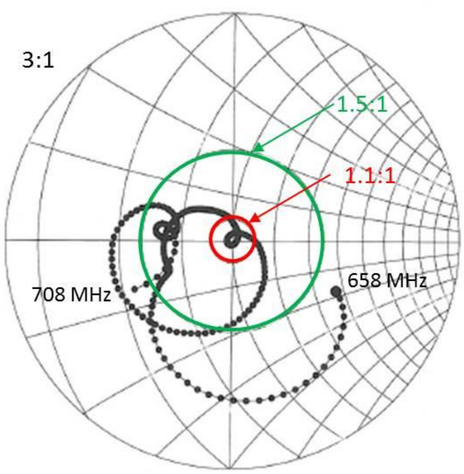


Figure 13: Impedance measurement of a typical single slotted coaxial antenna section such as is shown on the left of Figure 10.

The impedance measurement shown in Figure 13 is used to determine the expected bandwidth improvement when used in a multi-sectional configuration with optimum phase offset. Note that this analysis is independent of the number of layers or antenna sections as long as the phase offset conforms to equations (11) and (12). It does however include a real slot antenna response and the actual phase run out in the sections connecting feed lines due to the frequency spread. As is seen in Figure 14, the expected gain in bandwidth will improve between 2% and 3% while maintaining a VSWR less then 1.1:1.

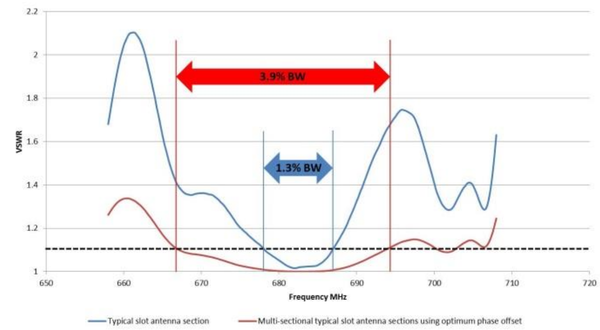


Figure 14: VSWR of typical slotted coaxial antenna as a single section and when used in a multi-sectional configuration with optimum phase offset.

Case study example of broadband slotted coaxial antenna design

Station: WNYT

Location: Glens Falls, NY

Antenna Type: TLP-12W/VP-R (SP)

The WNYT antenna is a 12 layer slotted coaxial design that was manufacture in two 6 bay sections. Each six bay section was again center fed producing a 4 way split into 3 layers each. Along with multi-sectional phase cancellation, the antenna was manufactured into relatively thin wall pipe and had vertical component thus leveraging Babinet’s principle. All three techniques lowered the overall Q of the slots. As shown in Figure 13, the VSWR for this antenna was under 1.1 over 60 MHz or 10 UHF channels.

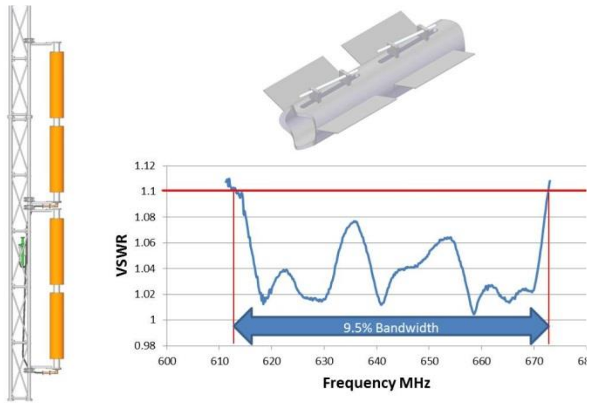


Figure 13: Broadband slot antenna with over 10 UHF channels of bandwidth

Conclusion

In this paper, it has been shown that the cumulative effect of using a conjugate dipole on a thin walled pipe and sectionalizing for the use of phase cancellation can boost the operating bandwidth of a slotted coaxial antenna to near 10%.

Method	% Increase in Bandwidth
Natural Bandwidth	1.0%
Babinet's Principle	3.8%
Thin Wall Pipe	1.5%
Phase Cancellation	3.0%
Total	**9.3%**

References

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

[2] David M. Pozar, Daniel H. Schaubert, “Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays” p. 168

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