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Wideband Harmonic Suppression Slot Antenna with Vertical Rounded Bow-Tie Slots

Junho Yeo*

Abstract—This paper proposes a coplanar waveguide-fed slot antenna with vertical rounded bow-tie slots for wideband harmonic suppression. Higher-order harmonics up to nine times the fundamental resonant frequency ($9f_o$) of the slot antenna was successfully suppressed by adding the slots in the middle of the two slot arms. A prototype of the antenna that resonates at 1 GHz was fabricated. The measured input reflection coefficient of the antenna remains over -3 dB at up to 9.15 GHz, which demonstrates the wideband harmonic suppression capabilities.

1. INTRODUCTION

Harmonic suppression has been investigated extensively for wireless communication systems. High-order harmonics are created by nonlinear devices or active circuits, which can reduce the system efficiency or cause electromagnetic interference in other systems [1]. It is well-known that the radio frequency (RF) front-end of a wireless RF power transfer system or a RF energy harvesting system usually has a rectifying circuit to convert the alternative current (AC) voltage from a receiving antenna to the direct current (DC) voltage. However, since the diode in the rectifying circuit is a nonlinear element, it generates harmonics of the fundamental frequency. These harmonics will reradiate through the antenna and cause a decrease in the efficiency of the rectifying circuit in converting RF energy to DC [2]. For instance, the RF-to-DC conversion efficiency was increased about 17.4% at 2.45 GHz by using the 2nd and 3rd harmonic rejection band pass filter [3]. Reflected (re-radiated) powers by the harmonics are proportional to the n power of the transmitted power in a certain condition where n is the order of the harmonics [4]. Therefore, wideband harmonic suppression beyond second or third harmonics might be necessary to achieve high conversion efficiency.

Various types of harmonic suppression antennas were combined with an integrated filter, and particularly, planar coplanar waveguide (CPW)-fed antennas with harmonic suppression capability have been widely studied. A band stop filter based on a defected ground structure with two different square-shaped lattices was etched on the ground plane of the CPW feed line for a loop slot antenna [5]. Two stepped-impedance slot resonators (SIRs) were added at the ends of a rectangular radiating slot of a CPW-fed slot antenna [6, 7]. A CPW-fed microstrip patch antenna with a compact CPW resonant cell inserted on the centre line was proposed [8]. However, most antennas suppress up to fourth-order harmonics, and the remaining harmonics above the fifth order cannot be suppressed.

Recently, several attempts have been tried to increase the harmonic suppression bandwidth. A stepped-impedance dipole filtering antenna with a stepped-impedance director and a feed-line low pass filter was proposed to suppress the harmonics up to 4.8 times the fundamental resonant frequency [9]. A compact microstrip dipole antenna with enhanced bandwidth and ultra-wideband harmonic suppression

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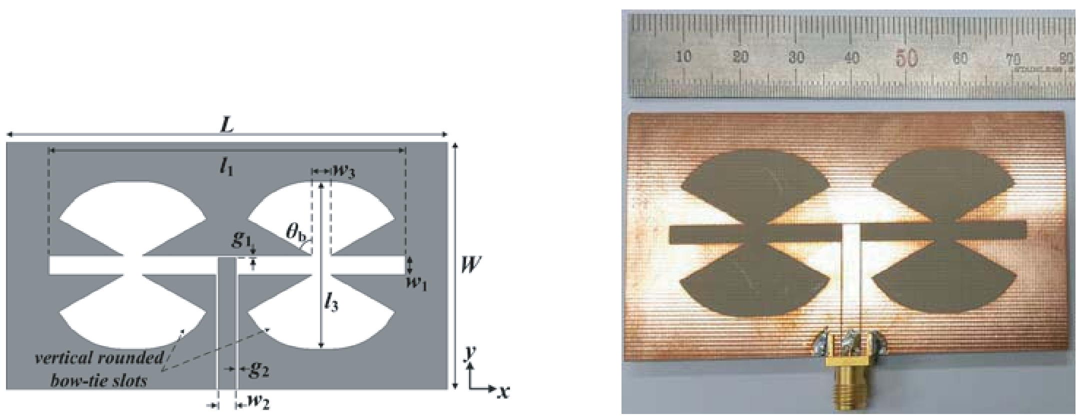
* Corresponding author: Junho Yeo (jyeo@daegu.ac.kr).
The author is with the School of Computer and Communication Engineering, Daegu University, Jillyang, Gyeongsan, Gyeongbuk 38453, Korea.

