Sensor and Simulation Notes

Note 462

26 October 2001

Some Topics Concerning Cable Feeds of Reflector IRAs

Carl E. Baum
Air Force Research Laboratory
Directed Energy Directorate

Abstract

The coaxial cables used to transport signals between the conical apex of the feed arms in a reflector IRA, and positions behind the reflector, are a limiting factor in the high-frequency performance of such an antenna. This paper explores various techniques for improving the design of the cables and their connections to the antenna.

This work was sponsored in part by the Air Force Office of Scientific Research, and in part by the Air Force Research Laboratory, Directed Energy Directorate.

1. Introduction

In the spirit of [7] which considered details of the feed-arm design for reflector impulse-radiating antennas (reflector IRAs), the present paper looks into the design of the feed cables transporting signals between some source or receiver behind the reflector and the conical apex of the feed arms (focal point of the paraboloidal reflector). For high-power transmitters there is a high-voltage problem with cables suitable for fast rise times. In this case the fast pulse can be generated by a switch at the apex, which is enclosed by media of high dielectric strength. In the present paper we are concerned with a reflector IRA in reception where low-voltages need to be transported (and perhaps combined) behind the reflector, or in transmission where low voltages (voltages low enough not to cause electrical breakdown in typical cables and connectors) are transmitted from behind the reflector.

The type of antenna under consideration is described as hyperband (band ratio greater than a decade) with typical band ratios of two decades having been achieved. The low frequency f_ℓ of operation is limited by the size of the reflector and feed arms being of the order of a half wavelength. The upper frequency f_u of operation has several governing factors. For high-voltage transmitters the switch speed is important. For both high and low voltages the geometrical accuracy of the paraboloidal reflector and of the feed arms and cable connections hnear the apex are important. For low-voltage cases the cable loss between apex and the back of the reflector is also a limiting factor. Understanding these various factors may allow one to further extend the band ratio.

2. Launching from Cables into Reflector IRA

One of the limiting factors in the high-frequency (early-time) performance of a reflector IRA concerns how, in transmission, the wave is launched from cables at the conical apex of the feed arms. While thinking in terms of transmission is convenient, the performance in reception is simply related by the time-domain reciprocity theorem [2].

Another paper [9 (Section 3)] has considered one example of such a launch from cables at the apex. In this case (for better polarization purity) a ground plane is established on a symmetry plane (ideally) of the antenna, the electric field being perpendicular to this plane (antisymmetric). This allows the cable coming up the central axis of the antenna to be bonded to the ground plane and rerouted along the ground plane to a position on the other side of the apex (away from the reflector). The cable shield can then be opened in the form of an unzipper [5, 10, 12] to transition the wave smoothly from the cable onto the conical TEM transmission line. This is indicated in side view below the ground plane in Fig. 2.1.

For the other cable coming down one of the feed arms as described in [1 (Fig. 4.1B)], we have some other problems. As the apex is approached the cable diameter eventually exceeds the width of the ideal flat conical plane, so the cable shield becomes the feed arm if one brings the cable shield as close as possible (within a cable diameter) to the apex. As discussed in [9 (Section 3)] one can also place the cable on the feed arm at a location of minimum field to provide minimum perturbation to the conical transmission line. This is near the center of the conical flat plate on the side with smallest field magnitude. This points out that for high-frequency (early-time) performance the smallest cable diameter (typically 100 Ω cable) is desired. In addition we need to turn the wave around toward the reflector. Judicious use of dielectric (a lens) can be used to slow the wave on the shortest paths to bring the propagation time more in line with that for the longer paths.

Alternately one might consider routing both the cables along the ground plane, but this requires that the signal on one of the cables be inverted. This requires a balun with limited high-frequency (early-time) performance. The advantage of one cable on a feed arm is that the "balun" (if one wishes to think of it that way) is ideal, i.e., there is no required high-frequency choke to stop the unwanted second wave on the cable shield. There is only one wave launched at the apex, with proper polarity. The choke at the feed-arm termination only enters the picture later in time and thereby does not significantly affect the early-time radiation from the reflector. The choke is, however, important for the lower frequencies. Note that both design approaches involve small-diameter cables with small center conductors making delicate connections to other conductors, a point to which we shall return.

