A Novel Low-Profile Compact Directional Ultra-Wideband Antenna: The Self-Grounded Bow-Tie Antenna

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***Abstract*—Low-profile directional ultra-wideband (UWB) antennas are strongly demanded in many UWB applications. However, few such UWB antennas have been reported. To meet the demands, an original novel low-profile directional UWB antenna—the self-grounded Bow-Tie is developed and presented here. This new UWB antenna has a compact and simple geometry, and ultra-wideband performance, such as presented here over a frequency range of 2–15 GHz with about -10 dB reflection coefficient, stable radiation patterns, and good time-domain impulse response. Measurements of a prototype of the antenna have verified the design and the simulation. It can be foreseen that this new antenna will find many applications in the different areas in UWB technology.**

***Index Terms*—Compact antenna, directional antenna, impulse response, stable radiation pattern, ultra-wideband (UWB) antenna.**

I. INTRODUCTION

ULTRA-WIDEBAND (UWB) technology finds many applications in different areas in the general society, such as UWB sensor network for precise ranging and geolocation, robust-to-fading-and-interference UWB short-range communication systems, UWB radar and imaging systems with superior penetration and high resolution, and super-sensitive UWB radio astronomy [1], [2]. Therefore, researches and developments of UWB antennas have obtained lots of attention for decades, and many types of UWB antennas have been developed.

UWB antennas can be classified roughly into four categories. The first is the scaled structure. Bow-Tie dipoles [3]–[6], biconical dipoles [3], [7], and log-periodic dipole arrays [8]–[10] are the examples of this group. The self-complementary structure [11] is the second group which includes many antennas, such as self-complementary spiral antennas [12]. Then comes the traveling-wave structure group, in which Vivaldi antennas [13] are well-known and widely used UWB antennas. The last one can be characterized as multiple-reflection (or resonance) structure [14]–[16]. Recently, a dielectric resonator antenna has also been designed for UWB applications [17].

Having a close look at the different groups of UWB antennas mentioned above, it can be found that small, low-profile UWB antennas are those from scaled structures, self-complementary structures or multiple-reflection structures, and their radiation functions are omnidirectional. Only antennas from the traveling-wave structures, such as Vivaldi antenna, provide the UWB directional radiation characteristics but however have high-profile geometry (large dimensions in the radiation direction). Using existing compact low-profile omnidirectional UWB antennas can cause signal loss and interference in many UWB applications, such as in UWB tracking, UWB geolocation, and UWB microwave tomography. Using UWB antennas of traveling-wave structures can make the system bulky, which is a drawback in many UWB applications.

Therefore, compact low-profile directional UWB antennas are strongly demanded. Recently, using artificial magnetic conductor (AMC) characteristic of electromagnetic band-gap (EBG) structure as a ground plane to obtain low-profile UWB antennas has been receiving more attention and some spiral UWB antennas on AMC ground have been reported [18]–[20]. However, it has been shown that there is a physical bound on the frequency band of AMC surface [21], [22] ($B \leq k_0 d/2$, where B, k_0, and d are the bandwidth, wave number at the center frequency and the thickness of the AMC surface structure, respectively), which will limit the applications of this type of UWB antennas.

This paper presents an original novel compact low-profile directional UWB antenna—the self-grounded Bow-Tie antenna. The antenna has a simple geometry, ultra-wideband performance with about -10-dB reflection coefficient and stable radiation beams for the frequency range of 2–15 GHz, and good time-domain impulse response.

It should be pointed out that this work is mainly focusing on the conceptual realization of the new antenna. We have not performed any optimization procedure to obtain an optimal performance of the self-grounded Bow-Tie antenna. We believe that by applying suitable optimization schemes, a better performance will be obtained for this new UWB antenna.

II. NEW CONCEPT AND MODELING

The infinite Bow-Tie dipole is a planar scaled structure and therefore is a frequency-independent antenna. In order to have a directional radiation (radiating mainly in one direction), a seagull-over-sea configuration of infinite Bow-Tie antenna is a natural choice, see Fig. 1, which is also a scaled structure with the frequency-independent characteristics. For practical

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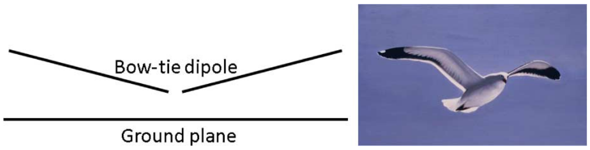


Fig. 1. Seagull-over-sea configuration of Bow-Tie.

