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Electrically small magnetic dipole antennas with quality factors approaching the Chu lower bound

Oleksiy S. Kim, Olav Breinbjerg, Member, IEEE, and Arthur D. Yaghjian, Life Fellow, IEEE

Abstract—We investigate the quality factor $Q$ for electrically small current distributions and practical antenna designs radiating the $TE_{10}$ magnetic dipole field. The current distributions and the antenna designs employ electric currents on a spherical surface enclosing a magneto-dielectric material that serves to reduce the internal stored energy. Closed-form expressions for the internal and external stored energies as well as for the quality factor $Q$ are derived. The influence of the sphere radius and the material permeability and permittivity on the quality factor $Q$ is determined and verified numerically. It is found that for a given antenna size and permittivity there is an optimum permeability that ensures the lowest possible $Q$, and this optimum permeability is inversely proportional to the square of the antenna electrical radius. When the relative permeability is equal to 1, the optimum permeability yields the quality factor $Q$ that constitutes the lower bound for a magnetic dipole antenna with a magneto-dielectric core. Furthermore, the smaller the antenna the closer its quality factor $Q$ can approach the Chu lower bound. Simulated results for the $TE_{10}$-mode multiarm spherical helix antenna with a magnetic core reach a $Q$ that is 1.24 times the Chu lower bound for an electrical radius of 0.192.

Index Terms—Electrically small antennas, magnetic dipole, quality factor, Chu limit, spherical modes, surface integral equation

I. INTRODUCTION

Electrically small antennas, that is, antennas that are small compared to the free-space wavelength at their frequency of operation, have been a subject of research for many years [1]–[8] and the challenges of these antennas are well known. Nevertheless, in recent years the escalation of miniaturized wireless technology has stimulated new research to develop small antennas with acceptable matching, bandwidth, and radiation efficiency [9]–[12]. In particular, it is of great interest to investigate how closely a small antenna can have its radiation quality factor $Q$ approach the Chu lower bound $Q_{Chu}$. For an antenna that is resonant (equal stored electric and magnetic energies) and that radiates either an electric-dipole field ($TM_{10}$ spherical mode) or a magnetic-dipole field ($TE_{10}$ mode) at a frequency with free-space wave number $k$, and with the smallest circumscribing sphere of radius $a$, this bound can be expressed as [4]

$$Q_{Chu} = \frac{1}{(ka)^3} + \frac{1}{ka}, \quad ka \ll 1. \quad (1)$$

It is sometimes stated that the Chu lower bound is based on the assumption that the internal volume of the circumscribing sphere does not store any energy — but this is not entirely correct. As pointed out by Chu [2, p. 1170] the internal volume can store the energy that may be needed to make the antenna resonant. For an electrically small $TM_{10}$ electric-dipole antenna, where the external stored electric energy dominates the internal stored magnetic energy, the internal volume must store a magnetic energy to compensate the difference of the external stored energies, and vice versa for a $TE_{10}$ magnetic-dipole antenna. In any case, this internal stored energy is taken into account since (1) is based on a total stored energy that is set to twice the maximum of the external stored electric and magnetic energies.

Internal stored energy, beyond that needed to make the antenna resonant, will obviously increase the quality factor above the Chu lower bound. An electrically small, spherical surface current distribution in free space that radiates the $TM_{10}$ electric-dipole field will have a significant internal stored electric energy, while a similar current distribution that radiates the $TE_{10}$ magnetic-dipole field will have a significant internal stored magnetic energy. Investigating a spherical coil antenna radiating the $TE_{10}$ magnetic-dipole field, Wheeler [13] reported a quality factor 3.0 times the first term of the Chu lower bound (1). More recently, Thal [8] showed that the inclusion of the internal stored energy results in a quality factor for electric surface currents radiating the $TM_{10}$ electric-dipole field that is 1.5 times the Chu lower bound, while the quality factor for electric surface currents radiating the $TE_{10}$ magnetic-dipole field is 3.0 times the Chu lower bound. That is,

$$Q_{TM_{10}} = 1.5Q_{Chu}, \quad ka \ll 1 \quad (2a)$$

$$Q_{TE_{10}} = 3.0Q_{Chu}, \quad ka \ll 1. \quad (2b)$$

Thal’s derivation [8] is based on his previously derived circuit equivalents for spherical vector waves [14] and is thus in line with the approach of Chu [2]. The authors of this manuscript have followed the more direct approach of Collin and Rothschild [4] to verify (2) by calculating the internal and external stored energies from spatial integrations of the electromagnetic fields [15]. These calculations show that for an electrically small, electric surface current density radiating the $TM_{10}$ electric-dipole field, the internal stored electric energy is 0.5 times the external stored electric energy. Furthermore, for an electrically small, electric surface current density radiating the $TE_{10}$ magnetic-dipole field the internal stored magnetic energy is 2.0 times the external stored magnetic energy.

