Miniaturized Tunable Meanderline Loaded Antenna with *Q*-factor approaching the Lower Bound

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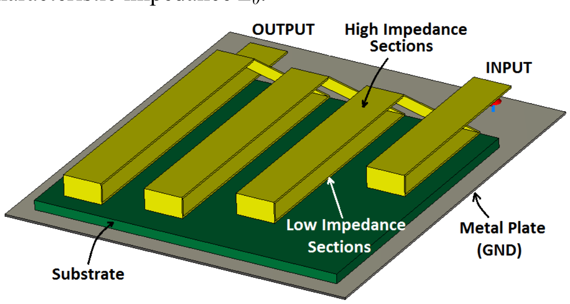
Abstract

Realizing a high-efficiency tunable antenna to cover a wide band with a good matching is an interesting topic, especially in the case when the physical size of the antenna has to be very small. A novel spherical monopole antenna which has been miniaturized through a couple of Meanderline sections is presented in this paper. This antenna, with maximum dimension of 0.05λ, has dual band operation with independent frequency-tuning capability in the 30 – 88 MHz frequency band. Thanks to the antenna geometry and the Meanderline miniaturization technique, the exact *Q*-factor of the antenna approaches the Thal lower bound.

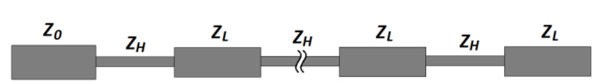
1. Introduction

Meanderline antennas are not a new topic in small antenna design. But Meanderline loaded antennas, MLAs, as presented in this paper, do represent a new type of topology. MLA structures usually have some parts with a Meanderline topology which usually have no radiating effect and play a connection role between the radiating parts. These antennas are usually made of a number of vertical and horizontal radiators where each one is separated electrically from its counterpart by an air gap in a way that no direct electrical connections exist between vertical and horizontal elements [1]. The Meanderlines which connect vertical and horizontal elements work as a tuning circuit to compensate the electric length of the antenna towards the desired operating frequency. A simple Meanderline is composed of different transmission lines with various characteristic impedances.

In an MLA, by switching between different lengths inside the circuit, a phase delay in the MLA transmission line can be achieved. In this way a frequency-tunable wideband antenna can be reached [2]. The implementation of delay lines for time delay and phase tuning purposes is a known method in tunable antennas. A meanderline is one common block to realize such delays, in which helical patterns for transmission lines with expansion in both latitude and longitude are used. A Meanderline is composed of a conductive plate and a number of parallel TLs placed above it. In such structure, there are two types of TL. The first type is closer to the metal plate, which gives a small characteristic impedance. The second type of TL is parallel to the first one, but further from the metal plate, i.e. at a higher position with respect to this plate. Therefore it has a higher characteristic impedance. These two types of TL are connected to each other by short vertical conductors. Fig. 1(a) shows a slow-wave Meanderline. In this figure, the low and high impedance sections can be seen. Zigzag conductors connect the consecutive sections, in this way forming a zigzag continuous tape from the Meanderline input to its output. Fig. 1(b) shows the equivalent circuit of Fig. 1(a). This periodic change in low and high impedance creates a slow-wave TL. It takes much longer for a wave to propagate through such structure in comparison to a normal microstrip line with the same length. Equation (1) shows the relation between the characteristic impedances of the lines and the wave propagation parameter, β. This equation is valid only if the ratio of the characteristic impedances of upper and lower line is greater than five [2]. The higher this ratio is, the bigger the Meanderline propagation number and the slower the line. This is valid for TLs, much smaller than a quarter wavelength, having the same length. Similar results are valid for logarithmically scaled lines. In (1) , Z_0 and β are the Meanderline characteristic impedance and wave propagation number, respectively. Z_L and Z_H are the characteristic impedances of the TL pieces forming the Meanderline and β_0 is the wave propagation number of a line with a characteristic impedance Z_0.



