CONICAL ANTENNAS

This article describes characteristics such as input impedance, radiation pattern, and directivity gain of conical antennas consisting of solid conducting cones, conducting conical plates, or their modifications. Conical conducting structures on which simple antenna elements such as dipole and a slot are mounted are also described. An important general feature of conical antennas is their lack of sensitivity to frequency variation, that is, their broadband characteristics. Note that a conical horn antenna is described in HORN ANTENNAS.

The history of the practical use of conical antennas is long. Sir Oliver Lodge constructed a biconical antenna in 1897 and made a wireless communication experiment, while a single cone antenna on the ground and a fan (flat triangular) antenna were used by Marconi and others. The history of the theory of conical antennas is also long. The spherical coordinate is one of the few coordinates for which the method of variable separation in electromagnetic field problems can be applied. The conical surface is defined by a constant polar angle $\theta = \psi$ in the spherical coordinate system. For this reason conical antennas and biconical antennas, in particular, have been extensively investigated by Schelkunoff (1,2), Smith (3), Tai (4,5), Papas and King (6), and many others.

In the limit as $\psi \to 0$ and π, the biconical antenna is reduced to a vanishingly thin linear antenna that is very sensitive to frequency (that is, of narrow bandwidth). As the cone angle increases, the antenna shows broadband characteristics that make it useful for practical applications.

Figure 1 shows an infinitely long, symmetric biconical conductor with a half-cone angle ψ and an infinitesimally small feeding gap (δ gap). The antenna is assumed to be located in free space. This structure can support the transverse electromagnetic (TEM) transmission line mode, that is, the outward-propagating principal spherical wave mode expressed by

$$H_\phi = \frac{1}{r \sin\theta} H_0 e^{-j\beta r} \tag{1}$$

$$E_\phi = \eta H_\phi \tag{2}$$

where $\beta = 2\pi/\lambda$ (λ: wavelength) is the free-space wave number and $\eta = \sqrt{\mu_0/\epsilon_0}$ is the free-space wave impedance. The characteristic impedance K of the biconical transmission line is given by the ratio of the transmission voltage (i.e., the integral of E_θ along the cone-meridian) to the conduction current along the cone as follows:

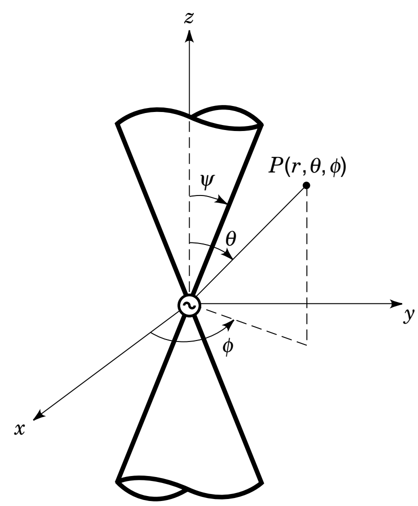


Figure 1. Infinite biconical conductor fed by a δ-gap generator.

$$K = \frac{\eta}{\pi} \ln\left[\cot\frac{\psi}{2}\right] \tag{3}$$

Figure 2 shows the characteristic impedance K versus the half-cone angle ψ.

BICONICAL ANTENNAS

Figure 3 shows the geometry of the biconical antenna. The conducting antenna surfaces are defined by the conical surfaces $\theta = \psi$ and $\theta = \pi - \psi$, and the two spherical end surfaces at $r = a$. The analytical procedure of the biconical antenna will be outlined below. In region I, the electric and magnetic fields are represented as a sum of the outward- and inward-traveling TEM principal modes and an infinite number of complementary (higher) transverse magnetic (TM) modes. In region II, the fields are represented by an infinite series of complementary radiating modes. Boundary conditions on the aperture indicated by the dashed lines in Fig. 3 and the end