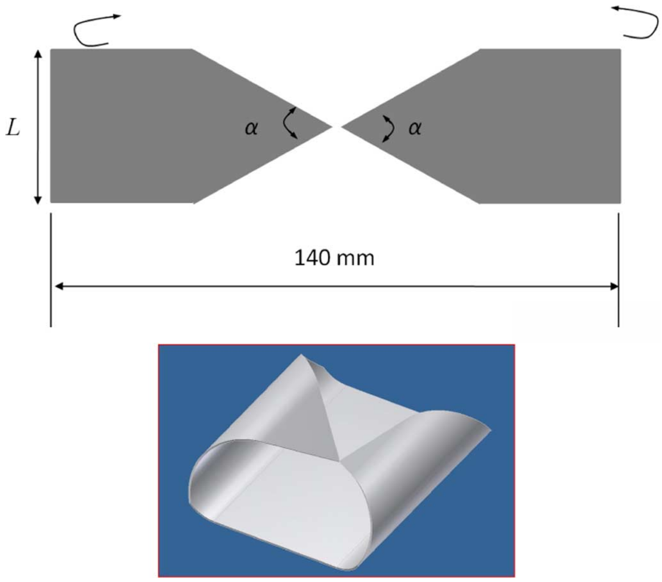


Fig. 2. Conversion from Bow-Tie antenna to self-grounded Bow-Tie antenna.

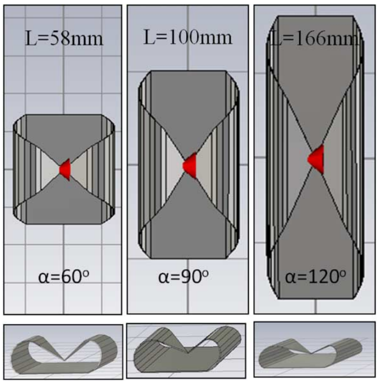


Fig. 3. Three self-grounded Bow-Tie antennas of different extended angles, α, modeled in CST Microwave Studio [28]. The red cone represents the input port with port impedance of 150 Ω.

antennas, truncation should be employed and the operating frequency band of a truncated scaled structure antenna will be finite. For the seagull-over-sea configuration of the Bow-Tie antenna, the truncation is done by connecting the radiating element to the ground at the outer end of the antenna. This truncation, from the experience we had from our UWB antenna research activities [23]–[26], helps reducing the size of UWB antennas and meanwhile retains the maximum operating frequency band. Fig. 2 shows the procedure of the conversion from Bow-Tie antenna to the self-grounded Bow-Tie antenna.

In this paper, three self-grounded Bow-Tie antennas have been investigated. As shown in Fig. 2, the width of the antenna is fixed as 140 mm, and the extended angle α has been chosen as 60°, 90°, and 120°, and therefore, the length of the antenna L is changed correspondingly; see Fig. 3. It should be noted that the choice of the extended angle here has been selected for comparison to those in [27], and the performance shown below was obtained by a parameter study, not a full optimization, which implies that those performances may be improved further more when a full optimization scheme is employed.

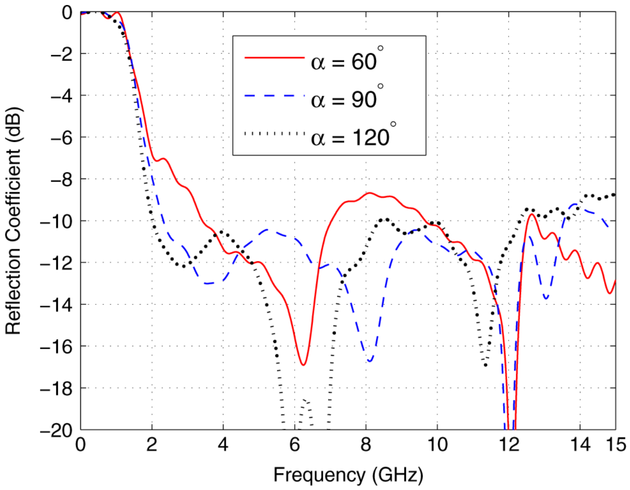


Fig. 4. Simulated reflection coefficients of the three self-grounded Bow-Tie antennas of different extended angles using CST for the input port impedance of 150 Ω.