(a) Perspective presentation of a slow-wave Meanderline



(b) Equivalent circuit of a slow-wave Meanderline

$$Z_0 = \sqrt{Z_H Z_L} \quad , \quad \beta = \beta_0 \sqrt{\frac{Z_L}{Z_H}} \quad , \quad \beta_0 = 2\pi / \lambda_0 \qquad (1)$$

Fig. 1. A slow-wave Meanderline section with equivalent circuit.

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2. The Fundamental Limit on the Antenna Miniaturization

Fundamentally, it is well understood that as an antenna becomes small ($ka < 0.5$, where k is the free space wave number and a is the radius of the smallest sphere enclosing the antenna), the ability of the antenna to radiate effectively is substantially reduced [3]. This fundamental limitation is most commonly described in terms of the quality factor, Q, of the antenna. In the absence of material or conductor loss, the Q of an antenna element is proportional to the ratio of the energy stored in the antenna to the rate at which the antenna emits radiation. Because the operating bandwidth of a single resonance antenna varies inversely with Q [7], it is desirable to achieve as low a Q as possible when designing a small antenna for a specific application. Small antenna elements are typically characterized by large values of Q [4], [5]. There exists a fundamental relationship between antenna size and Q, referred to here as the Thal limit [6]:

$$Q_{LB} = Q_{Thal}^{Sphere} = \frac{1.5}{(ka)^3} + \frac{0.707}{ka} \tag{2}$$

which approximates the minimum Q achievable for an antenna of size ka enclosed by a sphere with radius a. Of all problems typically encountered when designing small antennas (narrow bandwidth, impedance matching to low radiation resistance, low efficiency), the ability to design antennas whose performance approaches the Chu limit is the most challenging to solve. Indeed, in order to determine the ranking of a small antenna, it is necessary to evaluate the distance of the exact Q factor of the designed antenna from its permitted structure lower bound. For a spherical structure this is the Thal limit. This distance, which is a design penalty, can be considered as a Figure of Merit for the antenna miniaturization achieved:

$$FoM = P_{Design} = Q_{Ant} / Q_{St,lb} \tag{3}$$

The closer this figure is to the unit, the more the antenna is miniaturized. With this definition, we can de-embed the constraint coming from the circumscribing shape.

In addition the exact Q-factor of any antenna can be extracted from the input impedance of the antenna with [7]:

$$Q \approx \frac{1}{\eta} Q_z = \frac{1}{\eta}\left(\frac{\omega_0}{2R_0(\omega_0)} \left| Z'_{in}(\omega_0) \right| \right) \tag{4}$$

With this equation and considering (2) and (3), the FoM of an arbitrary antenna versus the frequency can be computed.

3. Antenna Miniaturization through Meanderline Loading

The goal is to design an electrically small antenna in the VHF frequency band (30-88 MHz) with dual band frequency-tunable response and a dimension smaller than $ka<0.4$. Considering these requirements, the electric monopole antenna with spherical top-loading is a suitable candidate. As shown in Fig. 2, this antenna has a vertical radiator loaded by two spherical electrically conductive skins. The parameters of the proposed antenna have been optimized to self-resonate at 60 MHz (the middle of the frequency bandwidth). In order to force the antenna to have a double resonance, two sets of Meanderlines are needed, providing us with two resonance lengths. Indeed by cutting the spherical skin top and reaching a structure similar to the one in Fig. 2, two planar spaces will provide us with the area needed for the Meanderline sections.

3.1. Spherical Monopole Antenna

Considering the fabrication requirements, a few modifications are applied to the proposed structure, producing the antenna shown in Fig. 3. The first modification is the cutting of the spherical skin. This simplifies the construction of the truncated skin: planar sheets are cut and shaped. Another minor change is the use of cylindrical type skin at the ends instead of spherical type skin. This change improves stability and eases installation of the antenna. The simulated impedance of the resulting structure shows a real part around 7.5 Ohm at resonance. To increase this real part, an integrated matching network has been implemented within antenna structure, consisting of stubs in the antenna feeding section. Fig. 3 shows these two parallel electrically short circuiting stubs (to the ground plate). The location of such stub determines the impedance. Simulation show that the best point is located 28 cm away from the centre.