It is interesting to note that recent electrically small $TM_{10}$ electric-dipole antennas by Best [9], [10] as well as $TE_{10}$ antennas...
magnetic-dipole antennas by Best [16] and Kim [17] exhibit quality factors that approach the values in (2) from above, and there is apparently no report in the literature of free-space antennas with quality factors below Thal’s lower bounds.

In order to overcome Thal’s lower bounds (2) and approach the Chu lower bound (1), an antenna with vanishing internal stored energy is required. For an electrically small, spherical electric surface current density radiating the TM$_{10}$ electric-dipole field, it is easily seen that the internal stored electric energy will increase, not decrease, if the internal volume is filled with a dielectric material. However, for an electrically small, spherical electric surface current density radiating the TE$_{10}$ magnetic-dipole field, the internal stored magnetic energy will decrease, not increase, if the internal volume is filled with a magnetic material; in fact, the internal stored magnetic energy will be inversely proportional to the permeability of the magnetic material. The latter case was pointed out already by Wheeler [13] and confirmed by Thal [8]; specifically, with $\mu_r$, denoting the relative permeability the quality factor becomes

$$Q = \left(1 + \frac{2}{\mu_r}\right) Q_{\text{Chu}}, \quad ka \ll 1. \quad (3)$$

It is noted, that the expression (3) holds only in the limit of vanishing electrical radius since it is necessary to avoid the cavity resonances that may result from filling a finite-sized spherical surface current density with a high-permeability material. Such resonances, with no external field, will of course make the quality factor approach infinity. Though the expression (3) constitutes a highly interesting limit, it is thus not guaranteed to apply to practical antenna designs of finite size. As will be shown in this manuscript, it does not, and for a given electrical size of the spherical current density, the lowest quality factor is not obtained with the highest permeability, because of resonances.

The purpose of this work is to investigate the quality factor $Q$ for electrically small current distributions and practical antenna designs radiating the TE$_{10}$ magnetic dipole field; in particular, to determine how close the $Q$ can approach the Chu lower bound. The current distributions are spherical surface current densities, and the practical antennas are conducting wires wound on a spherical surface — in both cases enclosing a magnetic or magneto-dielectric spherical core to reduce the internal stored magnetic energy. For the current distribution an analytical solution is derived in terms of spherical vector wave functions that leads to closed-form expressions for the internal and external stored energies as well as the radiated power for arbitrary values of the electrical radius of the sphere and the permeability/permittivity of the core. The influence of these parameters on the quality factor $Q$ can thus be investigated, and the optimal permeability for a given electrical radius can then be determined.

As a practical antenna, the TE$_{10}$-mode multiarm spherical helix antenna [17] augmented with a spherical magnetic/magneto-dielectric core is investigated. A numerical solution is obtained using the surface integral equation and higher-order method of moments [18].

Some preliminary results of this work were reported previously at the ISAP 2009 conference [19], [20]. This manuscript concentrates on the optimal permeability and the lowest possible $Q$ for a given antenna electrical radius. Furthermore, the influence of the core permittivity on the quality factor $Q$ is investigated both analytically and numerically.

II. SPHERICAL SURFACE CURRENT DENSITY ENCLOSING A MATERIAL CORE

A. Single TE$_{10}$ Mode

The configuration consists of a time-harmonic, spherical, electric surface current density $J$ of radius $a$ and amplitude $J_0$ enclosing a magneto-dielectric core with relative permeability $\mu_r$ and permittivity $\varepsilon_r$, and wave number $k_0 = \sqrt{\varepsilon_0 \mu_0} k$ (Fig. 1). The core material is assumed to be linear, isotropic, homogeneous, lossless, and dispersion-less. Introducing a spherical $(r\theta\phi)$ coordinate system with its origin at the center of the core, and employing phasor notation with suppressed time factor $\exp(-i\omega t)$, $\omega = kc > 0$ (where $c$ is the speed of light), the surface current density can be expressed as

$$J = a_\phi J_0 \sin \theta \quad (4)$$

where $a_\phi$ is the azimuthal unit vector. This electric surface current density is thus azimuthally directed with a sinusoidal polar variation, and it is proportional to the electric equivalent surface current density of the Huygens-Love field equivalence principle for a $z$-directed magnetic dipole located at the coordinate system origin.