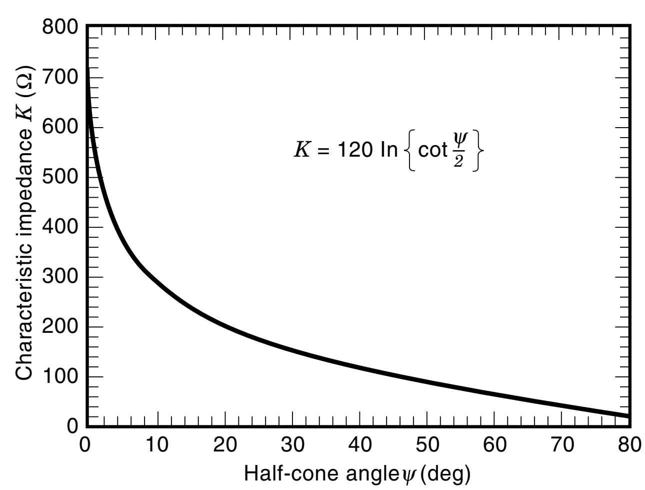


Figure 2. Characteristic impedance of a biconical transmission line.

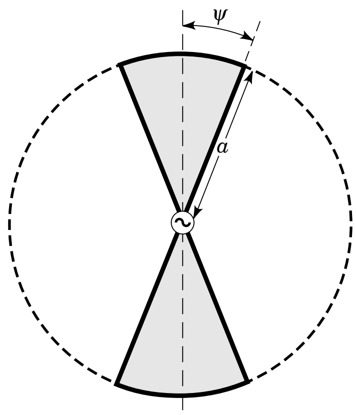


Figure 3. Symmetric biconical antenna.

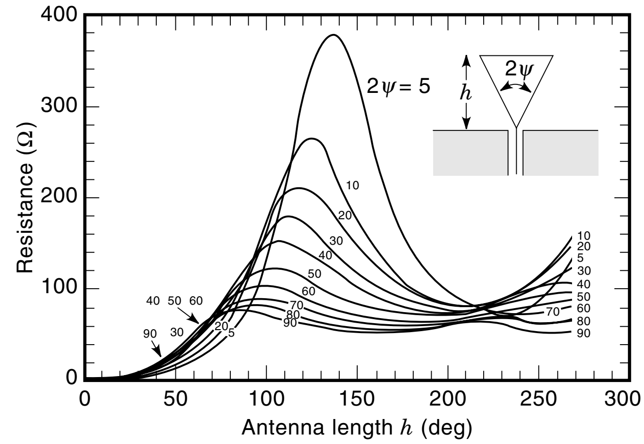


Figure 5. Measured input resistance of a conical unipole versus length in electrical degrees showing broadband characteristics with increasing cone-angle (from 10).

surfaces of the cone at $r = a$ are used to obtain an infinite set of linear algebraic equations from which the amplitudes of the complementary modes and the principal mode reflected back at the aperture are determined.

The input admittance of the biconical antenna is represented by the equivalent transmission line circuit as shown in Fig. 4, where K is the characteristic impedance given by Eq. (3). The terminal admittance Y_t represents the effect of the truncation of the biconical transmission line at $r = a$, that is, the transformation of the outward-traveling TEM mode into the complementary modes in both regions and the reflected TEM mode, which eventually determines the input admittance of the biconical antenna Y_i.

Schelkunoff (2) has formulated the above boundary value problem rigorously and has discussed in detail special cases of a vanishingly thin antenna and a very wide-angle cone, or a spherical antenna with a very narrow equatorial gap. Tai (4) has obtained the exact analytical solution of the terminal admittance of the vanishingly thin antenna, which has been found to be identical to the expression obtained ingeniously by Schelkunoff. Tai (5) has also made an important contribution to the development of the theory for biconical antennas by applying Schwinger's variational method. He has given the first order variational numerical solution for the specific wide cone-angles $\psi = 39.23°$, $57.43°$, and $66.06°$.

