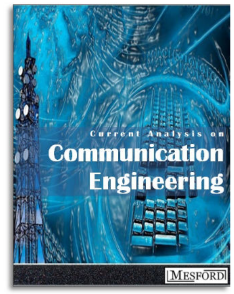

Gain Enhancement of a Wideband Monopole using Stacked Frequency Selective Surfaces

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Abstract:

This paper presents a previously reported wideband monopole design that maintains -10 dB return loss over a 9.4:1 bandwidth with a realized gain of 3.0 dB to 4.0 dB. A utilization of three layers of stacked frequency selective surfaces increases the realized gain to 4.0 to 10.0 dB over a 7:1 bandwidth. Now the realized gain of the monopole limits the bandwidth as opposed to the impedance match. The resulting antenna comes in a form factor of 8.1" x 8.1" x 3.1", and maintains a 60 degree beam width across the full 7:1 bandwidth.

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wideband, monopole, co-planar waveguide, resonant reflectors, gain enhancement, reduced profile

1. INTRODUCTION

THIS PAPER investigates a small and lightweight design of a monopole antenna that utilizes a co-planar waveguide (CPW) feed previously presented by Yu and Wang in reference [1]. CPW feeds are used for wideband impedance matching, and are capable of continuously transitioning from a 50Ω impedance to an arbitrary impedance via tapering [2,3]. Furthermore, there are different variations on the wideband monopole found in the literature where ground plane curvature provides additional bandwidth enhancement [1,4].

A typical monopole has a realized gain of 2.0 dB to 5.0 dB [5]. To increase the gain, placing a metallic surface one-quarter free-space wavelength (λo) below the antenna provides in-phase gain enhancement of about an additional 3 dB. However, this only provides periodic narrowband enhancement. Other attempts at wideband gain enhancement for monopole antennas will degrade as the radiation pattern suffers from beam tilt off broadside beyond the first octave of bandwidth. The more wideband the monopole is, the worse this beam tilt phenomenon becomes [6]. This paper proposes combining both a wideband CPW feed and a series of stacked resonant reflectors, otherwise known as frequency selective surfaces (FSS), to provide stable gain enhancement without degrading the wideband impedance match of the monopole. These resonant reflectors also help act to negate some of the beam tilt issues commonly seen with other wideband monopole antennas by acting similarly to a reflect array.

The monopole presented in this paper approximates that first proposed by Yu and Wang. The aperture utilizes CPW with an arced ground plane along with an arced monopole geometry to provide a smooth transition providing a wideband 9.4:1 bandwidth [1]. This paper scales the design to 0.5 GHz, aiming for an initial bandwidth of 0.5 GHz to 3.5 GHz in the first design phase. The form factor of the final design is 8.1" x 8.1" x 3.1" including three stacked FSS layers. The monopole utilizes a substrate of FR4 that makes the antenna both lightweight and low cost. The final form of the antenna shows a -10 dB return loss from 0.55 GHz to 3.5 GHz and a realized gain of 4.0 dB to 10.0 dB from 0.5 GHz to 3.5 GHz.

2. BASELINE PERFORMANCE OF THE MONOPOLE ANTENNA

This paper describes a wideband monopole design based on that proposed by Yu and Wang [1]. Fig. (**1**) shows the geometry of the antenna printed on an FR4 substrate with thickness of 1.6 mm and εr=4.4. Further dimensions in millimeters are given as L1=186.7, L2=201.1, L3=70.4, L4=107.2, L5=72.4, L6=36.2, g1=2.0, g2=4.0, w=24.1, r1=13.4 and r2=100.5. These dimensions scale so the impedance bandwidth covers 0.5 GHz to 5.2 GHz as shown in Fig. (**2**). The design in Fig. (**1**) removes two 90-degree fan angles of radius r1 from the upper corners of the monopole, and shapes the bottom of the monopole into an arc with radius r2. This provides a smooth transition from one resonant mode to another, to further increase bandwidth [1]. The tapered CPW matches the feed

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line to 50Ω eliminating the need for an additional matching network.

A reflective surface below the antenna increases the gain to broadside by reflecting the radiation below the antenna to add constructively with the radiated waves at the antenna aperture. This paper aims to increase the realized gain of the monopole in Fig. (**1**) by utilizing in-phase FSS reflectors tuned to resonate across specific frequency bands of the monopole where a quarter-wave reflector results in narrowband gain degradation.