A. Reflection Coefficient

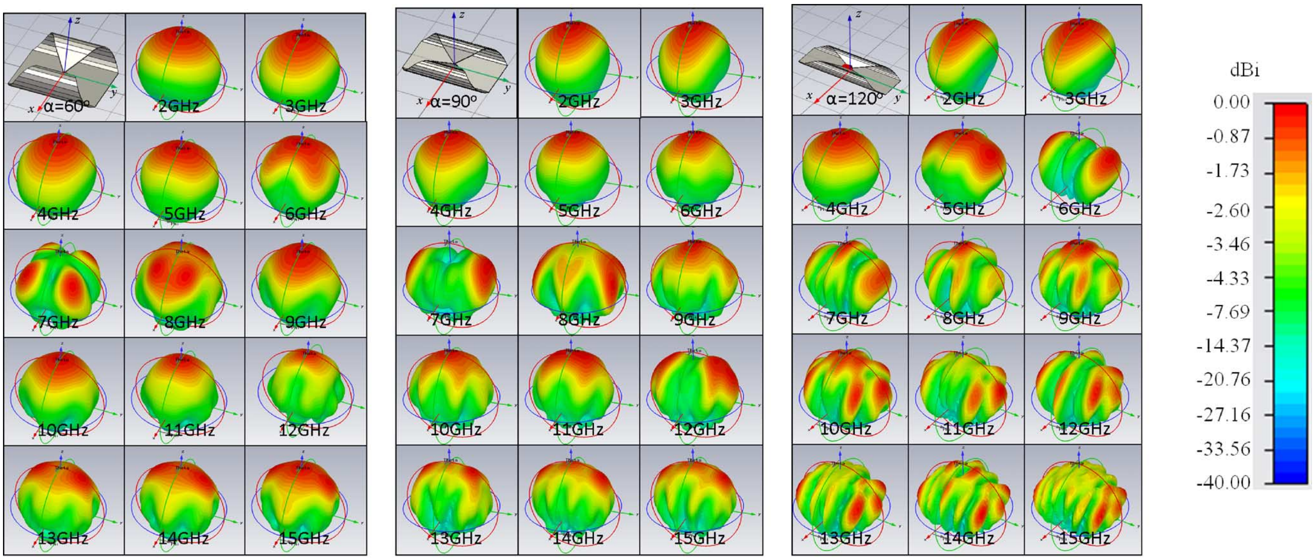
Fig. 4 shows the simulated reflection coefficients for the self-grounded Bow-Tie antennas with three different extended angles α of 60°, 90°, and 120° by using the 3-D electromagnetic simulation technology CST Microwave Studio, which is a commercial software for time or frequency domain simulation [28]. The input port impedance is chosen as 150 Ω which seems an optimal value for this type of the structure; see Fig. 3. From Fig. 4, it can be observed that in this preliminary investigation, the self-grounded Bow-Tie antenna with the extended angle of $\alpha = 90°$ has the best reflection coefficient performance, which is almost below -10 dB over the band of 2–15 GHz. For the antenna with the extended angle of $\alpha = 60°$, the reflection coefficient is below -8 dB over the most of the band.

B. Radiation Characteristics

Fig. 5 shows the simulated magnitude of far-field functions of the three self-grounded Bow-Tie antennas over the band of 2–15 GHz. It can be observed that the far-field function of the antenna with the extended angle of $\alpha = 60°$ has the most stable beam shape over the band: the main beams are directed in the normal of the ground plane except at 7 GHz. This characteristic is referred to as the directional radiation and strongly demanded in many applications. For the antennas with other two extended angles of $\alpha = 90°$ and $\alpha = 120°$, the far-field functions are split into multiple beams at high frequencies, which is referred to as nondirectional and may also find some application due to this characteristic.