The recent development of computers has made feasible the numerical solution of Schelkunoff's formulation. However, it is still not easy to solve the infinite set of linear determining equations with reasonable accuracy because of slow convergence of the infinite series when the cone-angle decreases. For example, 15 or more modes for $\psi = 5°$ (7), and 13 modes for $\psi = 5°$ (8) are necessary for computation of the input impedance. A conical monopole above an image plane driven by a coaxial line has been numerically analyzed by using the finite difference time domain method (9).

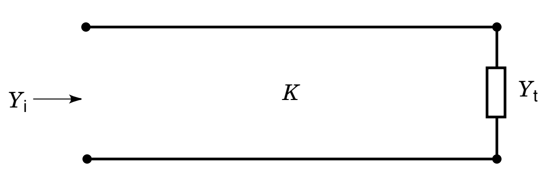


Figure 4. Equivalent circuit of a symmetric biconical antenna.

When the upper half-cone of the biconical antenna is mounted on an infinite conducting plane (ground plane), the antenna forms a conical unipole having one half of the input impedance of the biconical antenna. Figures 5 and 6 [Brown and Woodward, Jr. (10)] show respectively the measured input resistance and reactance of a conical unipole having flat caps instead of spherical caps. It is clear that the antenna tends to have a constant input resistance and a small reactance around zero versus frequency, showing broadband characteristics as the cone-angle is increased.

The radiation pattern of the biconical antenna has been computed by Papas and King (6) and by Bevensee (11). Figure 7 shows the far-zone electric field pattern (6) for the cone angle of $\psi = 30°$. It is found that the patterns are not much different from those of a straight wire antenna.

Theoretical analysis of biconical antennas loaded with and/or immersed in dielectric, lossy, and ferromagnetic mate-

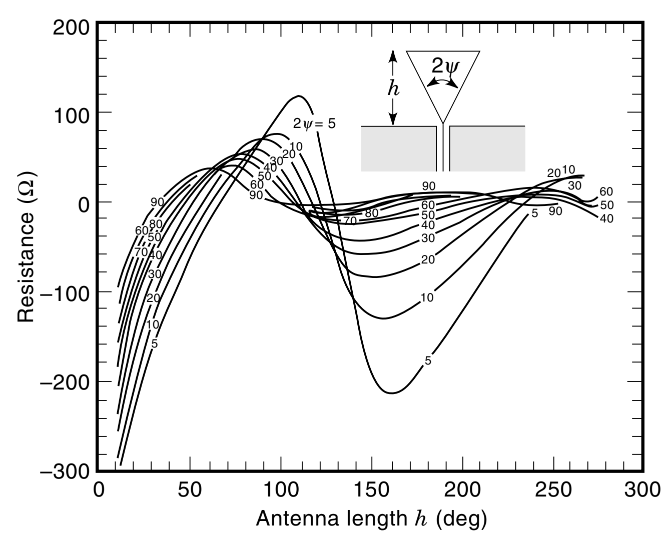


Figure 6. Measured input reactance of a conical unipole versus length in electrical degrees showing broadband characteristics with increasing cone-angle (from 10).

