TOROIDAL HELIX ANTENNA

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Introduction

The design and operation of Low Profile and Electrically Small Antennas has traditionally centered around the properties of efficiency and bandwidth for these structures. Over the years a variety of significant theoretical studies and experimental efforts have been performed by many well known investigators. Wheeler's monumental work of over 40 years, summarized in Ref.1, is worthy of special note. He has provided one of the most splendid practical techniques for characterizing and predicting the behavior of these small antennas. (Small, in this context, means that the entire antenna, and its images, fit within the radian sphere - a sphere of radius $\lambda_o/2\pi$. Small at VLF or ELF, of course, may entail substantial real estate.) Clearly, the bottom line on all this is that remarkable performance is certainly practical, provided only that one does not become too greedy in the size-efficiency-bandwidth tradeoff.

Electrically Small Antennas have always represented one of the major challenges to the RF engineering profession. (Indeed, the topic seems to reappear in regular cycles.) Traditionally, acceptable performance has been coaxed and tweaked out of these devices by either (1) reducing system losses (use thick wires on the antennas and low loss elements in the matching networks) or by (2) increasing the radiation resistance (say, by top loading short towers). Newmann has devised a third line of attack which is viable when a small antenna is to be located on a larger conducting support structure. The technique, apparently, is to (3) use the small antenna as a coupler to excite characteristic modes on the support. The method is especially useful if the small antenna, by itself, is not very efficient. Unfortunately, only the first two techniques are of value to AM broadcasters or for VLF/ELF communications.

Small Antennas at Low Frequencies

At these lower frequencies, another major electromagnetic factor is of considerable significance. Traditional small antenna analysis is usually formulated in a free space environment. At these lower frequencies, however, one must also contend with the Sommerfeld attenuation function. (In

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this regard, consult the remarkable work of Norton, who reduced the calculation of ground wave losses to a practical form appropriate for use by AM broadcasters in this country. Ref. 3) Simply put, at these lower frequencies the problem with electrically small antennas is not only to reduce system losses, but simultaneously to produce vertical polarization. At AM broadcast frequencies, horizontal polarization attenuates so rapidly as to be of no practical significance. Any radiated HP, in fact, represents a serious degradation of system performance. A simple coil, multiturn loop or helix, no matter how efficient, will produce elliptical polarization. No matter how well constructed, these electrically small antennas are of no commercial value whatsoever to AM broadcasters since the inherent horizontal component of the radiation represents wasted power, and must not appear in the numerator of the radiation efficiency expression. This genus of electrically small antennas would be of significant value at low frequencies if they could also be made self-resonant and exclusively vertically polarized, while at the same time either requiring a ground system no larger than conventional short vertical towers, or none at all.

The Toroidal Helix Approach

One particularly intriguing idea is to take a self resonant normal mode helix, pull it around into a closed torus and let the resulting structure combine the tuning and matching networks with the radiating element itself. (See Ref.4). The radiation resistance is now in series with the coil inductance, and this combination is shunted by the helix turn-to-turn capacitance. The impedance transforming nature of this lumped circuit equivalent is well known, and it also has the advantage of transforming a relatively small feedpoint current into a stepped up current passing through the radiation resistance. The circuit equivalent used to be called a "current amplifier" in the old books on network theory.

The field theory analysis of the antenna is fairly straightforward. Since the structure is a slow wave self resonant helix, it is reasonable to assume a superposed sinusoidal distribution of electric and magnetic current, where the electric current is given by

$$(1)\quad J(r') = I_o \cos(n\phi')\, \delta(\cos\theta')\, \frac{\delta(r'-a)}{a}\, \hat{\phi}'$$

the coordinates having their usual meanings, and the magnetic current is found from

$$(2)\qquad I_m = 2\pi f \mu (\pi b^2/s)\, I_o$$

where b is the helix radius and s is the turn-to-turn spacing. In these expressions, n is a mode number for the current distribution. The radiated fields are determined in Ref.4 as:

$$(3a)\quad E^e_\phi = -\frac{\beta_g a Z_o I_o}{2r} \cos n\phi \; J'_n(\beta_g a \sin\theta)\; e^{j(n\pi/2)}$$

$$(3b)\quad E^e_\theta = \frac{n\beta_g a Z_o I_o}{2r} \sin n\phi \; \frac{J_n(\beta_g a \sin\theta)}{\beta_g a \tan\theta}\; e^{j(n\pi/2)}$$

$$(3c)\quad E^m_\theta = -\frac{\beta_g a I_m}{2r} \cos n\phi \; J'_n(\beta_g a \sin\theta)\; e^{j(n\pi/2)}$$

$$(3d)\quad E^m_\phi = -\frac{n\beta_g a I_m}{2r} \sin n\phi \; \frac{J_n(\beta_g a \sin\theta)}{\beta_g a \tan\theta}\; e^{j(n\pi/2)}$$

The superscript e indicates a field component attributable to the electric current and m to the magnetic current. $J_n(x)$ is the usual Bessel function and β_g is the phase constant appropriate for the helix. These fields are not unlike those produced by the superposition of a resonant loop and a circular slot. However, because of the slow wave nature of the toroidal helix, the physical size has been considerably reduced.

Several variations of the basic configuration are now possible. By contrawinding the helix (Refs.4,5,6), the azimuthal component of electric current is cancelled out and one is simply left with what is commonly known as a poloidal flow of electric current. This is occasionally called a caduceus winding. The radiated fields are then given by only expressions (3c) and (3d). Further, and this is important, if one divides the Toroidal Helix into 4 or more segments it can be fed as Smith's cloverleaf antenna, so familiar from FM broadcasting. (See Refs.4,7). The resultant magnetic current distribution will be uniform, (n = 0), and the radiated field is described simply by equation (3c).

We now have a Low Profile, slow wave, **vertically polarized**, self resonant, omni-directional (in the azimuthal plane) radiator with a substantial feed-point impedance. Consequently, the structure has considerable desirability as an Electrically Small Antenna at frequencies where ground-wave propagation or ground effects are important.

One does not get something for nothing, however. Chu's fundamental limit, which relates the lowest achievable Q of a lossless Electrically Small Antenna to its maximum physical dimension, is still in force. The Toroidal Helix is a remarkable structure, but it has been bought at the price of reduced bandwidth. Of course, one may make a trade-off between operational bandwidth and efficiency, if one so desires.

Lastly, several experimentally measured electrical properties should be reported. A typical structure consisting of 32 contrawound rings 1/60 th of a wavelength in diameter, arranged in a torus of radius 1/21 th of a wavelength had a resonant feed-point impedance on the order of 1500 ohms (purely resistive). The Toroidal Helix produced purely vertical polarization. (The horizontal component was at least 35 dB, or more, down from the vertical component.) The structure had a Q on the order of 35, as determined from impedance measurements. The measured field intensity was within 3 dB of a quarter wave monopole above 36 radials one quarter-wavelength long.

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