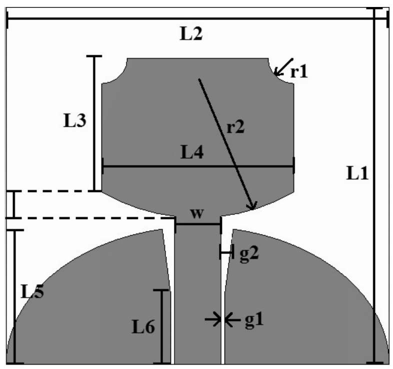

Fig. (1). Geometry of the CPW fed monopole.

A. Monopole with Quarter-wave Metallic Reflector

Typically, for antennas that radiate in both normal directions, a metallic reflector will reflect the downward radiation back to broadside, thereby increasing the radiated power. However, in order to get in-phase reflection, there needs to be an λo/4 separation between the antenna and the reflector [7]. Since the electrical separation is dependent on frequency, this approach on its own provides a periodic narrowband solution for gain enhancement.

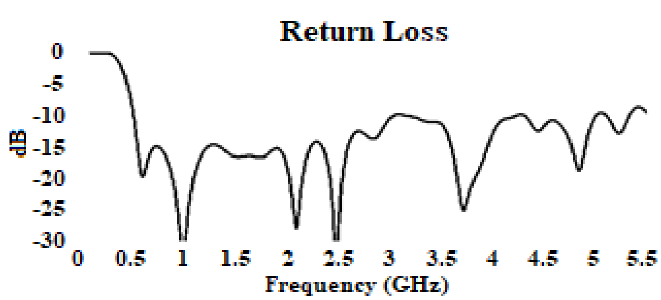

Fig. (2). Simulated return loss versus frequency of the monopole geometry in Fig. 1.

Fig. (**3**) clearly shows the periodic narrowband characteristics of this approach. At odd multiples of λo/4, there is a realized gain between 8.0 dB to 10.0 dB. At multiples of λo/2, there is out-of-phase addition of the reflected wave and the radiated wave, which cancels radiation to broadside. Ideally, a wideband design would maintain the improved performance and negate the out-of-phase cancellation shown in Fig. (**3**). Shadrokh, *et al.* shows preliminary results that stacking multiple FSS layers may provide in-phase reflection at spacing less than λo/4 [8]. The following sections investigate the effectiveness of this approach as well as whether a FSS can be tuned to enhance gain over specific frequency bands thereby cancelling the negative effects of out-of-phase addition of the reflected wave to the radiated wave.

3. DESIGN OF STACKED RESONANT REFLECTORS

The previous section shows that utilizing a metallic reflector will not yield a wideband monopole with stable realized gain to broadside. In reference [8], an approach utilizing multiple FSS layers to improve realized gain over a wide bandwidth yields promising results. In this case, a periodic pattern of unit cells comprised of a metallic pattern etched onto a dielectric substrate defines a FSS. The dimensions of the periodic metallic structures and gaps between said structures gives the FSS a unique resonant response [9].

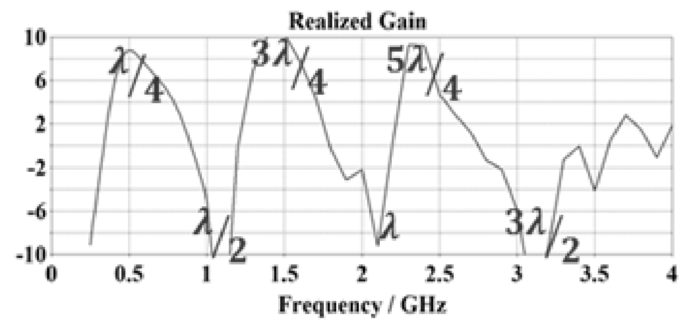

Fig. (3). Realized gain (dB) versus frequency of the CPW fed monopole accompanied by a metallic reflector λo/4 away at 500 MHz.

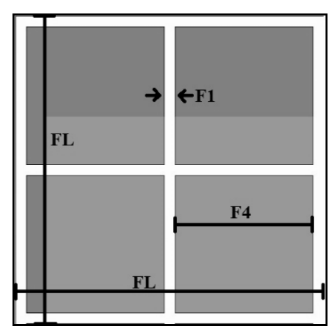

Fig. (4). Geometry of the resonant unit cell tuned to any frequency by scaling dimensions by wavelength.