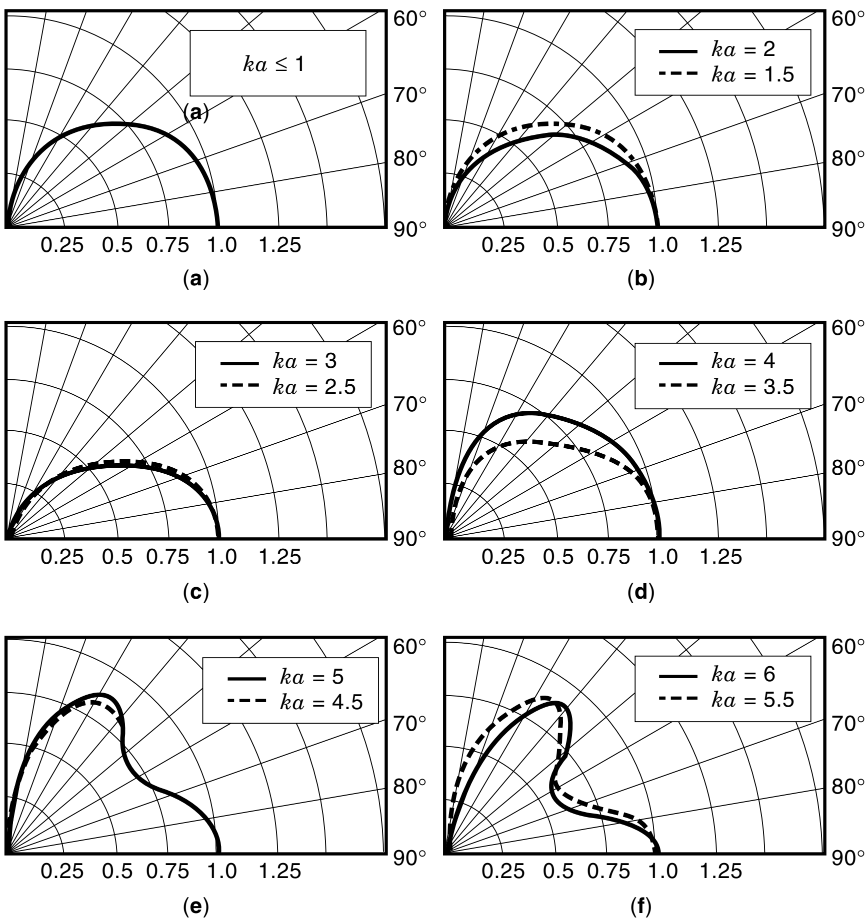


Figure 7. Far-zone electric field patterns of a biconical antenna, $\psi = 30°$. Patterns do not change very much from $ka = 0$ to $ka \approx \pi$.

rials has been provided by Schelkunoff (2), Tai (4), Polk (12), and others. These topics are reviewed by Wait (13). The theory of an asymmetric biconical antenna was also discussed by Schelkunoff (2). The variational approach by Tai was extended to a semi-infinite asymmetric conical antenna consisting of an infinite cone and a finite cone (14).

To reduce wind resistance and/or weight, a solid biconical antenna can be replaced by a skeletal conducting wire structure using several radial rods (15,16). It has been found, however, by analysis using the moment method that a considerable number of wires (e.g., 16) is required to approximate the solid biconical antenna.

ANTENNAS ON CONICAL STRUCTURE

In practice, a conical structure on which simple antenna elements such as dipole, disk, cone, slot, or patch are mounted to excite a cone is often used. The infinite cone excited with an axial dipole at the tip has shown (14) that the strong radiation occurs along the small-angle cone unless the dipole length is about a half-wavelength. Figure 8 shows a finite wide-angle cone excited with a quarter-wavelength long and a half-wavelength long dipole (17). Note that the maximum radiation can be directed toward the horizontal plane by proper choice of a and θ_0 at a desired frequency. A cone excited with an axially symmetric circumferential slot close to the tip (18) shows radiation characteristics similar to those of a dipole-excited cone, since a small circumferential slot (magnetic current loop) is equivalent to a small axial electric dipole. When the circumferential slot is not too close to the tip, that is, apart by 2.5 wavelength ($2\psi = 30°$), the radiation pattern shows a rather complicated lobe structure (18). The cone excited with a circular disk at the tip is called a discone antenna (19). This antenna is fed with a coaxial cable whose inner conductor terminates on the center of the disk and whose outer conductor terminates on the tip of the cone. The radiation pattern of the discone is similar to that of a dipole antenna, but its input impedance bandwidth is exceedingly broad compared with an ordinary dipole antenna.

Figure 9 shows the measured input VSWR (for 57.6 Ω cable) versus frequency of the finite conical antenna with different exciting elements at its tip (17). The cone excited with a conical element (an asymmetric biconical antenna) indicates very broadband characteristics, particularly in lower-frequency regions, without affecting the radiation pattern.