C. Time-Domain Characteristics

One important aspect of designing UWB antennas is the time-domain impulse response. Here we use the envelope



(a) (b) (c) (d)

Fig. 5. Simulated amplitude of far-field functions of the self-grounded Bow-Tie antennas of three different extended angles. (a) Extended angle of 60°. (b) Extended angle of 90°. (c) Extended angle of 120°. (d) Color scale.

width τ_{FWHM} which is defined as the width of the magnitude of the envelope $|h^+(t)|$ at half maximum (FWHM), and the ringing duration $\tau_{r=\alpha}$ to characterize the impulse response of the self-grounded Bow-Tie antenna. The envelope $|h^+(t)|$ localizes the distribution of energy versus time. For detailed definitions of τ_{FWHM} and $\tau_{r=\alpha}$, please refer to [29]. τ_{FWHM} and $\tau_{r=\alpha}$ can be expressed analytically as

$$\begin{aligned} \tau_{\text{FWHM}} &= t_2|_{t_2>t_1, |h^+(t_2)|=p/2} - t_1|_{|h^+(t_1)|=p/2} \\ \tau_{r=\alpha} &= t_2|_{t_2>t_1, h^+(t_2)=\alpha p} - t_1|_{h^+(t_1)=p}. \end{aligned} \tag{1}$$

In this work, we calculate the impulse response of the antenna by simulating the impulse response of a setup consisting of two self-grounded Bow-Tie antennas of the extended angle $\alpha = 60°$, shown in the upper part of Fig. 6, by using CST. The two antennas are separated apart by a $r = 400$ mm distance, which fulfills the far-field region condition of $r \geq D^2/\lambda$, where $D = 80$ mm is the diameter of a sphere which contains the structure of the self-grounded Bow-Tie antenna (size of $54 \times 58 \times 24$ mm^3), $\lambda = 20$ mm the wavelength at 15 GHz. The simulated impulse response is shown in Fig. 6. Since this is a response of two antennas, we estimate τ_{FWHM} and $\tau_{r=0.22}$ roughly by halving the values obtained in Fig. 6. So we have $\tau_{\text{FWHM}} = 100.5$ ps and $\tau_{r=0.22} = 260$ ps. Compared to $\tau_{\text{FWHM}} = 140$ ps and $\tau_{r=0.22} = 185$ ps of the Bow-Tie antenna in [29], the present self-grounded Bow-Tie antenna has very similar characteristic time-domain response parameters, which is also considered as a good impulse response performance.

III. SIMULATED AND MEASURED RESULTS

Since the self-grounded Bow-Tie antenna with the extended angle of $\alpha = 60°$ presents the most stable directive radiation performance in the CST simulations, a prototype of this antenna has been manufactured and measured in order to verify the design. The hardware of this prototype occupies a volume of $54 \times 58 \times 24$ mm^3 as shown in Fig. 7 (upper right), where the radius of curvature of the folded arms is 12 mm.

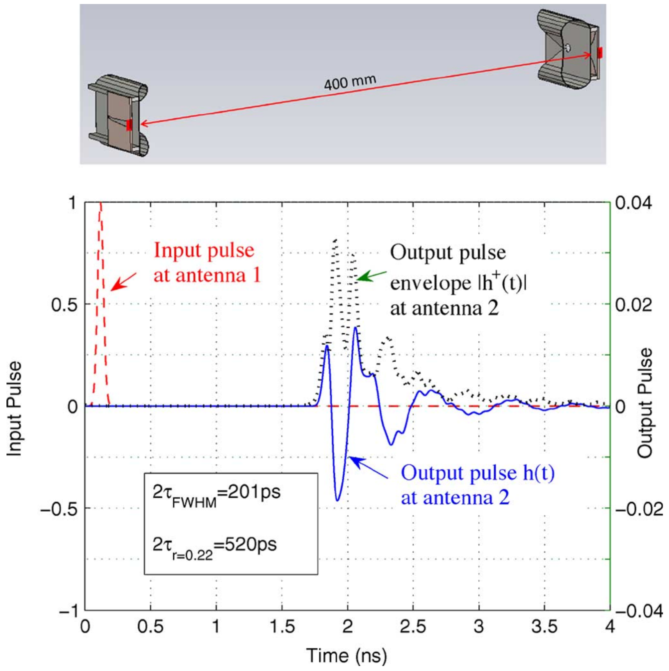


Fig. 6. Simulated time response of a pulse through two self-grounded Bow-Tie antennas separated by 400 mm.