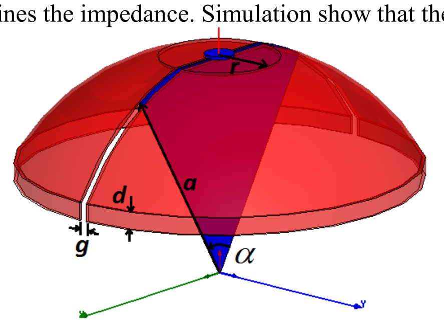


Fig. 2. Spherical monopole antenna with a slotted skin, (a=50 cm, α=50˚, β=45˚, d=5 cm g=1cm and r=18 cm)

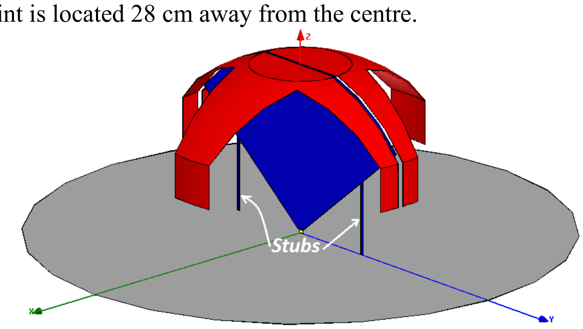
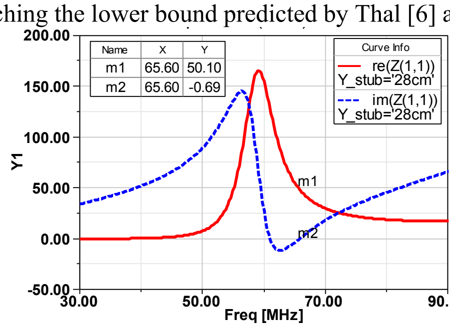
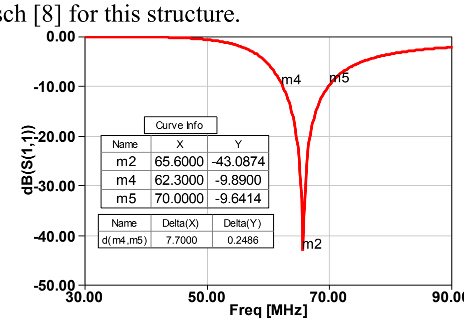


Fig. 3. Spherical monopole antenna with shaped skin

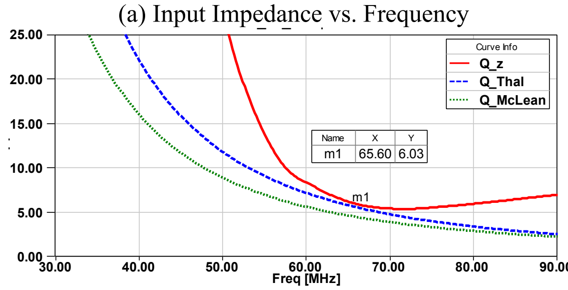
Simulation results for this antenna are shown in Fig. 4. As seen, the input impedance at the resonance frequency (65.5 MHz) is close to 50 ohms with a return loss better than 40 dB and $Q_z=6.03$. This value of Q_z, predicts a bandwidth (VSWR<2:1) of $B_V=0.707/Q_z=\%11.73$ [7] which is identical to what results from the S11 plot in Fig. 4(b): $BW=7.7\ MHz\ /\ 65.6\ MHz=\%11.72$. The most important parameter is the *FoM* which is around 1.07 (see Fig. 4(d)). It is approaching the lower bound predicted by Thal [6] and Vandenbosch [8] for this structure.