TRIANGULAR (BOW-TIE) ANTENNAS

A triangular plate antenna above a conducting ground plane and a bow-tie antenna are shown in Figs. 10(a) and 10(b). These antennas also possess broadband characteristics, though not as broad as a solid conical antenna. The theoretical characteristics of the bow-tie antenna have been obtained numerically (20) by using the method of finite difference time domain (FDTD). Figures 11(a) and 11(b) show the calculated input impedance. The input impedance of the triangular plate

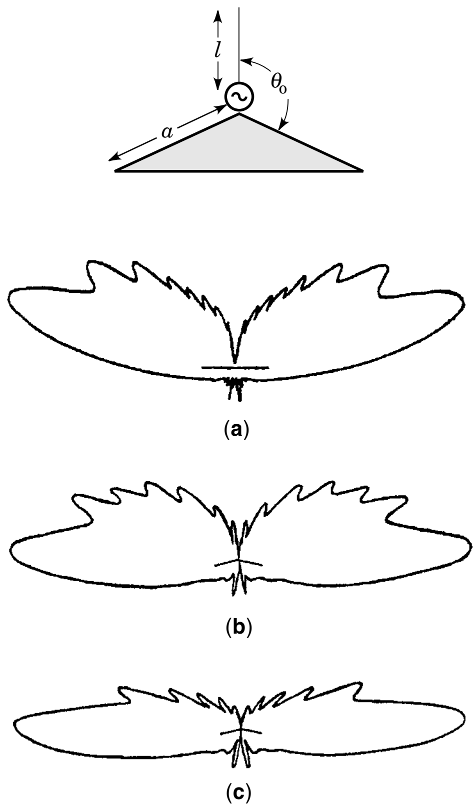


Figure 8. Far-zone electric field pattern of a tip-excited conical antenna, $\beta a = 50$. (a) $\theta_0 = 90°$, $l = \lambda/4$; (b) $\theta_0 = 103.8°$, $l = \lambda/4$; (c) $\theta_0 = 103.8°$, $l = \lambda/2$. Radiation beam can be directed to horizon by slanting a cone downward (from 17).

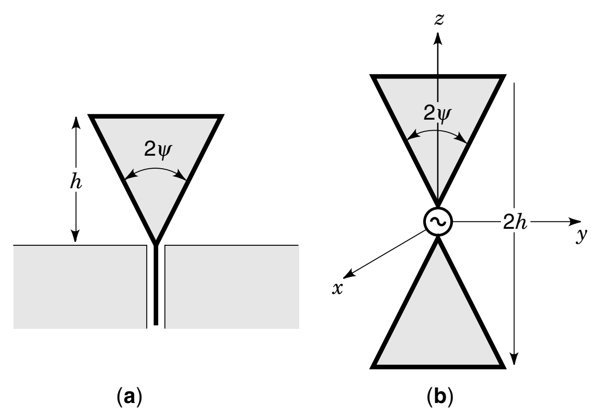


Figure 10. (a) Triangular plate antenna and (b) bow-tie antenna.