The high-frequency (early-time) performance of this part of the antenna is then composed of several factors. First, there is the accuracy of the conical-transmission-line geometry near the apex. Second, there is the smallness of the cable diameters near the apex. Third, there is the quality of the transition from cable exit onto the conical wave launcher, including perhaps small lenses to bend (redirect) the waves.

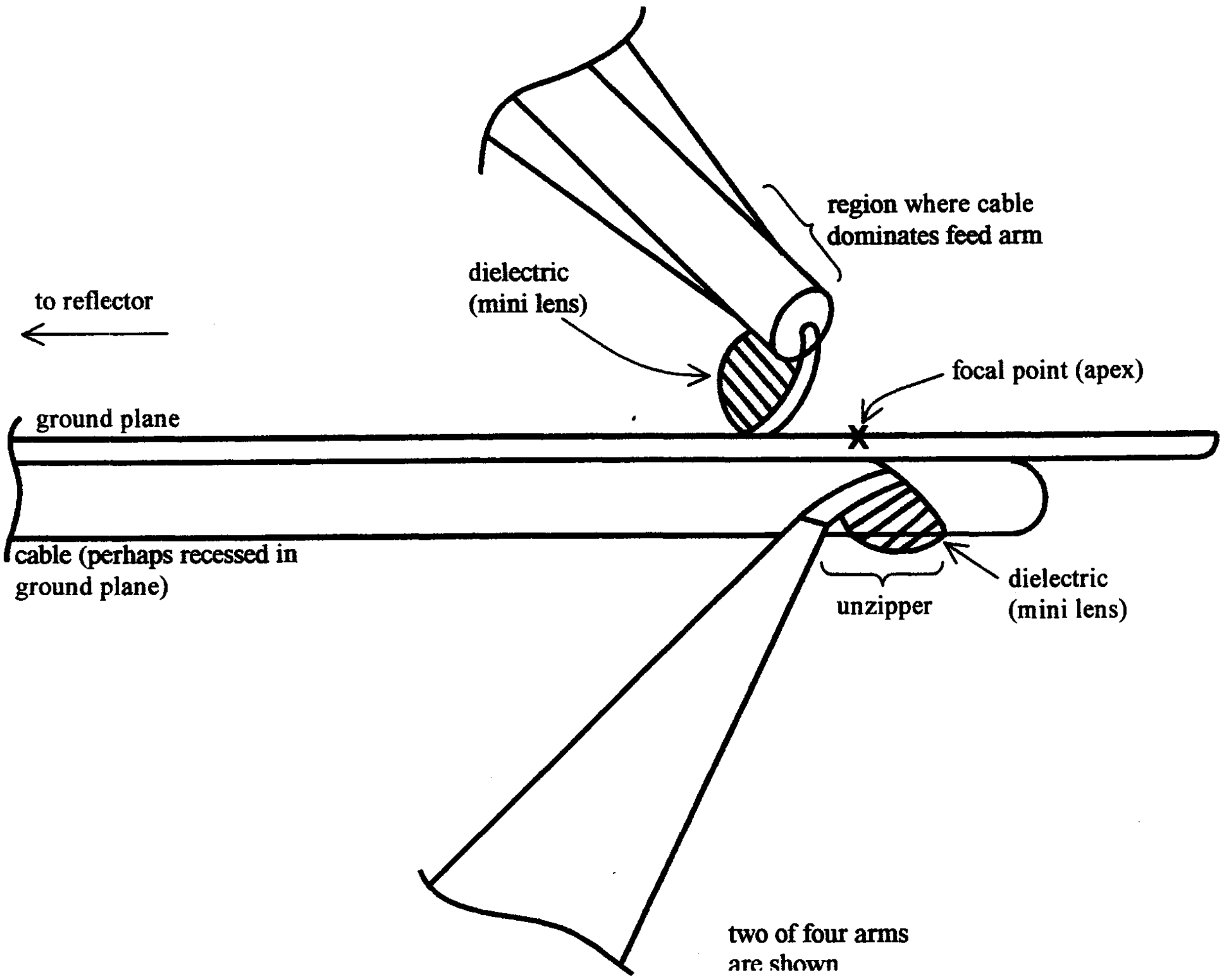


Fig. 2.1 Focal Region With Ground Plane

3. Cable Splitters/Combiners and Bends

A common design feature is the transition of one cable (typically 50 Ω) to the parallel combination of two identical cables (typically 100 Ω each). As illustrated in Fig. 3.1A this is typically in the form of a tee which may or may not have a surrounding metal block. One problem with this approach is the abrupt change from one TEM mode (50 Ω) to the other two TEM modes. In the junction region one can model the discontinuity by lumped capacitance and inductance. In a temporal sense the rise time of the transmitted waves are proportional to the cross-section dimensions of the junction region.