1) Analytical solution: The radiated field is obtained by expressing the internal field for $r < a$ as a spherical vector wave of the standing wave type, the external field for $r > a$ as a spherical vector wave of the outward propagating type, and then enforcing the appropriate boundary conditions at $r = a$ to determine the complex amplitudes $C^-$ and $C^+$ of the internal and external fields, respectively. Since the surface current density is azimuthally constant and has a first-order polar variation, this will also be the case for the radiated fields; thus, only the magnetic-dipole spherical vector wave with azimuthal index $m = 0$ and polar index $n = 1$ will be present; that is the TE$_{10}$ mode. Employing the notation of

$^1$It is assumed that the frequency dispersion of $\mu_r$ and $\varepsilon_r$ is negligible over the relevant bandwidth, and thus, $\mu_r > 0$ and $\varepsilon_r \geq 1$ [21].
Hansen [22], the interior and exterior electric and magnetic fields can be expressed as

\[
E^-(\mathbf{r}) = \frac{k_s}{\sqrt{\eta_s}} C^- F^{(1)}_{101}(\mathbf{r}) \tag{5a}
\]

\[
H^-(\mathbf{r}) = -i k_s \sqrt{\eta_s} C^- F^{(1)}_{201}(\mathbf{r}) \tag{5b}
\]

\[
E^+(\mathbf{r}) = \frac{k}{\sqrt{\eta}} C^+ F^{(3)}_{101}(\mathbf{r}) \tag{5c}
\]

\[
H^+(\mathbf{r}) = -i k \sqrt{\eta} C^+ F^{(3)}_{201}(\mathbf{r}). \tag{5d}
\]

In these expressions \(\eta\) and \(\eta_s\) are the intrinsic admittances of free space and the core, respectively. Furthermore, the \(F\)-functions are the power-normalized spherical vector wave functions

\[
F^{(1)}_{101}(\mathbf{r}) = \frac{\sqrt{6}}{4\pi} \frac{1}{k_s r} \left\{ -\cos k_s r + \frac{\sin k_s r}{k_s r} \right\} \sin \theta \alpha \phi \tag{6a}
\]

\[
F^{(1)}_{201}(\mathbf{r}) = \frac{\sqrt{6}}{2\pi} \frac{1}{(k_s r)^2} \left\{ -\cos k_s r + \frac{\sin k_s r}{k_s r} \right\} \cos \theta \alpha \phi
\]

\[
- \frac{\sqrt{6}}{4\pi} \frac{1}{k r} \left\{ \sin k_s r + \frac{\cos k_s r}{k_s r} - \frac{\sin k_s r}{(k_s r)^2} \right\} \sin \theta \alpha \phi \tag{6b}
\]

\[
F^{(3)}_{101}(\mathbf{r}) = \frac{\sqrt{6}}{4\pi} \frac{1}{k r} \left( 1 + \frac{i}{k r} \right) \sin \theta \alpha \phi \tag{6c}
\]

\[
F^{(3)}_{201}(\mathbf{r}) = \frac{\sqrt{6}}{2\pi} \frac{e^{i k r}}{(k r)^2} \left( 1 + \frac{i}{k r} \right) \cos \theta \alpha \phi
\]

\[
- \frac{\sqrt{6}}{4\pi} \frac{e^{i k r}}{k r} \left\{ -i + \frac{1}{k r} + \frac{i}{(k r)^2} \right\} \sin \theta \alpha \phi \tag{6d}
\]

and the \(C^-\) and \(C^+\) coefficients are given by

\[
C^- = J_0 i a \frac{\sqrt{\eta_s}}{\eta} \frac{4\pi}{\sqrt{6}} \left( 1 + \frac{i}{k a} \right) I \tag{7a}
\]

\[
C^+ = -J_0 i a \frac{e^{-i k a}}{\sqrt{\eta}} \frac{4\pi}{\sqrt{6}} \left( -\cos k_s a + \frac{\sin k_s a}{k_s a} \right) \left. I \right. \tag{7b}
\]

where

\[
I = \left\{ \left( -i + \frac{1}{k a} + \frac{i}{(k a)^2} \right) \left( -\cos k_s a + \frac{\sin k_s a}{k_s a} \right) + \frac{\eta_s a}{\eta} \left( 1 + \frac{i}{k a} \right) \left( \sin k_s a + \frac{\cos k_s a}{k_s a} - \frac{\sin k_s a}{(k_s a)^2} \right) \right\}^{-1}. \tag{8}
\]

