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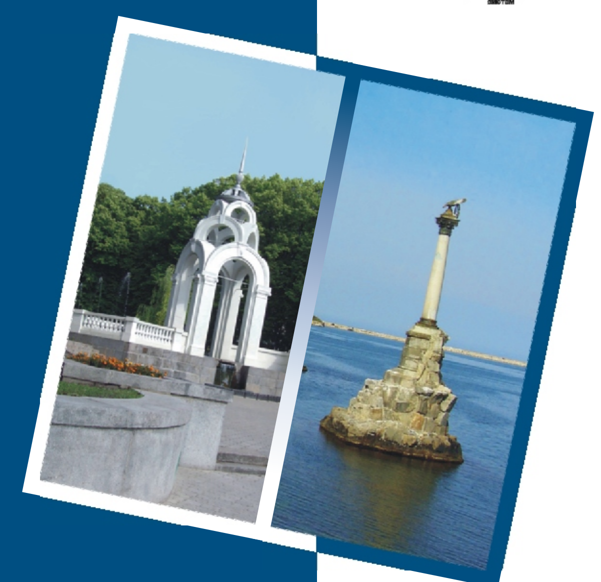

Sevastopol, Ukraine

September 17 – 21, 2007

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GENERAL ANTENNA THEORY

MICROWAVE COMPONENTS AND CIRCUITS, FIBER-OPTICS LINKS

International Conference on Antenna Theory and Techniques, 17-21 September, 2007, Sevastopol, Ukraine pp. 116-118

60 YEARS OF ELECTRICALLY SMALL ANTENNAS THEORY

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Abstract

In 2007 60 years from the moment of the publication of the first theoretical work which have proved fundamental limits of achievable parameters so-called Electrically Small Antennas (ESA) are executed. On the eve of a anniversary of the given event - it is high time to sum up the 60-years way gone by theorists and developers of aerials in understanding of limiting restrictions in realization effective of ESA-solutions. The given report also is devoted to this review.

Keywords: Electrically small antennas (ESA), quality factor, fundamental limit.

In 2007 60 years from the moment of the publication of the first theoretical work which have proved fundamental limits of achievable parameters so-called Electrically Small Antennas (ESA) are executed. It was article of Harold A. Wheeler [1]. On the eve of a anniversary of the given event - it is high time to sum up the 60-years way gone by theorists and developers of aerials in understanding of limiting restrictions in realization effective of ESA-solutions. The given report also is devoted to this review.

The author it is offered to distinguish in a history of development of the passives ESA's theory four stages. First of them covers the period from the moment of the publication of Harold A. Wheeler's article, and development, becoming since 1948 of the fundamental limit's theory of Quality Factor of Chu within of the concept of equivalent electric circuits, a concrete definition of its positions from Harrington in 1960.

The Wheeler's definition of a Electrically Small Antenna is antenna with geometrical dimension which fits inside a sphere of radius $a = 1/k$ where $k = 2\pi/\lambda$ is the wave number associated with the electromagnetic field (Fig. 1).

The radiative properties of such electrically small antennas were first investigated by Wheeler [1] who coined the term "radiation power factor" as the inverse of the radiation Q (Quality Factor). Using circuit concepts for a capacitor and inductor acting as an antenna, he showed that the radiation power factor for either kind of antenna is somewhat greater than

$$Q^{-1} > \frac{4\pi^2}{3\lambda^3}\mathrm{Vol},$$

where Vol is the volume of the cylinder containing the antenna and λ is the wavelength.

A year later, Chu [2] derived an approximate lower limit for the radiation Q (Quality Factor) of an electrically small antenna:

$$Q = \begin{cases} \dfrac{2\omega W_e}{P}, \ W_e > W_m, \\ \dfrac{2\omega W_m}{P}, \ W_m > W_e. \end{cases}$$

If lower the Q factor for the antenna, then wider the useable frequency band of the antenna.

Chu was the first to derive analytic results using Maxwell's equations for omnidirectional, linearly polarized radiation. He obtained expressions for the minimum radiation Q that can be obtained for an antenna that fit within a sphere of a given radius. This result assumed no energy remained within the sphere. The fields outside the sphere were expanded in spherical wave functions. The stored energy and radiated power were calculated for each mode using the complex Poynting Theorem and a ladder circuit derived for each mode.

Chu obtained results for transverse-magnetic (TM) and transverse-electric (TE) linearly polarized and circularly polarized modes.

In 1960, Harrington [3] related the effects of antenna size, gain and minimum Q for the near and far

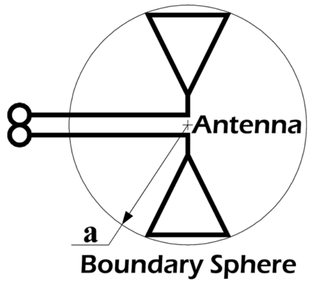

Fig. 1. Electrically Small Antenna.

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field diffraction zones for linearly and circularly polarized waves, and also treated the case where the antenna efficiency h is less than 100%. Harrington also extended this theoretical result to include the maximum possible gain. The Chu-Harrington's limit of Q for linearly polarized waves can be written:

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

or approximated for $ka << 1$

$$Q \approx \frac{1}{k^3a^3}. \qquad (2)$$

The beginning of the second stage is connected with offered in 1964. Robert E. Collin and S. Rothschild a method of calculation of limiting Quality Factor ESA on the basis of analytical Equations for the full reserved energy of an electromagnetic field close ESA [4]:

$$Q \approx \frac{1}{k^3a^3} + \frac{1}{ka}. \qquad (3)$$

This result conflicted with the Chu-Harrington's limit. The same period was marked by split of theorists on two camps-supporters of the theory of Chu and adherents of its revision.