A smoother transition from one to two cables is illustrated in Fig. 3.1B. In this case the common-mode impedance of 50 Ω is preserved at each cross section with a gradual change of the cross-section shape, and thereby a gradual change in the TEM mode. Note also the presence of a symmetry plane so that the voltages/currents on the center conductors of the two 100 Ω cables are identical.

Related to the problem of the cable splitter is the cable bend, i.e., the cables need to bend as they follow the various paths around the antenna. Such bends introduce dispersion in the wave. A simple way to think of this is to look at the difference in propagation times between the inside and outside of the cable bend. This time difference is just

$$\Delta t = 2a\frac{\Delta\phi}{\mathrm{v}}$$

a = inner radius of outer conductor

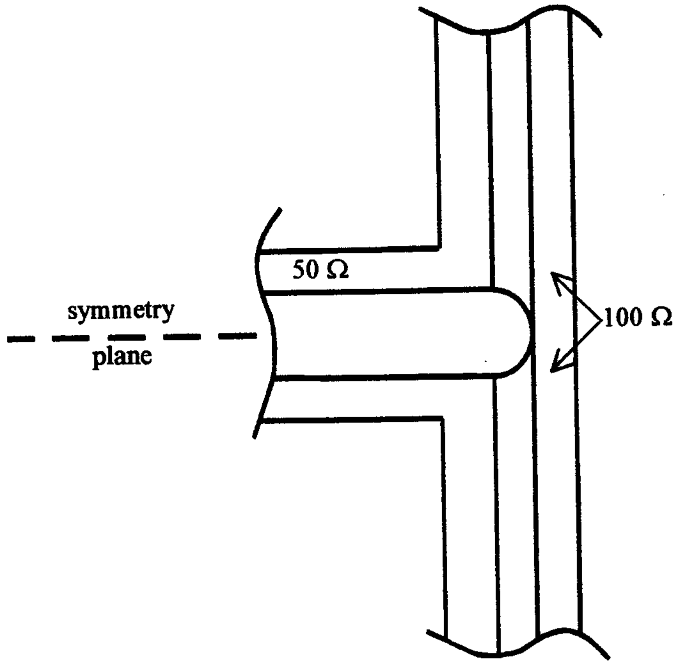
$$\Delta\phi = \text{bend angle (radians)} \qquad (3.1)$$

$\mathrm{v} = [\varepsilon\,\mu_0]^{-1/2}$ = propagation speed in cable dielectric