up to 6 times the fundamental frequency [10]. A compact CPW-fed slot antenna using stepped-impedance slot resonators and a feed-line band stop filter was introduced to suppress the harmonics up to eight times the fundamental frequency [11].

This paper presents a CPW-fed slot antenna with vertical rounded bow-tie slots for wideband harmonic suppression up to the ninth order. The antenna consists of a CPW-fed slot antenna with vertical rounded bow-tie slots added in the middle of the two slot arms. The design procedure for the proposed antenna is explained using several antenna structures. Full-wave simulation results for the antenna were obtained with the commercial electromagnetic simulator CST Microwave Studio.

2. ANTENNA CONFIGURATION AND DESIGN

Figure 1 shows the configuration and fabricated prototype of the proposed antenna. The antenna consists of a rectangular slot fed by a 50 Ω capacitively coupled CPW feed line and two vertical rounded bow-tie slots in the middle of the two arms of the rectangular slot. The final geometric parameters for a fundamental resonant frequency of 1 GHz with up to ninth-order harmonic suppression are as follows (all units are in millimetres): $L = 80$, $W = 45$, $l_1 = 64.6$, $w_1 = 3.4$, $g_1 = 0.2$, $w_2 = 3.2$, $g_2 = 0.25$, $l_3 = 30.5$, $w_3 = 3.4$, and $\theta_b = 60°$. The antenna is printed on an RF-35 substrate with dielectric constant $\varepsilon_r = 3.5$, thickness $h = 0.76$ mm, and loss tangent of 0.0018.



(a) (b)

Figure 1. Configuration and fabricated prototype of proposed antenna: (a) configuration and (b) fabricated prototype.

To help explain the design procedure, four antenna structures are considered for performance comparison, as shown in Figure 2. Figure 2(a) shows the reference CPW-fed rectangular slot antenna without harmonic suppression capability (antenna 1), and Figure 2(b) shows the CPW-fed slot antenna with end-aligned SIRs (antenna 2). Figure 2(c) shows the CPW-fed slot antenna with centre-aligned SIRs (antenna 3). Figure 2(d) shows the proposed CPW-fed slot antenna.

Figure 3 compares the corresponding input reflection coefficient characteristics of the four antenna structures in Figure 2. The capacitively coupled CPW-fed rectangular slot reference antenna without harmonic suppression capability resonates at 1.60 GHz, and there are several higher-order resonances at 5.30, 8.64, and 12.16 GHz. The length and width of the rectangular radiating slot are the same as those of the proposed antenna. The input reflection coefficient remains over −3 dB at up to 4.76 GHz after the first resonant frequency of 1.58 GHz. Therefore, harmonics up to 2.98 times the first resonant frequency are suppressed.

Next, two SIRs with a length of 3.4 mm and width of 30.5 mm are symmetrically added to the rectangular slot at both ends, as shown in Figure 2(b) [7]. The first resonant frequency moves to 1.06 GHz, and higher-order resonances occur at 4.16, 7.30, 8.86, and 11.70 GHz. Since the input reflection coefficient remains over −3 dB at up to 3.94 GHz, harmonics up to 3.72 times the first resonant