The stored energies and the radiated power are determined through direct spatial integration of the radiated fields. In the calculation of the external stored energy the contribution of the propagating field is subtracted from that of the total field to obtain the energy density of the non-propagating field only [4], [6]. With \(W^-\), \(W^+\), \(W_-\), and \(W_+\) denoting the internal electric, internal magnetic, external electric, and external magnetic stored energy, respectively, it is found that

\[
W^- = \frac{1}{4\omega} |C^-|^2 \left\{ \frac{\sin^2 k_s a}{k_s a} + \frac{k_s a}{2} + \frac{\sin 2k_s a}{4} \right\} \tag{9a}
\]

\[
W^+ = \frac{1}{4\omega} |C^+|^2 \left\{ \frac{\sin^2 k_s a}{k_s a} + \frac{\sin 2k_s a}{(k_s a)^2} \cos^2 k_s a - \frac{k_s a}{4} \right\} \tag{9b}
\]

\[
W^+_e = \frac{1}{4\omega} |C^+|^2 \left\{ \frac{1}{(k a)^3} + \frac{1}{k a} \right\}. \tag{9c}
\]

\[
W^+_h = \frac{1}{4\omega} |C^+|^2 \left\{ \frac{1}{(k a)^3} + \frac{1}{k a} \right\}. \tag{9d}
\]

Finally, the radiated power is

\[
P_{\text{rad}} = \frac{1}{2} |C^+|^2. \tag{10}
\]

It is noted that these expressions hold for arbitrary electrical radius \(k a\) of the sphere, and thus allow us to investigate the relationships between \(k a\), relative permeability \(\mu_r\) and permittivity \(\varepsilon_r\), and the quality factor \(Q\) in the case of finite-sized spheres.

2) Stored energy: First, we consider a pure magnetic core, that is, \(\varepsilon_r = 1\). Figure 2a shows the ratio of the total stored electric energy \(W^- = W^+ + W^-\) to the total stored magnetic energy \(W^+ = W^+ + W^-\) vs. free-space electrical radius \(k a\) in the range from 0 to 1 for four values of the relative permeability \(\mu_r = 1, 2, 8, \text{and } 100\). For vanishing electrical radius the magnetic energy clearly dominates the electrical energy and the current distribution is thus not resonant. As the electrical radius increases, the electrical energy becomes relatively larger and eventually equals the magnetic energy at the resonances.

The complimentary dependence of the ratio \(W^-/W^+\) vs. the relative permeability \(\mu_r\) for three different values of \(k a = 0.1, 0.25, \text{and } 0.5\) is presented in Fig. 3a. The total dominance of the magnetic energy for \(k a = 0.1\) is observed in the entire shown range of \(\mu_r\), whereas for \(k a = 0.25\) and 0.5 the magnetic energy dominates only away from the resonances.

Figure 2b shows the ratio of the internal stored energy \(W^- = W^+ + W^-\) to the total stored energy \(W_{\text{total}} = W^- + W^+ + W^- + W^-\) vs. free-space electrical radius \(k a\). In the free-space case, \(\mu_r = 1\), the internal energy is seen to constitute 2/3 of the total energy — and thus it is equal to twice the external energy — for vanishing electrical radius. As the relative permeability \(\mu_r\) increases to 2, 8, and 100, the energy ratio decreases to 0.5, 0.2, and 0.02, respectively. However, for non-zero electrical radius the dependence of the energy ratio on permeability \(\mu_r\) is different, and for the internal cavity resonances the total stored energy is actually entirely internal. It is thus seen that the smallest energy ratio is not obtained with the largest permeability for finite values of \(k a\).