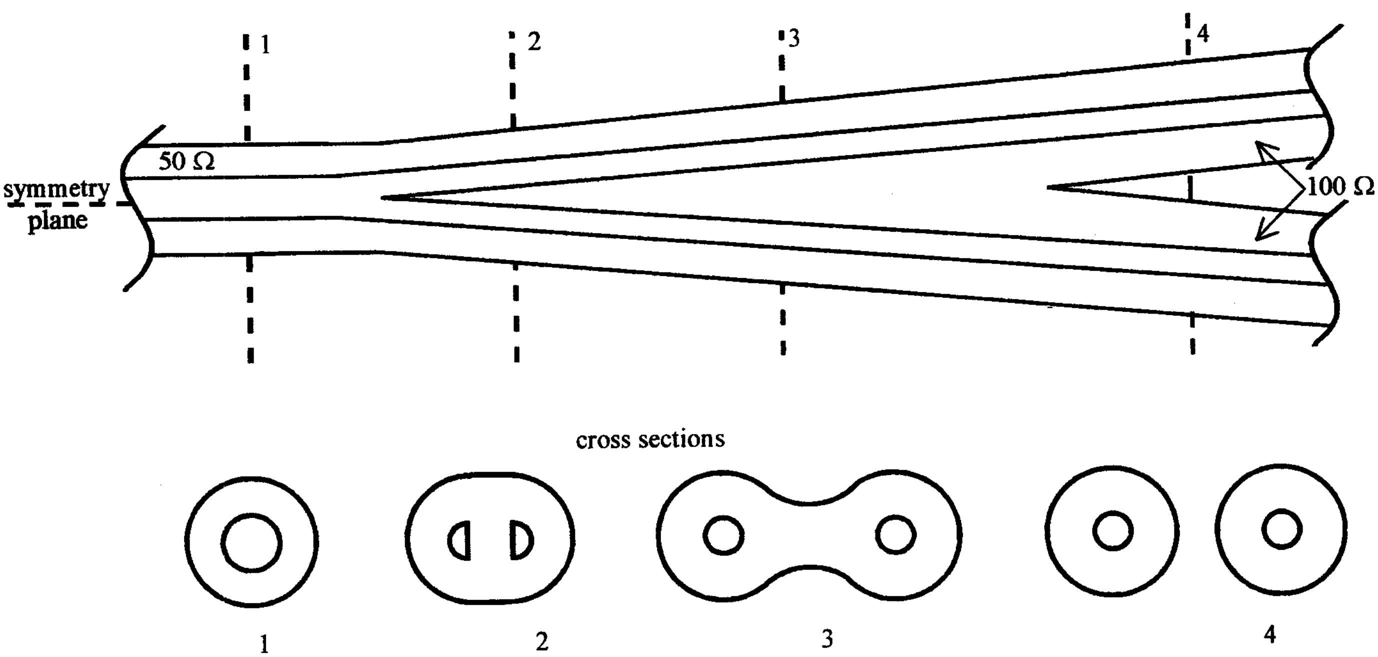
One way to minimize Δt is to minimize a, i.e., use as small a cable diameter as practical.

Another approach to this bend problem involves a lens in the bend region filled with a CID (cylindrically-inhomogeneous-dielectric) medium [6, 8]. Of course this is a more complicated structure to build. One can imagine using inhomogeneous dielectrics in splitters as well to improve the performance.

So one is presented with a tradeoff. For low voltages small diameter cables may be adequate. For high voltages large cable diameters are needed and special considerations involving transition of TEM modes and lenses may be required.



A. Tee junction



B. Smooth transition: continuous 50 Ω common mode

Fig. 3.1 Cable Splitters/Combiners

4. Cable Considerations

Now consider the cables themselves. There are losses, particularly from skin effect, primarily in the center conductor but also in the outer conductor. This introduces dispersion and limits the rise time from a transmitted step function. As discussed in [11, 13] the conductors should be rounded for low loss (no sharp edges). The common circular coax with solid center and outer conductors (semirigid) is appropriate for low loss. Summarizing, such a coax has a step response characterized by

$$\operatorname{erfc}\left(\left[\frac{\tau}{t_r}\right]^{\frac{1}{2}}\right)u(t_r) \equiv \text{unit step response}$$

$$t_r \equiv \text{retarded time (zero at first signal arrival)}$$

$$\tau = \left[\frac{z}{4}\frac{\Xi}{Z_{c0}}\right]^2$$

$$Z_{c0} \equiv \text{cable characteristic impedance (50 }\Omega\text{ or 100 }\Omega\text{)}$$

$$z = \text{cable length (meters)}$$

$$\Xi = \frac{1}{2\pi\Psi_1}\left[\frac{\mu_1}{\sigma_1}\right]^{\frac{1}{2}} + \frac{1}{2\pi\Psi_2}\left[\frac{\mu_2}{\sigma_2}\right]^{\frac{1}{2}}$$

$$\Psi_{\substack{1\\2}} = \begin{cases}\text{inner conductor radius}\\ \text{inner radius of outer conductor}\end{cases} \tag{4.1}$$

$$\mu_{\substack{1\\2}} = \text{permeability of} \begin{Bmatrix}\text{inner}\\ \text{outer}\end{Bmatrix} \text{conductor}$$

$$\sigma_{\substack{1\\2}} = \text{conductivity of} \begin{Bmatrix}\text{inner}\\ \text{outer}\end{Bmatrix} \text{conductor}$$

The above formulae can tell us some important things about cable selection. First τ increases as the square of the cable length, and, hence, so does the rise time. Combining lengths of cable, the composite τ is the square of the sum of the square roots of the individual τ values. Doubling the cable length quadruples τ. So short cable lengths are a consideration.