A. Balun Design

In order to excite the new UWB antenna, a new UWB balun has been designed. The UWB balun is a transformer from a 50-Ω-impedance microstrip line to a 150-Ω-impedance twin-line transmission line, as shown in Fig. 8 by the modeling in CST. Since this work is mainly focusing on the conceptual development, the balun is designed on an available-at-hand Rogers RO4003 board (RO4003: $\epsilon_r = 3.38$ and $\tan\delta = 0.0027$@10 GHz) by a few parameter studies of the structure without applying a full optimization. Fig. 9 shows the measured and the simulated reflection coefficient (S_{11}) and transmission coefficient (S_{21}) of a two-balun back-to-back

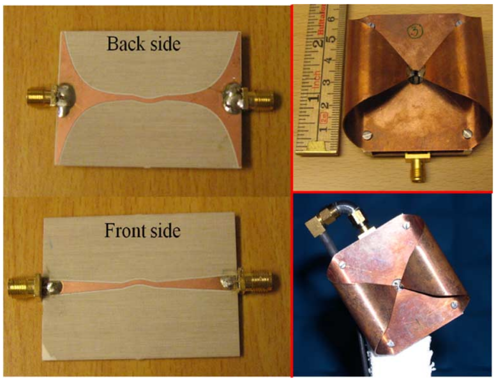


Fig. 7. Photos of back-to-back baluns (left), prototype of the self-grounded Bow-Tie antenna (upper right) and the mounting setup for pattern measurement (lower right).

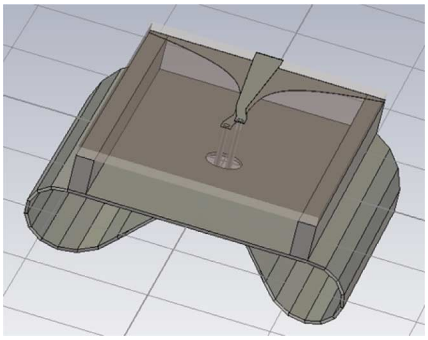


Fig. 8. Modeling of the UWB balun integrated with the antenna in CST. The substrate board for balun is half transparent in order to show the configuration.

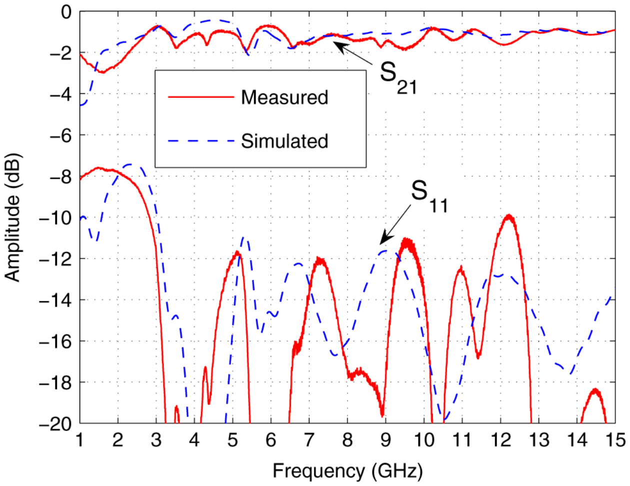


Fig. 9. Measured and simulated performance of the circuit of two-balun back-to-back structure.

circuit shown in Fig. 7 (left). From Fig. 9, it can be concluded that the reflection coefficient of one balun is below -8 dB and the transmission coefficient is about -0.5 dB over the band of 2–15 GHz.

B. Reflection Coefficient

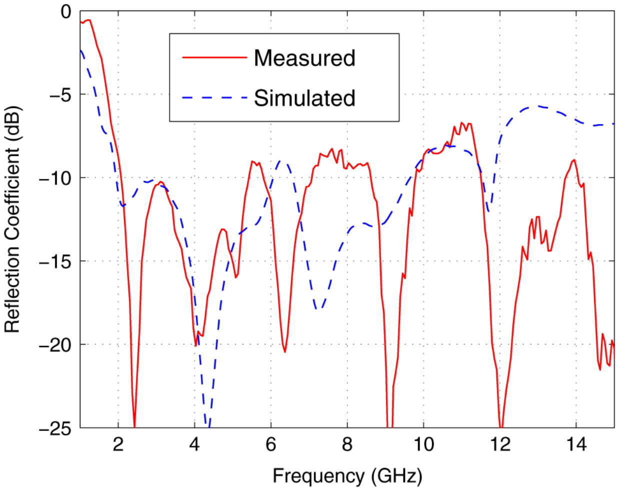


Fig. 10. Measured and simulated reflection coefficients of the self-grounded Bow-Tie antenna with the balun.