The latter observation is also clearly illustrated in Fig. 3b, where the ratio \(W^-/W_{\text{total}}\) is plotted (note the logarithmic scale) vs. the relative permeability \(\mu_r\) in the range from 1 to 500 for three different values of \(k a = 0.1, 0.25, \text{and } 0.5\). The ratio only decreases monotonically for the very small electrical radius \(k a = 0.1\), whereas for larger electrical radii...
3) **Quality factor:** The radiation quality factor $Q$ is defined as $2\pi$ times the ratio of the stored electric and magnetic energy.
Fig. 4. (a) Values of $\mu_\text{r}$ for which the relative error between the exact $Q$ and expression (3) becomes larger than 1%, as a function of $ka$ with $\varepsilon_\text{r}$ as a parameter.

(by the radiated power per period. However, in order to establish a resonant system (equal electric and magnetic stored energy) the stored energy is set to twice the maximum of the electric and magnetic energies. It is understood that the lesser of the two has been increased to equal the larger by use of, e.g., a lumped-component tuning circuit. For the TE$_{10}$ magnetic-dipole antenna, the magnetic energy dominates for small electrical radii but the electric energy may dominate at larger radii. Thus, the quality factor $Q$ is determined from (9) and (10) as

$$Q = 2\omega \frac{\max(W_H^+ + W_H^- + W_E^-)}{P_{\text{rad}}}.$$ (11)

Figure 2c shows the quality factor $Q$, normalized by the Chu lower bound $Q_{\text{Chu}}$, vs. free-space electrical radius $ka$ of the magnetic sphere for different relative permeabilities $\mu_\text{r}$. For $\mu_\text{r} = 1$ (non-magnetic core) the normalized $Q$ is equal to 3 for vanishing $ka$ and it remains fairly constant for $ka < 1$ (this agrees with Thal [8, Table I]). For $\mu_\text{r} = 2$, 8, and 100 the normalized $Q$ equals 2, 1.25, and 1.02, respectively, for small $ka$ in agreement with (3). This is also demonstrated in Fig. 3c, where the ratio $Q/Q_{\text{Chu}}$ is plotted as a function of $\mu_\text{r}$ for different values of the free-space electrical radius $ka$. In the shown range of the relative permeability, the curve for the smallest sphere with $ka = 0.1$ very closely follows the expression (3).

For larger values of $ka$ the resonance behavior of the fields in the core manifests itself in the fact that the curves start diverging from (3). In the following this divergence is investigated for a general magneto-dielectric core, that is, the relative permittivity $\varepsilon_\text{r}$ is allowed to be greater than 1. Figure 4 shows the values of permeability $\mu_\text{r}$, for which the relative error between the exact $Q$ (11) and (3) becomes larger than 1%, as a function of $ka$ with the permittivity $\varepsilon_\text{r}$ as a parameter. A general observation is that the smaller $ka$ and the lower $\varepsilon_\text{r}$ the larger is the range of $\mu_\text{r}$ in which the expression (3) holds.

From Fig. 2c and 3c we can also conclude that the Chu lower bound can be approached with modest values of $\mu_\text{r}$; e.g., within 25% for $\mu_\text{r} = 8$ and $ka < 0.5$. Furthermore, the smallest $Q$ is not necessarily obtained with the largest $\mu_\text{r}$. For a given $ka$ and permittivity $\varepsilon_\text{r}$ there is an optimum permeability $\mu_\text{r}^{\text{opt}}$ for which the ratio $Q/Q_{\text{Chu}}$ is minimal. These values $\mu_\text{r}^{\text{opt}}$ have been determined numerically and are plotted in Fig. 5a as a function of $ka$ with the core permittivity $\varepsilon_\text{r}$ as a parameter. The curves in Fig. 5a very accurately follow the expression

$$\mu_\text{r}^{\text{opt}} = \frac{1}{\varepsilon_\text{r}} \frac{(2.816)^2}{(ka)^2}$$ (12a)

or

$$\sqrt{\varepsilon_\text{r} \mu_\text{r}^{\text{opt}} ka} = k_\text{s} a = 2.816.$$ (12b)

The minimum achievable ratios $Q/Q_{\text{Chu}}$ corresponding to $\mu_\text{r}^{\text{opt}}$ (12a) are plotted in Fig. 5b, from which it is seen that in order to reach the Chu lower bound a magnetic dipole antenna should have a vanishing electrical size $ka$. For finite values of $ka$, the curve corresponding to $\varepsilon_\text{r} = 1$ shows the lower bound for a magnetic dipole antenna with a magneto-dielectric core.
B. Higher-Order Modes