One also should minimize the parameter Ξ on which τ also depends quadratically. Thus μ_0 (free-space permeability) should be used for the metals (nonmagnetic). The conductivities should be maximized (copper, silver), especially for the center conductor. The radii of the conductors (most notably the center conductor) should be maximized. Large cable diameter is in conflict with some earlier considerations.

The conflict between large and small cable diameters can be partially alleviated by combining both large and small diameters, connecting them by smooth transitions as illustrated in Fig. 4.1. This allows large diameter cables to be used over long lengths, and small diameter cables to be used over short lengths, such as near the apex (Section 2) and perhaps for splitters and bends (Section 3). In the transition the characteristic impedance (conical transmission line) should be matched to both coaxes. A longer transition reduces the transit-time difference (dispersion) between paths along the inner and outer conductors. One also needs to consider the dielectrics in the cables and transition to best match the wave transmission. For short transitions one can choose the dielectric constants and shape of the dielectric interfaces to form lenses at both interfaces involving prolate-spheroidal and/or hyperboloidal surfaces [3, 4, 14].

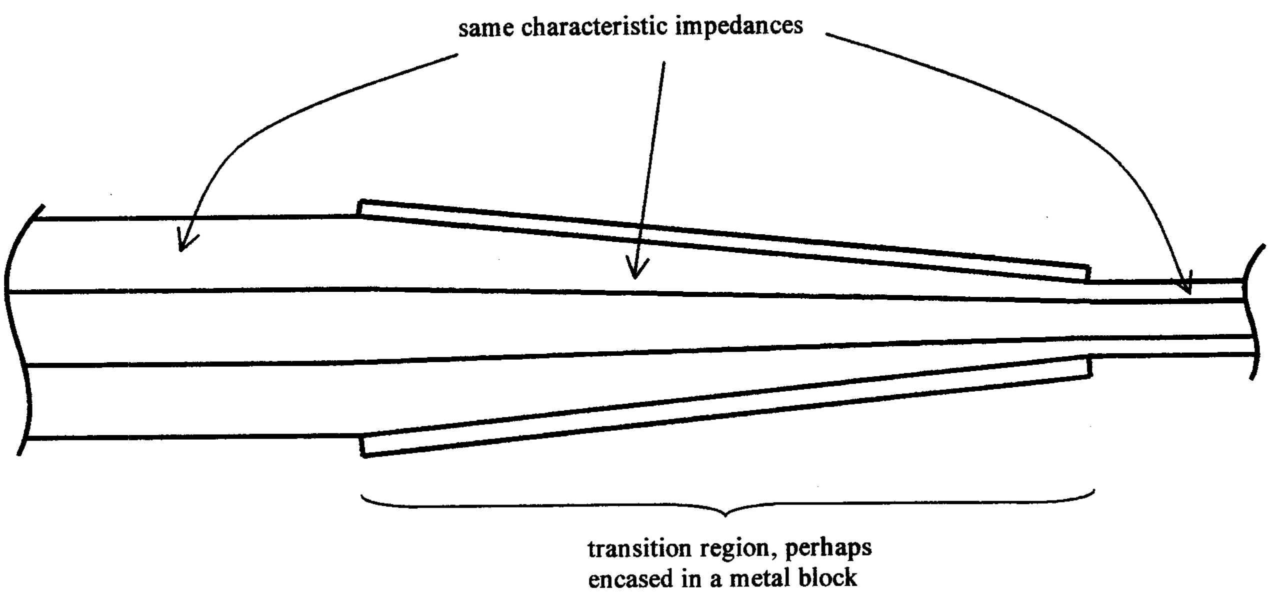


Fig. 4.1 Transition Between Coaxial Cables of Different Diameters

5. Mechanical/Electromagnetic Interaction Near Focal Point

The foregoing electromagnetic considerations are not the only concern. In Section 2 we find that small cables (implying small center conductors) are desired near the apex. These connect between major conductors (feed arms, ground plane, perhaps central post (pipe)). (Note that if a central pipe is used the cable(s) inside it should be peripherally electrically connected to the pipe end as it exists toward the focal point.) However, the electrical connections involving the cable center conductors (in particular) are mechanically weak. Any relative motion between the major conductors places severe stress on these electrical connections. To protect these electrical connections one needs to prevent the relative motion between major conductors and/or provide stress relief (which does not significantly distort the geometry near the conical apex) to these electrical connections.