Fig. (**4**) shows the geometry for the FSS unit cell while table **1** lists the dimensions relative to λfr. Where λfr represents the wavelength at desired resonance frequency of the FSS. Fig. (**3**) identifies frequencies of 750 MHz and 1750 MHz based on two of the realized gain dropouts shown at λo/2 and λo. The dimensions of the FSS unit cell given in Table **1** are based on those given by Shadrokh, *et. al* [8]. The dielectric used for the FSS layer is an FR4 substrate with thickness of 1.6 mm and εr=4.4. However, a FSS requires the periodic repetition of unit cells over the entire reflective surface.

A. Tuned FSS Layers

Fig. (**5**) shows the geometry of the wideband monopole suspended above two resonant reflectors. The spacing between the antenna and the two resonant reflector layers was determined through optimization in CST Microwave Studio 2019. Table **1** gives the dimensions for Fig. (**5**).

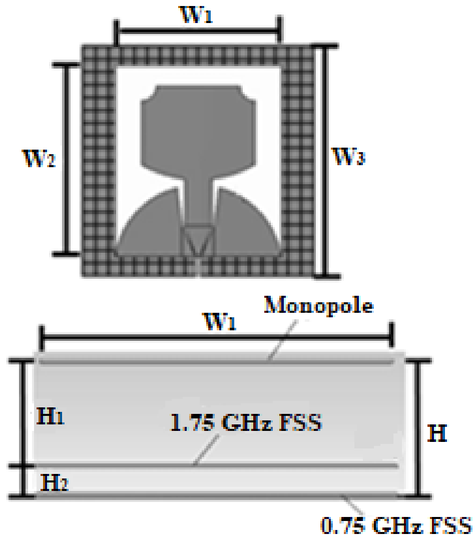

Fig. (5). Top view (top) and side view (bottom) of the monopole and two resonant reflectors.

Fig. (**6**) shows an -10 dB impedance bandwidth from 550 MHz to 3500 MHz. There is some degradation in the impedance bandwidth over the previous iterations of the wideband monopole in sections 2.0 and 2.A; however, Fig. (**7**) shows an improvement in the realized gain bandwidth. The monopole now shows a relatively stable realized gain of 4.0 dB to 8.0 dB from 500 MHz to 2000 MHz with the following caveats.

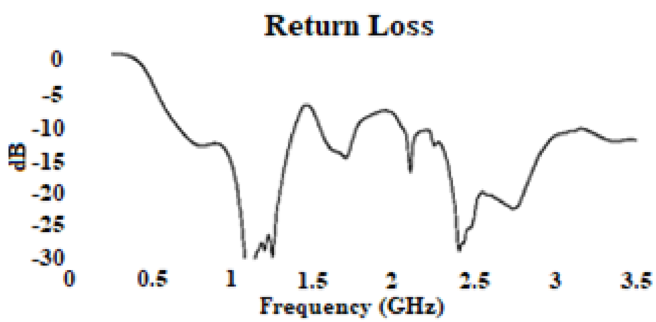

Fig. (6). Simulated return loss versus frequency of the monopole with two stacked FSS layers.

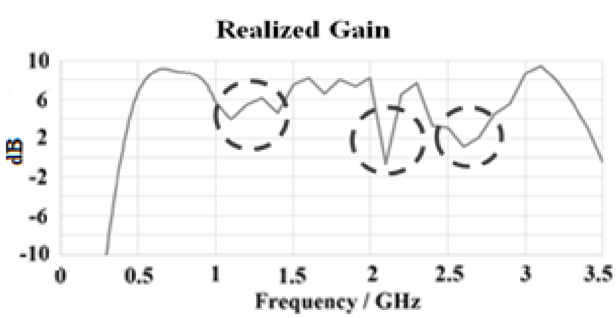

Fig. (7). Simulated realized gain versus frequency of the monopole with two stacked FSS layers.

Fig. (**8**) shows three radiation patterns across the frequency band showing a 3 dB beam width of 60° or better at these frequencies. However, at 2200 MHz the beam shows bifurication or split off broadside.