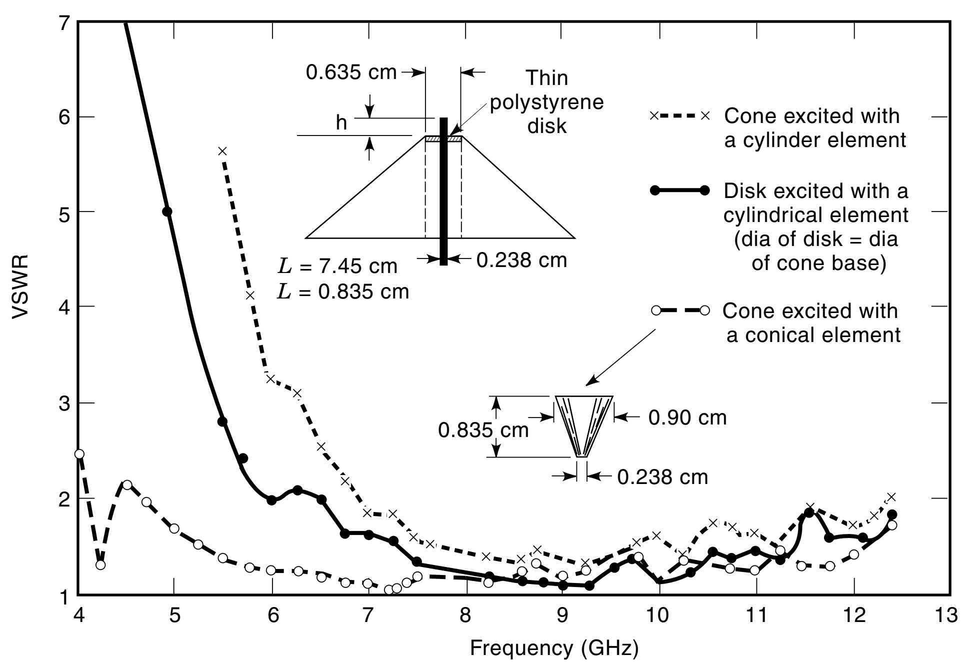


Figure 9. VSWR versus frequency of a disk and a cone excited with a cylindrical element or a conical element showing that a cone excited with a conical element is most broadband (from 17).