The third stage was marked by detection in 1996 McLean [5] a long-term mistake in treatment of results of Chu admitted Harrington, and the further specification on this basis of Equations for limiting Quality Factor ESA. MacLean [5] re-examined the fundamental limit in order to achieve the highest possible accuracy because it makes little sense to speak of approximate fundamental limits. McLean then presented an exact expression for the minimum radiation Q. Like Chu, he assumed that the antenna radiates only one mode, in this case the $n=1$ spherical mode. The fields of this mode are equivalent to the fields radiated by a short dipole antenna. He computed the stored energy due to the total fields and then subtracts the stored energy due to the radiated fields, leaving only the non-propagating stored energy from which the radiation Q is determined. The resulting expression for Q and linearly polarized waves is

$$Q = \frac{1+2k^2a^2}{k^3a^3\left(1+k^2a^2\right)} = \frac{1}{k^3a^3} + \frac{1}{ka\left(1+k^2a^2\right)}. \qquad (4)$$

For $ka << 1$ this can be approximated

$$Q \approx \frac{1}{k^3a^3} + \frac{1}{ka}.$$

This result confirmed Collin-Rothschild's limit. Figure 2 shows the minimum Q of (1) – (4) for 100 % efficiency.

The McLean's limit of Q for circularly polarized waves can be written:

$$Q \approx \frac{1}{2k^3a^3} + \frac{1}{ka}. \qquad (5)$$

Caswell, Davis and Stutzman [6] re-formulated the theory using the time-domain approach. The classical derivation of the fundamental limits assumed that the electric and magnetic stored energies are completely orthogonal. However, this is not the case for an antenna.

For the time-domain derivation, the Caswell's definition of Q for circularly polarized waves is modified as follows

$$Q = \frac{\omega \cdot \max\left[W_e + W_m\right]}{P}.$$

Computing the peak stored energy in the time domain assuming that the antenna radiates only one mode, $n=1$, gives the final result for radiation Q

$$Q = \frac{1}{2k^3a^3} + \frac{1}{ka} + \sqrt{\frac{1}{4k^6a^6} + \frac{1}{k^2a^2}}. \qquad (6)$$

The same result give in 1998 Dale M. Grimes and Craig A. Grimes [7].

Figure 3 shows the minimum radiation Q of (3) as derived by Robert E. Collin, S. Rothschild and MacLean compared to the Q in (5) for 100% efficiency. For small ka, both curves converge to the same value. However, as ka increases, the curves diverge. The commonly accepted size limit for small antennas is

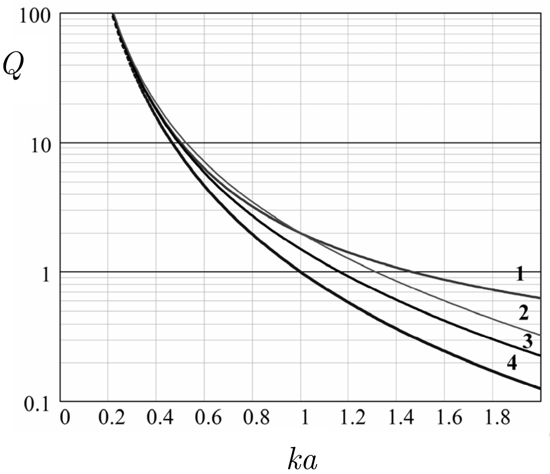

Fig. 2. The Family of limits: 1 – (3), 2 – (1), 3 – (4), 4 – (2).

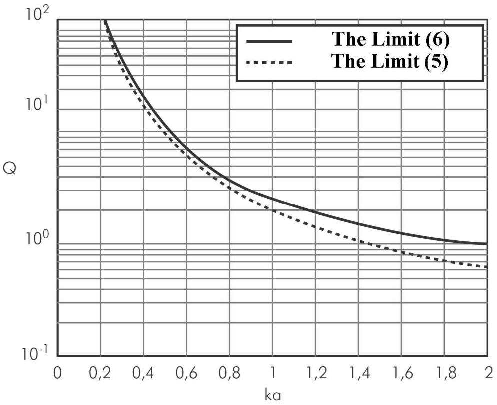

Fig. 3. The Family of limits (5) and (6).

$ka = 1$. At the size, the ratio of the two curves is 1.31.

The present, fourth stage, originates in 2003 from publication Thiele, Detweiler and Penno [8] of a limit of Quality Factor ESA for sine wave distribution of a current in a conductor (Fig. 4). Since this moment the basic direction of development of theory ESA is search of the limits sold in practice which are as much as possible taking into account all physical effects in ESA solutions.

For more information about problems of ESA's Theory please look in [9].

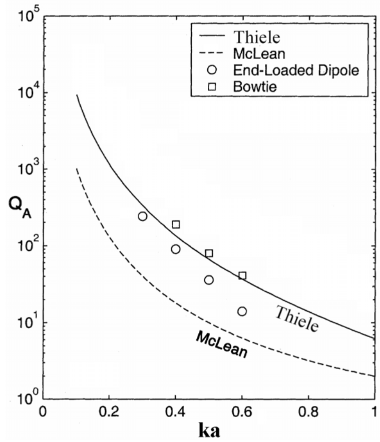

Fig. 4. The Thiele's limit and Q of the some antennas [8].

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НАУКОВЕ ВИДАННЯ
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