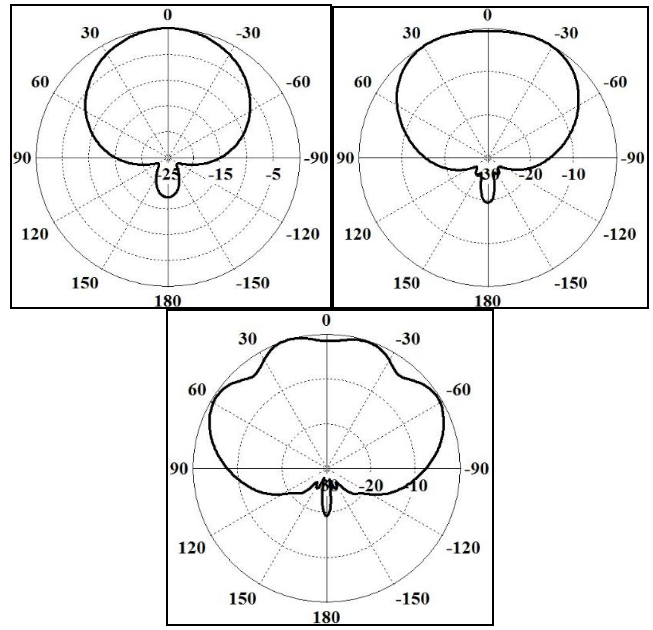

Fig. (8). Simulated normalized radiation patterns: 0.5 GHz (top left), 1.2 GHz (top right), 2.2 GHz (bottom).

Starting at 1200 MHz extending to 1500 MHz there is an improvement in realized gain up to 4 dB. At 2100 MHz, a narrowband dropout in realized gain down to 0 dB also degrades performance of the monopole. Furthermore, the monopole shows degraded realized gain from 2350 MHz to 2800 MHz of about 2.0 dB to 4.0 dB. In the regions centered on the resonant frequencies of the two reflectors from 500 MHz to 1000 MHz and 1500 MHz to 2000 MHz, a stable realized gain of about 7.0 dB to 8.0 dB presents itself.

Overall, the implementation of two layers of resonant reflectors is very encouraging. In the regions where the reflectors resonate, an improvement in the realized gain spanning about 500 MHz is apparent. This leads to the belief that incorporating additional resonant reflectors will mitigate gain dropouts seen at higher frequencies in Fig. (**7**), and extend the useable bandwidth of the wideband monopole across its entire impedance bandwidth while maintaining a relatively flat realized gain to broadside versus frequency. The flat gain response would indicate a mitigation of the monopole's beam tilt issues as well.

B. Addition of a Third Resonant Reflector

This section investigates the addition of a third resonant reflector resonant at 2100 MHz. Investigation of a third layer, goes beyond the scope of what was shown by Shadrokh, *et. al.* Fig. (**7**) demonstrates a resonance of 2100 MHz for the third FSS layer based on one of the dropouts seen in the realized gain curve. Fig. (**9**) shows the geometry of the wideband monopole suspended above the three resonant reflectors. The spacing between the antenna and the three resonant reflectors was determined via a genetic optimization algorithm using CST Microwave Studio 2019. Table **1** lists the dimensions for the geometry in Fig. (**9**).

Fig. (**10**) shows a -8 dB bandwidth from 555 MHz to 3500 MHz and an approximate -10 dB bandwidth from 800 MHz to

3500 MHz. There is a similar degradation in return loss in Fig. (**10**) as there is in Fig. (**6**) at 1400 MHz. This is an artifact of the spacing between the resonant reflector layers. Further optimization will alleviate this behavior, but that tends to degrade the realized gain curves as well. The engineer is responsible for analyzing the resulting tradeoffs, and constraints on the antenna's application will further dictate those tradeoffs.

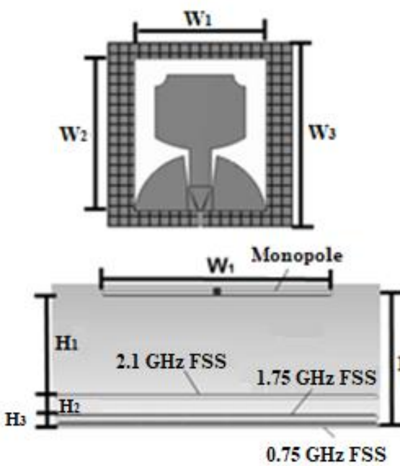

Fig. (9). Top view (top) and side view (bottom) of the monopole and 3 resonant reflectors.