In the investigation of Section II-A above, it is assumed that there is only a single TE$_{10}$ mode excited in the system. The situation changes in the presence of higher-order spherical modes that might be excited in a practical antenna when the current distribution deviates from (4). If these modes are not suppressed, they increase the stored energy inside the magnetic core and, in the worst case of a resonance, make the $Q$ diverge. In particular, the TM modes with the polar index $n = 1$ are problematic, since in a magnetic sphere they generate the lowest frequency resonance. Whereas the first TE$_{10}$-mode resonance occurs at $k_s a = 4.493$, the first resonance for the TM$_{1m}$ modes is at $k_s a = 2.744$. Consequently, the presence of any of the TM$_{1m}$ modes makes the optimum $k_s^opt a = 2.816$ found in Section II-A a poor choice. Furthermore, the range of usable core permeabilities $\mu_r$ is now limited by the TM$_{1m}$-mode resonance, i.e., it is reduced to almost half of the range for the single TE$_{10}$-mode case. The optimum core permeability $\mu_r^{opt}$ and the minimum achievable $Q$ for a given $ka$ depend in each particular case on the power ratios between TM$_{1m}$ and TE$_{10}$ modes as well as on the presence of other spherical modes.

III. Multiarm Spherical Helix (MSH) Antenna

In this section we extend the theory presented in the previous Section II by numerical results obtained for a practical TE$_{10}$-mode antenna configuration with a magneto-dielectric core. We employ the magnetic dipole MSH antenna first reported in [17]. This antenna consists of multiple wire arms twisted into two symmetric hemispherical helices and excited by a curved dipole placed at the equator of the antenna (Fig. 6). As shown in [17], where an air-core version of the MSH antenna is thoroughly investigated, the resonance frequency of this self-resonant electrically small antenna is determined by the length of the wire arms, whereas the input resistance at the resonance is nearly independently controlled by the length of the excitation dipole. By placing a material core inside the antenna we change its resonance frequency and thus the electrical size. To avoid this change we adjust the length of the arms for each value of permeability/permittivity so that the resonance frequency is kept constant at $f_0 = 300$ MHz.

For our investigation we have chosen a 4-arm antenna configuration with the wire radius of $r_w = 0.5$ mm. The length of the excitation dipole is quantified in angular units; the half-length is $\alpha = 143^\circ$. The antenna is assumed to be lossless and fed by a delta-gap voltage generator in the middle of the excitation dipole. To ensure a well-behaved numerical solution the radius of the core $a$ is always set 1 mm less than the helix radius $r_0$.

The $Q$ is calculated from the antenna input impedance $Z(\omega)$ using the expression from [7]

$$Q \approx \frac{\omega_0}{2R_0}|Z'(\omega_0)| = \frac{\omega_0}{2R_0} \sqrt{R'(\omega_0)^2 + X'(\omega_0)^2}$$

where $R(\omega)$ and $X(\omega)$ are the input resistance and reactance, respectively, and $R_0 = R(\omega_0)$ with $\omega_0$ being the resonance frequency.

A. Magnetic Core

First, we consider two antenna configurations of radii $r_0 = 40$ mm (electrical radius $k(r_0 + r_w) = 0.254$) and $r_0 = 30$ mm ($k(r_0 + r_w) = 0.192$), respectively, with a pure magnetic core ($\varepsilon_r = 1$). The radii of the core are $a = 39$ mm and $a = 29$ mm for the first and second configuration, respectively. The quality factor $Q$ normalized to the Chu lower bound $Q_{Chu}$ is plotted in Fig. 7a as a function of the core permeability $\mu_r$. It is observed that the ratio $Q/Q_{Chu}$ steeply decreases from its initial free-space value — $Q/Q_{Chu} = 3.40$ for $r_0 = 40$ mm and $Q/Q_{Chu} = 3.32$ for $r_0 = 30$ mm — to a level below 1.5 as the permeability reaches only $\mu_r = 10$. The rapid drop of the stored magnetic energy inside the core requires a corresponding decline of the TM$_{20}$ mode (Fig. 8a), since this mode acts as a distributed reactive matching circuit providing the stored electric energy needed to make the antenna self-resonant. The strength of the TM$_{20}$ mode is proportional to the number of turns, and the latter reduces as well (Fig. 7b). The input resistance $R_0$ also initially reduces to about 50-60 ohms and then remains relatively stable until the first resonance is reached (Fig. 7c). This resonance occurs at roughly $\mu_r \approx 130$ for $r_0 = 40$ mm and at $\mu_r \approx 240$ for $r_0 = 30$ mm, which in both cases correspond to $k_s a \approx 2.8$, i.e., to the first TM$_{11}$-mode internal resonance in a magnetic spherical core ($k_s a = 2.744$). Thus, the TM$_{11}$ mode present in the antenna radiation spectrum (Fig. 8b) gives rise to a spike in the $Q/Q_{Chu}$ curve.