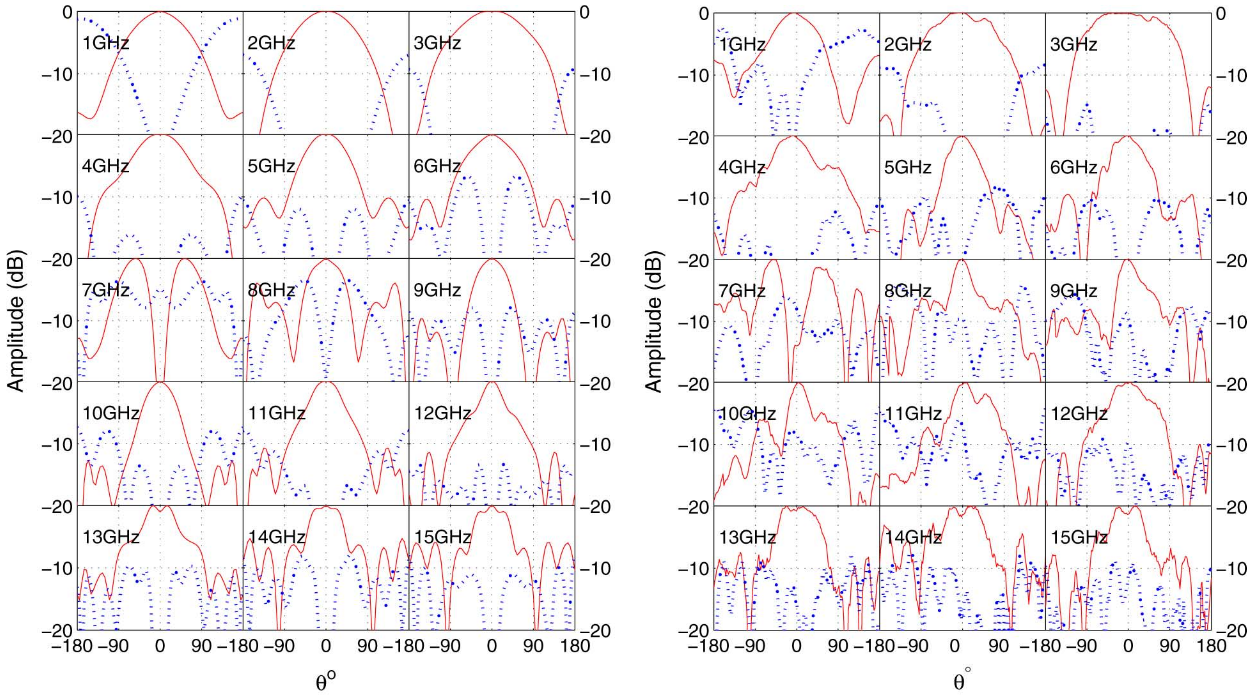
Fig. 7 shows the manufactured prototype of the self-grounded Bow-Tie antenna with the balun, and the measured and simulated reflection coefficients of the antenna with the balun are shown in Fig. 10. It can be observed that the reflection coefficient is below -10 dB over the most part of 2–15 GHz, and below -7 dB over the whole band. We believe that this performance can be improved to be below -10 dB over the whole band of 2–15 GHz by employing some optimization schemes, and even cover wider bandwidth.

It is also very interesting to see here if the size of the self-grounded Bow-Tie antenna agrees with the theoretical limitation of small antennas by the cutoff for gradual transition antennas presented in [30], i.e., $\lambda_{\text{cutoff}} = 2\pi a$ where a is the radius of the smallest sphere surrounding the antenna. Taking the self-grounded Bow-Tie antennas with extended angle of $\alpha = 60^\circ$ as an example, we have $a = 0.7 \cdot 58$ mm $= 40$ mm. Therefore, $\lambda_{\text{cutoff}} = 6.28 \cdot 40$ mm $= 240$ mm, i.e., $f_{\text{cutoff}} = 300/240$ mm $= 1.25$ GHz, which matches pretty well the results in Fig. 10. Thus, the $\alpha = 60^\circ$ self-grounded Bow-Tie is very close to the smallest UWB antenna that can be made of gradual-transition type.