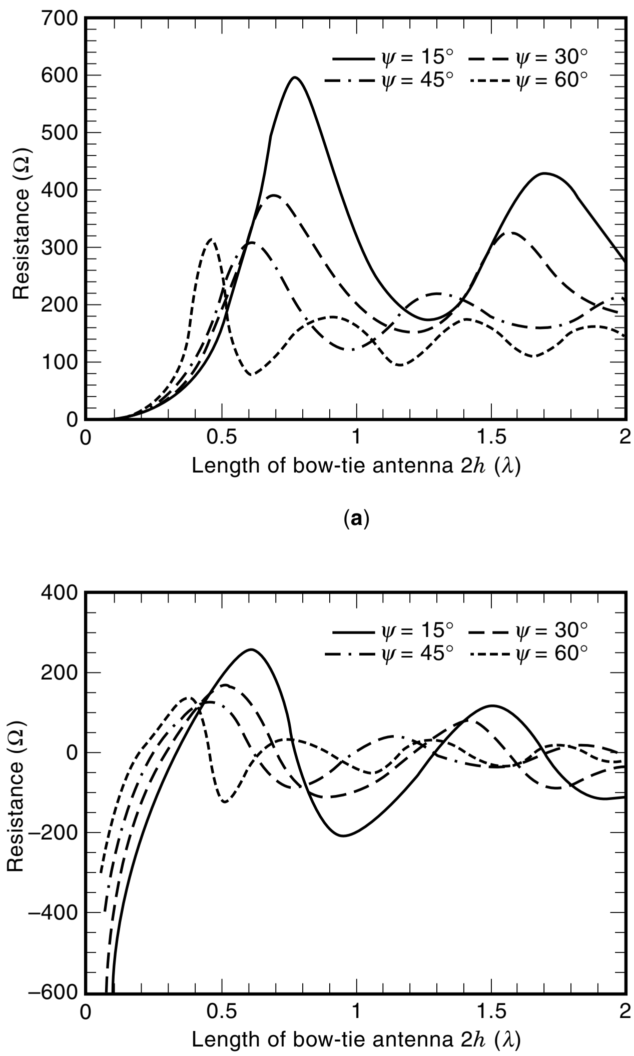
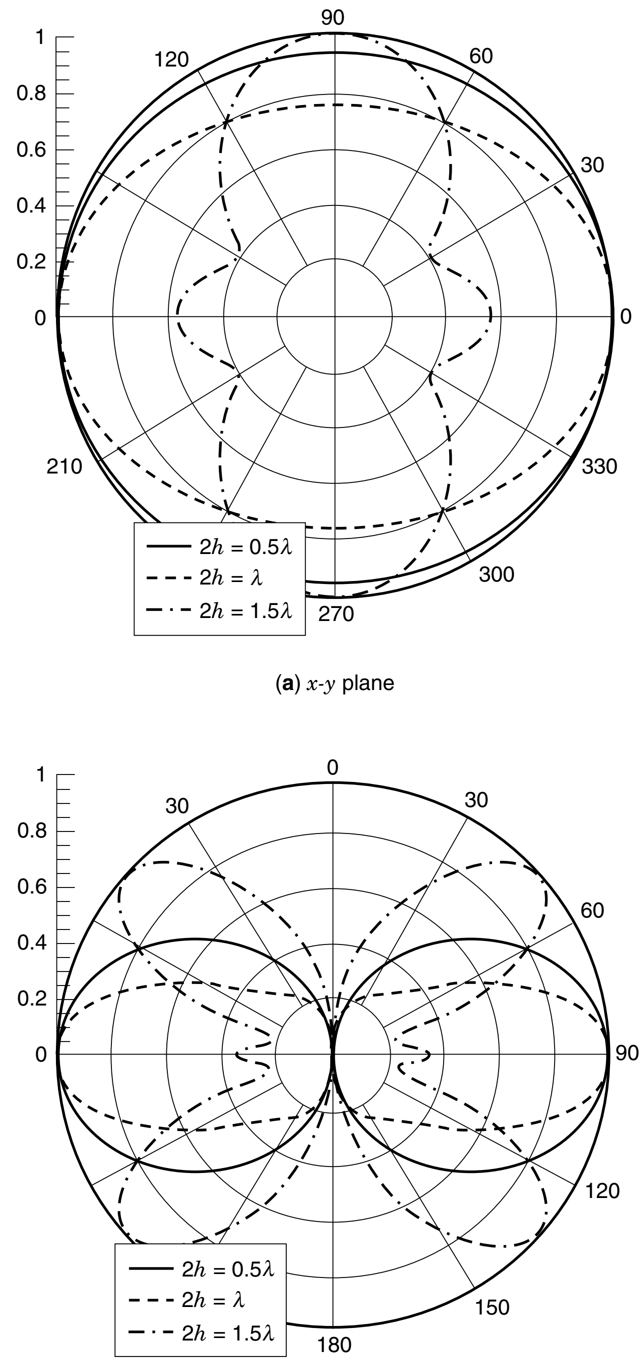


Figure 11. Input impedance of a bow-tie antenna showing the broadband characteristics with increasing flare angle (from 20).



(**b**) x-z plane

Figure 12. Far-zone electric field pattern of a bow-tie antenna, $\psi = 30°$ (from 20).

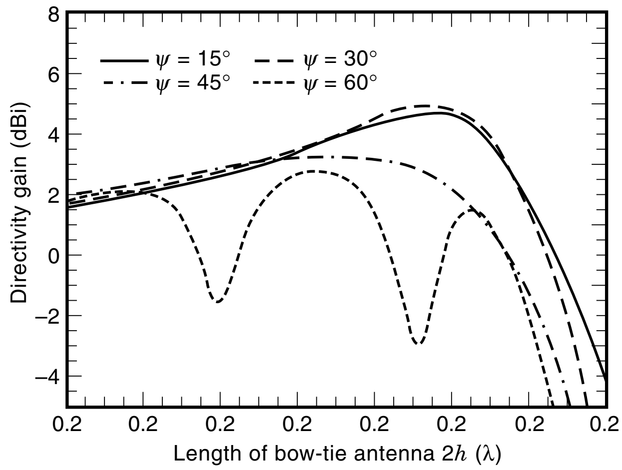


Figure 13. Directivity gain of a bow-tie antenna in x-direction (from 20).

antenna above the ground plane is half of that of the bow-tie antenna.