Having passed the first resonance, the $Q$ for the configuration with $r_0 = 40$ mm monotonically grows with $\mu_r$ and reaches the TE$_{10}$-mode internal core resonance at $\mu_r \approx 330$, or $k_s a \approx 4.5$. The minimum value of the $Q$ is found below the TM$_{11}$ resonance at $\mu_r \approx 45$ for $r_0 = 40$ mm and at $\mu_r \approx 60$ for $r_0 = 30$ mm. The corresponding ratios $Q/Q_{Chu}$ are 1.28 and 1.24. This result is consistent with the observations in Section II, i.e., the lowest achievable ratio $Q/Q_{Chu}$ decreases with the antenna electrical size.

B. Magneto-Dielectric Core

For the core permittivity larger than unity ($\varepsilon_r > 1$), the core resonances, which are functions of $k_s a = \sqrt{\varepsilon_r \mu_r} ka$, shift
Fig. 7. Numerical results for the TE\textsubscript{10}-mode MSH antenna with a magnetic core (\(\varepsilon_r = 1\)). (a) Quality factor (normalized by Chu lower bound); (b) Number of turns; (c) Input resistance \(R_0\).

consistently with the theoretical prediction illustrated in Fig. 5.

The higher \(\varepsilon_r\) the more electric energy is stored in the core, and, as a consequence, less number of turns is required to make the antenna self-resonant (Fig. 9b). The input resistance \(R_0\) also decreases (Fig. 9c), which, if necessary, can be easily compensated by truncating the excitation dipole [17].

**IV. Conclusion**

An analytical solution has been derived for the TE\textsubscript{10}-mode magnetic dipole field radiated by a spherical, electric surface current density enclosing a magneto-dielectric core. Through direct spatial integration of the radiated fields, this solution led to closed-form expressions for the internal and external electric and magnetic stored energies, as well as the radiated power, and thus the radiation quality factor \(Q\) for arbitrary values of the electrical radius. It is shown that the internal stored energy reduces with increasing permeability \(\mu_r\) of the core and, for vanishing free-space electrical radius, \(k_0a \ll 1\), the radiation quality factor \(Q\) approaches the Chu lower bound.
$Q_{\text{opt}}$ arbitrarily closely as $\mu_r \to \infty$, in agreement with the prediction of Wheeler [13]. For finite-sized spheres the internal resonances of the magneto-dielectric core limit the minimum value of the quality factor $Q$. However, it was seen that the Chu lower bound can be approached with even modest values of the permeability $\mu_r$, e.g., within 25% for $\mu_r = 8$ and $ka < 0.5$. On basis of the analytical solution, for a given antenna size and permittivity $\varepsilon_r$ the minimum value of the quality factor $Q$ was determined numerically and it was found to occur for the relative permeability $\mu_r^{\text{opt}}$ that satisfies the relation (12a). By substituting $\mu_r^{\text{opt}}$ corresponding to $\varepsilon_r = 1$ into (7)-(11) the lower bound for a magnetic dipole antenna with a magneto-dielectric core is established.

The analytical results are consistent with numerical simulations conducted for the TE$_{10}$-mode multiarm spherical helix antenna with a magneto-dielectric core. The radiation quality factor $Q = 1.24Q_{\text{Chu}}$ is obtained for the antenna with free-space electrical radius $ka = 0.192$.

Generally, the smaller the antenna the closer its radiation $Q$ can approach the Chu lower bound. In addition, a magnetic core with $\varepsilon_r = 1$ and the absence of the parasitic TM$_{1m}$ modes are prerequisites for the lowest possible $Q$ of a magnetic dipole antenna.

REFERENCES

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