C. Radiation Patterns

The mounting setup of the UWB antenna for radiation pattern measurement is shown in the lower right part of Fig. 7. We present here the co- and cross-polar radiation patterns in $\varphi = 45^\circ$ in Fig. 11, both simulated and measured. From the figure, it can be concluded that the antenna has the directive radiation characteristics over the whole band of 2–15 GHz. The main beam is also directed in the positive z-axis over the band, except around 7 GHz. It is also noticed that the agreement between the simulated and the measured radiation patterns is good in a general sense, and there are some difference for the detailed beam shapes. For example, the measured patterns are not symmetrical as they should (indicated by the simulations). This can be explained by the effect of the connectors and the cable used in the pattern measurement shown in the photo at the lower-right corner of Fig. 7. We even used some absorb material to cover the connectors and cable during the measurement but the effect still exists. The asymmetry of the patterns is caused by the connectors and cable.

Fig. 12 shows the measured and simulated directivity of the self-grounded Bow-Tie antenna with the 60° extended angle. The directivity is about 5–8 dBi over the frequency band of



(a) (b)

Fig. 11. Simulated and measured co-(solid line) and cross-(dashed) polar radiation patterns in $\varphi = 45^\circ$ of the self-grounded Bow-Tie antenna with the balun. (a) Simulated. (b) Measured.

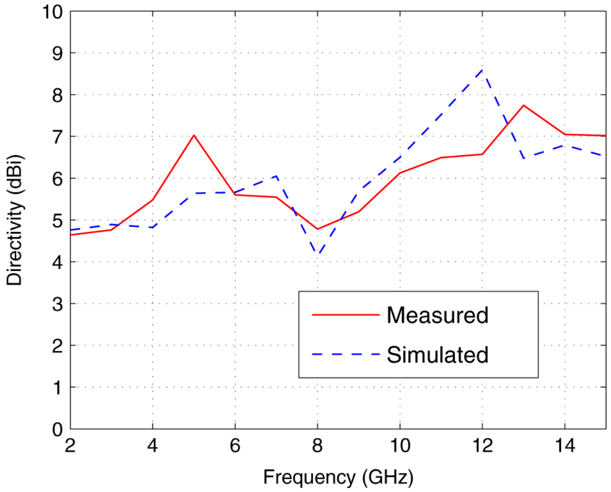


Fig. 12. Measured and simulated directivity of the self-grounded Bow-Tie antennas of 60° extended angle.

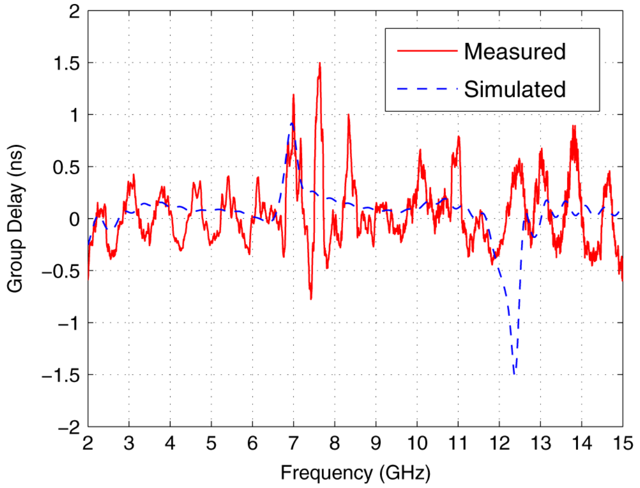


Fig. 13. Measured and simulated group delay of the setup of two self-grounded Bow-Tie antennas shown in Fig. 6.

2–15 GHz, which means that the self-grounded Bow-Tie antenna has quite stable radiation patterns compared to other UWB antennas, for example, open boundary quad-ridged horn [31], where the directivity varies from 6 to 13 dBi over 2–15 GHz. Note that the simulated and measured directivity are done over 2–15 GHz with 1-GHz interval (14 points), and the maximum beam directions are along the normal of the antenna ground plane at all frequency points except at 7 GHz, which we are looking into for the reasons.