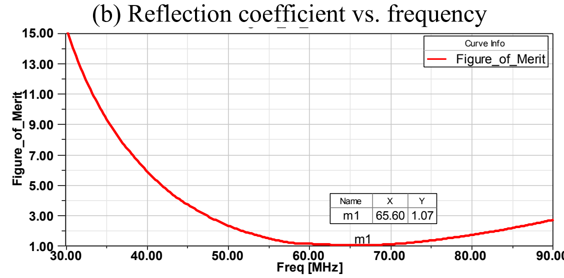
(a) Input Impedance vs. Frequency



(b) Reflection coefficient vs. frequency



(c) Q_z and bounds for spherical structures vs. frequency



(d) FoM vs. frequency

Fig. 4. Simulation results for a two-branched spherical monopole with matching stubs.

3.2. Meanderline Loading

Two similar sets of Meanderlines, as shown in Fig. 1(a), are used to load this antenna,. In each set, five lines with various lengths are implemented. Details of the connection between the Meanderline and the two-branched spherical dipole antenna are shown in Fig. 5. Each Meanderline input has been attached to the vertical radiator by a small pin. At the Meanderline output; the connection to the spherical skin is realized through a small vertical pin.

In order to have a frequency-tunable antenna, it is necessary to tune the length of the lines in each Meanderline set. A good technique to change electrical lengths is to use electronic switches, such as FET or PIN Diodes, between the low and the high impedance section in each Meanderline. Obviously, in high power applications, mechanical switches are advised. These switched are located in the Meanderline sets in order to connect low impedance lines to shortened (electrically) high impedance ones when in active (ON) state. By doing so, the part of the Meanderline which is between switch and end point is ousted and the effective length of the line is reduced. In this design the length of the lines in the Meanderline sections are 165, 160, 150, 135 and 100 mm. These lines with width of $W_L=15\ mm$ are implemented on a substrate with thickness 1.6 mm and relative permittivity 2.2. The air gap between the high and the low impedance section is 8 mm. Simulation results show that with this embodiment, 24 switches in the whole structure are required. These switches are controlled through a micro-controller circuit equipped with a DC bias network and power supply. This excessive board can be easily placed inside the antenna covered by the spherical skin.

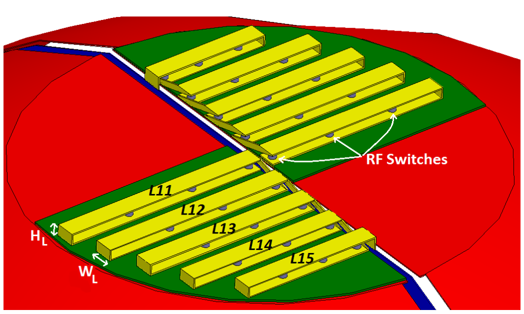


Fig. 5. Meanderline sets loading in a spherical monopole antenna with switch placement

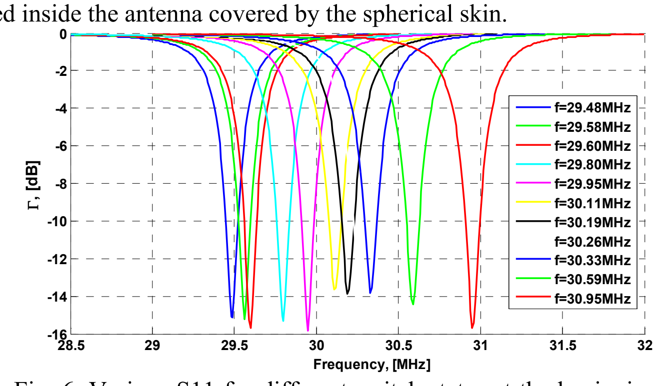
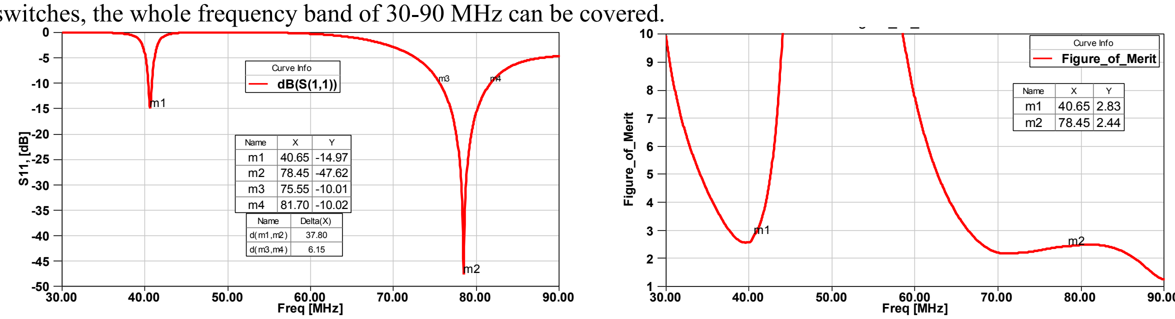