For rigidly fixing the major electrical conductors relative to each other there are various efficient mechanical configurations of dielectric that one may consider. By efficient is meant designs, which minimize the amount of dielectric required to achieve a certain rigidity, particularly to bending. A common technique consistent with this uses a truss involving cross bracing to form a set of triangles such as commonly used in bridge design. With three or more longitudinal members (noncoplanar) so cross-braced, such a structure is very resistive to bending. Utilizing these to connect between the feed arms, and perhaps a ground plane or central post as indicated in Fig. 5.1, one can construct a very strong structure. Keeping the dielectric (preferably of low dielectric constant) away from the focal region, the wave from the apex is presented with a sparse dielectric structure, which has minimal optical coverage to interfere with the spherical TEM wave passing through toward the reflector.

We have now formed what might be called the outer box. The major electrical conductors (plates, central post) from here on out can be made of rigid (thick) metal. Inside this box we can now design differently. We may have one or more assemblies of more flexible materials for strain relief involving thin metal sheets to which the small cables (preferably somewhat flexible, perhaps using braided conductors) are attached. If desired, a similar but even lighter box type structure can be included in this interior region to take forces away from the cable connections at the apex, with stress relief provided between the two box structures (such as with sliding contacts and/or flexible conductors). Of course multiple such structure ("boxes") can be employed to further distribute the stresses, starting from weak ones near the apex to strong ones as one approaches the reflector, perhaps with log-periodic spacing.

If one does include some dielectric (other than the lenses in Fig. 2.1) at the cable-center-conductor connections between the major conductors for mechanical strength, one must recognize the limitations it can impose on the high-frequency performance. Generally the transit time from the apex through the dielectric should be kept small compared to the short times of interest.