D. Group Delay

It is much easier to measure the group delay of a UWB antenna, from which the impulse response can be determined, than the impulse response directly which is not available at our lab at the moment. Fig. 13 shows the measured and simulated group delays of a setup which consists of two self-grounded Bow-Tie antennas separated apart 400 mm; see the upper part of Fig. 6. From Fig. 13, it can be concluded that the measured maximum group delay is within 1 ns for one self-grounded Bow-Tie antenna, which indicates a very good time domain impulse response of the antenna and verifies the simulated impulse response presented in Fig. 6.

E. Radiation Efficiency

Radiation efficiency is a measure of ohmic loss of an antenna, which is an important characteristics for UWB antennas. The radiation efficiency can be measured very efficiently by using re-

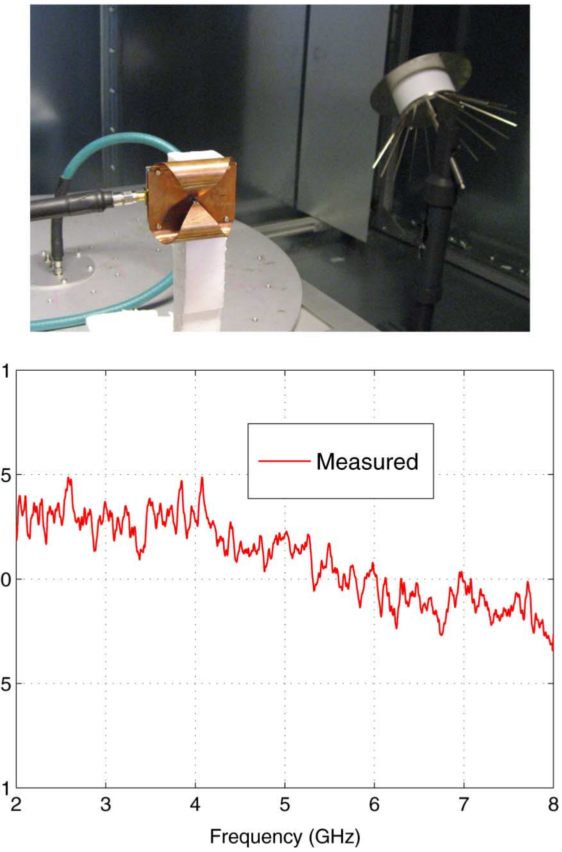


Fig. 14. Measured radiation efficiency using a Bluetest reverberation chamber.

verberation chamber [32]. Fig. 14 shows the measurement setup in a Bluetest reverberation chamber [33].

The Bluetest reverberation chamber is a resonant, 3-D metal cavity with a rectangular form. This cavity supports a set of resonant modes, which are stirred by moveable objects inside the cavity. Each resonant mode can be considered as eight incident plane waves [34]. Thereby, a multipath environment is created in the chamber, which enable us to measure radiation efficiency of an antenna in a very efficient way.

The measured radiation efficiency of the present UWB antenna over a frequency band of 2–8 GHz is shown in Fig. 14. The reason that the measurement was done up to only 8 GHz instead of 15 GHz is that the Bluetest Chamber provides the operation up to 8 GHz at the moment. The positive value of the radiation efficiency is caused by the 0.5-dB measurement error with this method [32]. Nevertheless, the measured data indicates that the prototype of the new UWB has almost no ohmic loss at the low end of the frequency range of 2–8 GHz and the ohmic loss starts to increase at the high end of the band. We believe that the ohmic loss of the antenna is mainly introduced by the dielectric board of the balun. Therefore, careful choosing of a low-loss dielectric board will be addressed in the future development of the self-grounded Bow-Tie antennas.

IV. CONCLUSION

A novel low-profile directional ultra-wideband antenna—the self-grounded Bow-Tie antenna is presented in the paper. The design and the new concept have been verified by the simulations in CST and the measurements. The new UWB antenna has many unique characteristics: compact size, low profile and at the same time directive radiation function, low reflection coefficient, and good time domain impulse response. It can be foreseen that the self-grounded Bow-Tie antenna will find many applications in UWB communication systems, UWB radar and tracking systems, UWB indoor geolocation systems, UWB sensing and microwave tomography, and more. Further development on this UWB antenna and its applications will be reported in the near future.

The self-grounded Bow-Tie antenna is protected by a pending patent [35].

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