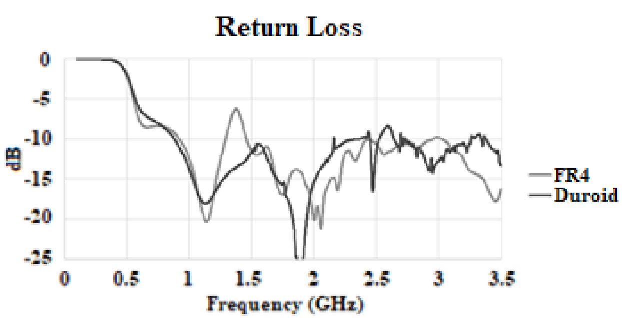

Fig. (10). Comparison of simulated return loss versus frequency of the monopole with three FSS layers utilizing FR4 and ROGERS 5870 substrates.

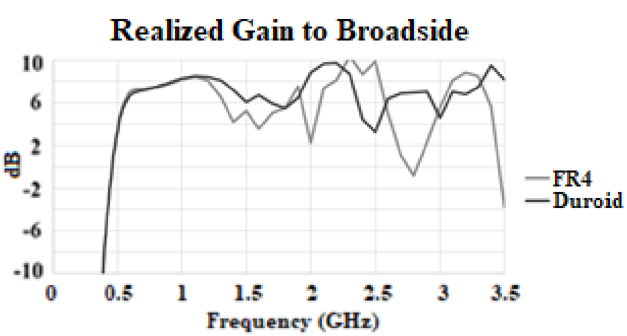

Fig. (11). Comparison of simulated realized gain versus frequency of the monopole with three FSS layers utilizing FR4 and ROGERS 5870 substrates.

Fig. (**11**) shows a mitigation of the realized gain dropout seen at 2100 MHz in Fig. (**7**). Fig. (**11**) now shows a realized gain of 2 dB at 2000 MHz as opposed to 0 dB. While this is not as drastic an improvement in realized gain shown by the introduction of the resonant reflectors at 750 MHz and 1750 MHz, this may also be further optimized via the spacing of the 2100 MHz resonant reflector in the normal direction of the monopole.

C. Simulation of Stacked Resonant Reflector Monopole using ROGERS 5870 Dielectric

All results up to this point utilize FR4 (εr=4.4, tanδ=0.025) as the dielectric substrate for the resonant reflectors and monopole layers. FR4 has a high loss tangent for a dielectric, but is commonly used for prototypes because FR4 is cheap, easy to mill, and easy to cut. ROGERS 5870 (εr=2.33, tanδ=0.001) is an order of magnitude less lossy. Replacing FR4 with ROGERS 5870 as the dielectric substrates for all FSS and antenna substrate layers should result in a noticeable improvement in the realized gain curves of Fig. (**7**). A slight shift in resonant frequency will also occur due to the differing εr of the two dielectrics. Fig. (**10**) compares the simulated return loss curve of the stacked FSS monopole design using FR4 and ROGERS 5870 as the dielectric material. The simulation utilizing ROGERS 5870 shows an improvement in the return loss curve at 1400 MHz extending the -10 dB impedance bandwidth of the monopole. Furthermore, the realized gain curves cease to show a drop in realized gain centered at both 1500 MHz and 2000 MHz and 2750 MHz. The simulation shows that when using ROGERS 5870 as the dielectric for all resonant reflective layers and the monopole, the realized gain spans 4.0 dB to 10.0 dB across the entire bandwidth from 500 MHz to 3500 MHz. Based on the past designs, adding an additional FSS layer at 2500 MHz could further enhance the realized gain to broadside.

4. EXPERIMENTAL RESULTS

This section details the experimental data for a prototype fabricated based on the dimensions in Table **1**. A network analyzer and anechoic antenna chamber enabled the measurements of return loss and realized gain respectively. Fig (**12**) shows the prototype with all antenna and FSS layers fabricated on FR4 dielectric substrates. The FSS layers are not visible because the pieces of foam cover them. The foam approximates the free space separation between the FSS layers shown in Fig. (**9**).

Table 1. Dimensions for Resonant Unit Cells and Monopole Geometry.