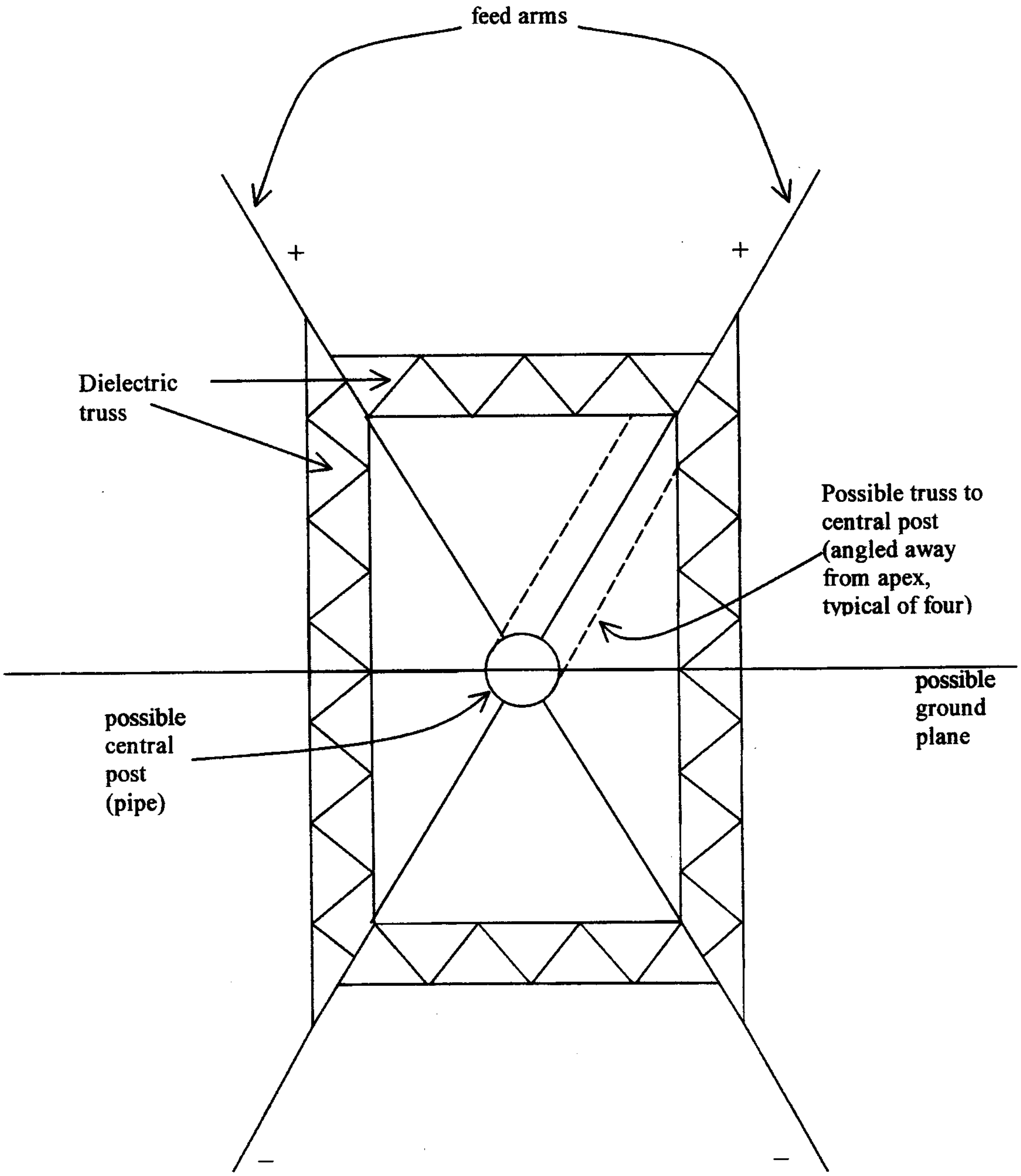


Fig. 5.1 Dielectric Mechanical Structure Near Focal Region

6. Concluding Remarks

There are now several considerations concerning coaxial cables used in reflector IRAs. These are primarily concerned with the upper frequency f_u in the band ratio f_u / f_ℓ where f_ℓ is the lower frequency given by the overall sie of the antenna. By careful attention to the geometrical accuracy of the reflector and focal region, and optimization of the cable parameters f_u can be extended, further increasing the band ratio.

References

1. C. E. Baum, "Configurations of TEM Feed for an IRA", Sensor and Simulation Note 327, April 1991.

2. C. E. Baum, "General Properties of Antennas", Sensor and Simulation Note 330, July 1991.

3. C. E. Baum, J. J. Sadler, and A. P. Stone, "A Prolate Spheroidal Uniform Isotropic Dielectric Lens Feeding a Circular Coax", Sensor and Simulation Note 335, December 1991.

4. C. E. Baum, J. J. Sadler, and A. P. Stone, "Uniform Isotropic Dielectric Equal-Time Lenses for Matching Combinations of Plane and Spherical Waves", Sensor and Simulation Note 352, December 1992.

5. E. G. Farr, G. D. Sower, and C. J. Buchenauer, "Design Considerations for Ultra-Wideband, High-Voltage Baluns", Sensor and Simulation Note 371, October 1994.

6. C. E. Baum, "Use of Generalized Inhomogeneous TEM Plane Waves in Differential Geometric Lens Synthesis", Sensor and Simulation Note 405, December 1996.

7. C. E. Baum, "Some Topics Concerning Feed Arms of Reflector IRAs", Sensor and Simulation Note 414, October 1997.

8. W. S. Bigelow and E. G. Farr, "Compensation of an Electrically Large Coaxial Transmission Line Bend by a Layered Dielectric Lens", Sensor and Simulation Note 445, July 2000.

9. C. E. Baum, "Symmetry in Single-Polarization Reflector Impulse-Radiating Antennas", Sensor and Simulation Note 448, July 2000.

10. C. E. Baum, "Multiconductor-Transmission-Line Model of Balun and Inverter", Measurement Note 42, March 1993.

11. C. E. Baum and J. S. Tyo, "Transient Skin Effect in Cables", Measurement Note 47, July 1996.

12. G. D. Sower, L. M. Atchley, and D. E. Ellibee, "Low-Voltage Prototype Development of an Ultra-Wideband High-Voltage Unzipper Balun", Measurement Note 50, December 1996.

13. J. S. Tyo and C. E. Baum, "Reduced Skin Loss Dissipation at the Edges of a Conducting Plane Using High-Voltage Rollups", Measurement Note 51, April 1997.

14. E. G. Farr, D. E. Ellibee, J. Elizondo, C. E. Baum, and J. M. Lehr, "A Test Chamber for a Gas Switch Using a Hyperboloidal Lens", Switching Note 30, March 2000.