Fig. 6. Various S11 for different switch states at the beginning of the frequency band for a spherical MLA.

Now, the antenna structure is complete. By tuning the Meanderlines we can tune the single frequency response in the 30-88 MHz frequency bandwidth. For example, if all switches are in OFF state, the antenna will resonate at 29.5 MHz (0.5 MHz above the required frequency to compensate possible shifts). Fig. 6 shows various S11 curves for different switch states at the beginning of the frequency band for the proposed antenna.

With all switches in ON state, the antenna is tuned at 57.5 MHz, a little shift from 65.5 due to the small size of the MLA in ON state. The remaining frequency band, from 58 MHz up to 88 MHz, can be covered by the second resonance (anti-resonance) of the antenna. For instance, a state at which two longer lines of each Meanderline set has been ousted through shortening to the ground of the MLAs, with the rest lines producing delays is simulated. Two resonance frequencies occur at 40.65 and 78.45 MHz, as shown in Fig. 7. Similar to the first band, by changing the line length; these frequencies will be tunable too. The important point here is the wide bandwidth of 6.2 MHz (with a rather acceptable *FoM* of 2.5) which will be covered by long steps and therefore few frequency channels. By using 24 RF switches, the whole frequency band of 30-90 MHz can be covered.

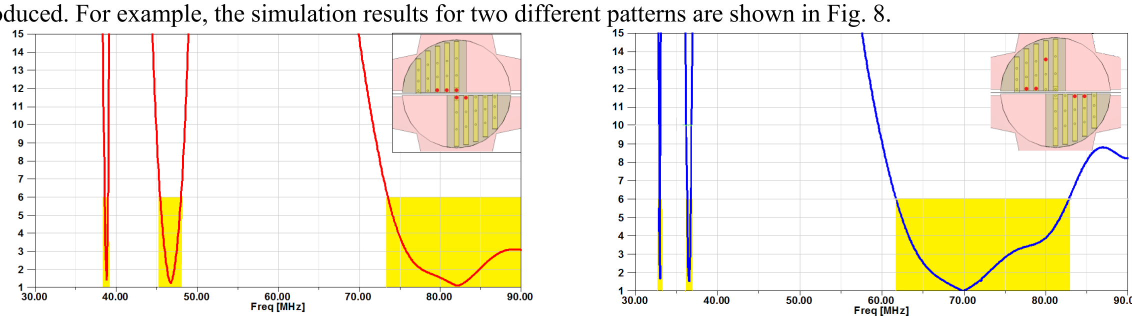


(a) S11 versus frequency (b) *FoM* versus frequency

Fig. 7. Occurrence secondary resonance frequency

3.3. Dual-Band Operation

By choosing different switching patterns for each Meanderline, two resonance frequencies close together can be produced. For example, the simulation results for two different patterns are shown in Fig. 8.



(a) (b)

Fig. 8. Simulated VSWR versus frequency for dual-band spherical antenna for two different switching patterns.

4. Conclusion

A novel spherical Meanderline loaded antenna has been presented. This antenna uses two Meanderline sections to miniaturize the antenna dimension to 0.05λ. The antenna shows a small Q-factor approaching the Thal lower bound. The proposed antenna has dual band operation with independent frequency-tunable capability in the 30 – 88 MHz frequency band. The antenna is under fabrication and the measurement results will be presented at the conference.

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