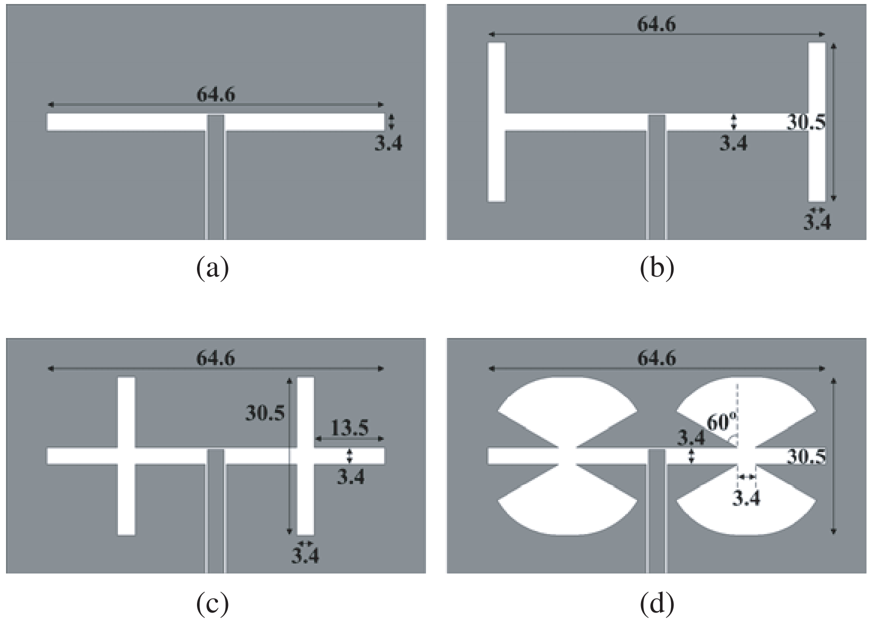


Figure 2. Geometries of four antennas considered in design procedure: (a) antenna 1, (b) antenna 2, (c) antenna 3, and (d) antenna 4.

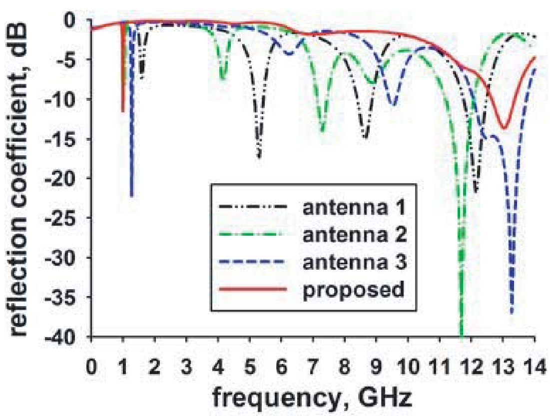


Figure 3. Harmonic suppression characteristics comparison for the four antenna structures in Figure 2.

frequency are suppressed. We note that the addition of the two SIRs has an effect of size-reduction in antenna dimensions compared to the conventional rectangular slot antenna and the impedance bandwidth decreases [12].

The effect of the locations of the two SIRs along the rectangular slot was investigated by moving the two SIRs to the middle of the two arms of the rectangular slot, as shown in Figure 2(c). In this case, the first resonant frequency shifts toward high frequency at 1.28 GHz, and there are higher-order harmonics at 6.24, 9.52, and 13.28 GHz. Harmonics up to 4.60 times the first resonant frequency are suppressed because the input reflection coefficient remains over -3 dB at up to 5.89 GHz. Therefore, we can conjecture that harmonic suppression performance is better when the two SIRs are located in the middle of the arms than that with the end-aligned SIRs.

The vertical rounded bow-tie slots are used to further extend the harmonic suppression bandwidth, as shown in Figure 2(d). The proposed vertical rounded bow-tie slots comprise two SIRs and rounded bow-tie slots with a flare angle of $\theta_b = 60°$ added along the sides of the SIRs. The flare angle of the rounded bow-tie slots was optimized through a parametric study to achieve the maximum harmonic suppression. The first resonant frequency moves toward a low frequency at 1.0 GHz after adding the rounded bow-tie slots, and a higher-order harmonic appears at 13.03 GHz. The input reflection coefficient remains over −3 dB at up to 10.73 GHz, and harmonics up to 10.73 times the first resonant frequency are suppressed. The proposed vertical rounded bow-tie slots also have a size-reduction effect similar to the SIRs. An impedance matching structure might be added to increase the bandwidth.