Symbol	Quantity	Value (mm)
F_L	unit cell length	85.5
F_1	unit cell gap	0.83
F_4	unit cell patch width	10.63
H	height of antenna structure	78.4
H_1	height between 1st reflector and monopole	59.64
H_2	height between 1st and 2nd reflector	10.1
H_3	height between 2nd and 3rd reflector	1.68
W_1	monopole substrate width	147.4

W_2	monopole substrate length	170.18
W_3	resonant reflector width	206.25
W_4	monopole substrate width	147.4

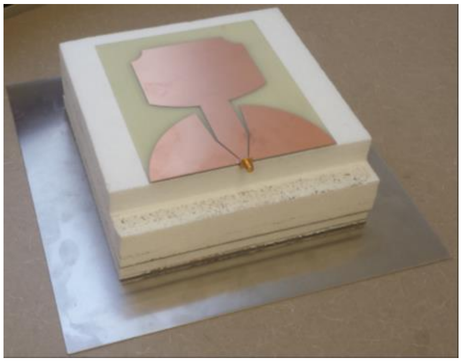

Fig. (12). Measured and simulated return loss versus frequency for the prototype of Fig. (**12**).

Fig. (**13**) shows the measured versus simulated return loss versus frequency. The measured return loss shows improvement over simulated return loss with a -10 dB bandwidth spanning 550 MHz to 3500 MHz.

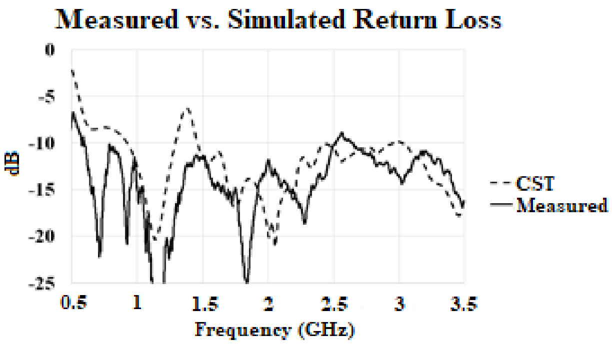

Fig. (13). Comparison of measured and simulated return loss versus frequency for the prototype of Fig. (**12**).

Fig. (**14**) shows the measured versus simulated realized gain to broadside versus frequency. Simulation shows a dropout in gain to 2.0 dB at 2000 MHz. However, Fig. (**14**) shows a dropout of closer to 0 dB closer to 2250 MHz. The results suggest potential issues in fabrication of the foam spacers between the resonant reflector layers. Cutting by hand using a band saw made ensuring the foam thickness to a tolerance of better than ±2.0 mm difficult. Tolerance errors in the spacing between the resonant reflective layers explain differences both in the return loss and realized gain versus frequency seen in Fig. (**13**) and (**14**). The prototype of Fig. (**12**) still agrees or exceeds performance of the model from 500 MHz to 2100 MHz. Furthermore, the realized gain shows similar tendencies between simulation and measurement from 2500 MHz to 3500 MHz taking into account a 7% frequency shift.

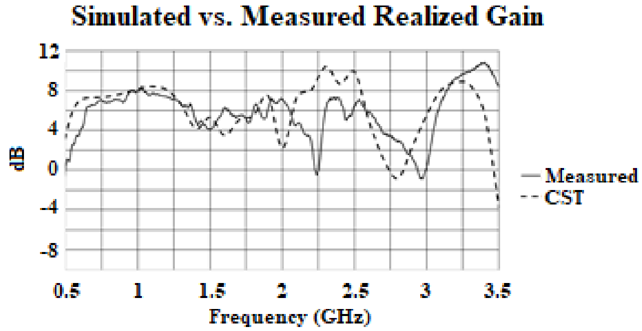

Fig. (14). Comparison of measured and simulated realized gain versus frequency for the prototype of Fig. (**12**).

5. CONCLUSION

This paper presents a CPW fed wideband monopole antenna utilizing stacked resonant reflectors to increase the realized gain bandwidth of a typical design. The impedance bandwidth is 550 MHz to 3500 MHz, while the realized gain is 4.0 dB to 10.0 dB from 500 MHz to 3500 MHz when using a ROGERS 5870 substrate. Furthermore, the incorporation of additional stacked resonant reflector layers shows the potential to extend this realized gain bandwidth beyond 3500 MHz. The final monopole design also has a 3 dB beam width of 60o over a wide bandwidth. The size of the antenna is 8.1” x 8.1” x 3.1”, and the stacked resonant reflector approach give superior realized gain over typical wideband monopole designs as well as helping to mitigate the beam tilt issue.

CONFLICT OF INTEREST

The author declares that there are no conflicts of interest.

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