The far-zone electric field patterns in the x-y plane and in the x-z plane are shown in Figs. 12(a) and 12(b), respectively. Note that the radiation is enhanced in the direction perpendicular to the antenna plate for the antenna length $2h \lesssim \lambda$, because the radiation from the antenna surface current is added in phase in that direction. The theoretical directivity gain of the bow-tie antenna in the direction of the x-axis is shown in dBi in Fig. 13 versus the antenna length $2h/\lambda$ for various cone angles (20). It is noted here that the bow-tie antenna can also be simulated by several radial wire rods as the solid biconical antenna.

BIBLIOGRAPHY

1. S. A. Schelkunoff, Principal and complementary waves in antennas. *Proc. IRE,* **34** (1): 23–32, 1946.
2. S. A. Schelkunoff, *Advanced Antenna Theory,* New York: Wiley, 1952.
3. P. D. P. Smith, The conical dipole of wide angle, *J. Appl. Phys.,* **19** (1): 11–23, 1948.
4. C. T. Tai, On the theory of biconical antennas, *J. Appl. Phys.,* **19** (12): 1155–1160, 1948.
5. C. T. Tai, Application of variational principle to biconical antennas, *J. Appl. Phys.,* **20** (11): 1076–1084, 1949.
6. C. H. Papas and R. W. P. King, Radiation from wide-angle conical antennas fed by a coaxial line, *Proc. IRE,* **39** (1): 49–51, 1951.
7. S. A. Saoudy and M. Hamid, Input admittance of a biconical antenna with wide feed gap, *IEEE Trans. Antennas Propag.* **38** (11): 1784–1790, 1990.
8. V. Badii, K. Tomiyama, and D. M. Grimes, Biconical transmitting antennas, a numerical analysis, *Appl. Comput. Electromagn. Soc. J.* **5** (1): 62–93, 1990.
9. J. G. Maloney, G. S. Smith, and W. R. Scott, Jr., Accurate computation of the radiation from simple antennas using the finite-difference time-domain method, *IEEE Trans. Antennas Propag.,* **38** (7): 1059–1068, 1990.
10. G. H. Brown and O. M. Woodward, Jr., Experimentally determined radiation characteristics of conical and triangular antennas, *RCA Rev.,* **13** (4): 425–452, 1952.
11. R. M. Bevensee, *Handbook of Conical Antennas and Scatterers,* New York: Gordon and Breach, 1973.
12. C. Polk, Resonance and supergain effects in small ferromagnetically or dielectrically loaded biconical antennas, *IRE Trans. Antennas Propag.* **7** (Special Supplement): 414–423, 1959.
13. J. R. Wait, Electromagnetic radiation from conical structures, In R. E. Collin and F. J. Zucker (eds.), *Antenna Theory,* New York: McGraw-Hill, 1969.
14. S. Adachi, A theoretical analysis of semi-infinite conical antennas, *IEEE Trans. Antennas Propag.,* **8**: 534–547, 1960.
15. C. E. Smith, C. M. Butler, and K. R. Umashanker, Characteristics of a wire biconical antenna, *Microw. J.,* **22** (9): 37–40, 1979.
16. O. Givati and A. P. C. Fourie, Analysis of skeletal wire conical antennas, *IEEE Trans. Antennas Propag.,* **44**: 844–858, 1996.
17. S. Adachi, R. G. Kouyoumjian, and R. G. Van Sickle, The finite conical antenna, *IEEE Trans. Antennas Propag.,* **7** (Special Supplement): S406–S411, 1959.
18. L. L. Bailin and S. Silver, Exterior electromagnetic boundary problem for sphere and cones, *IRE Trans. Antennas Propag.* **4** (1): 5–16, 1956, and Corrections, **4** (3): 313, 1957.
19. A. G. Kandoian, Three new antenna types and their applications, *Proc. IRE,* 70W–75W, 1946.
20. Private communication from Y. He, T. Uno, and S. Adachi, 1997.

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