3. EXPERIMENT RESULTS

A prototype of the proposed antenna was fabricated, and its performance was measured by using an Agilent N5230A network analyzer, as shown in Figure 4. The measured input reflection coefficient resonates at 1 GHz and remains −3 dB at up to 9.15 GHz, which is a little lower than the simulated result because of a shallow resonance with a level of −5.40 dB at around 10.15 GHz. This resonance might be due to fabrication and measurement errors. Hence, higher-order harmonics up to at least nine times the first resonant frequency are successfully suppressed.

The radiation patterns of the proposed antenna in the y-z and z-x planes at 1 GHz are compared in Figure 5. The measured patterns in both planes agree well with the simulated results.

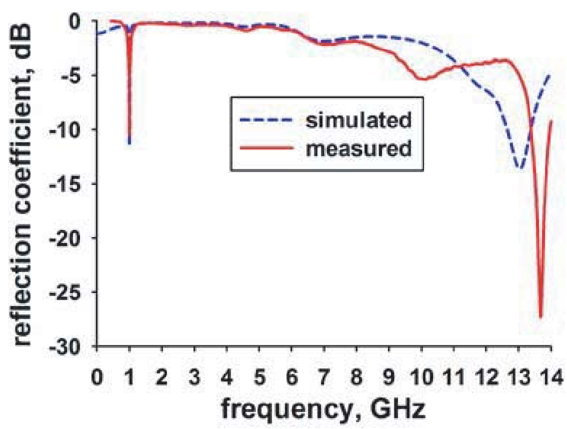
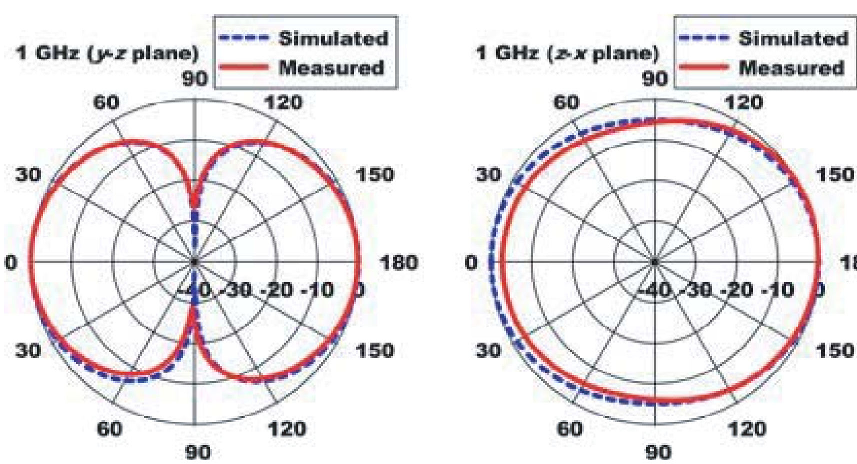


Figure 4. Comparison of simulated and measured reflection coefficient characteristics of the proposed antenna.



(a) (b)

Figure 5. Measured radiation pattern at 1 GHz: (a) y-z plane, and (b) z-x plane.

4. CONCLUSION

A CPW-fed slot antenna was designed for wideband harmonic suppression up to nine times the first resonant frequency using vertical rounded bow-tie slots. The harmonic suppression performance was compared with that of several conventional harmonic-suppressed slot designs.

The measured input reflection coefficient of the fabricated prototype resonates at 1 GHz and remains -3 dB at up to 9.15 GHz, which makes it suitable for super-wideband harmonic suppression antennas in wireless power transfer or RF energy harvesting applications. The equivalent circuit model of the proposed antenna can be described as a combination of a resonant circuit model of the rectangular slot antenna with a model of vertical rounded bow-tie slots. We will try to extract the equivalent circuit model as our future work.

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