A Compact Polyimide-Based UWB Antenna for Flexible Electronics

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***Abstract*—In this letter, we present a compact ultrawideband (UWB) antenna printed on a 50.8-μm Kapton polyimide substrate. The antenna is fed by a linearly tapered coplanar waveguide (CPW) that provides smooth transitional impedance for improved matching. The proposed design is tuned to cover the 2.2–14.3-GHz frequency range that encompasses both the 2.45-GHz Industrial, Scientific, Medical (ISM) band and the standard 3.1–10.6-GHz UWB band. Furthermore, the antenna is compared to a conventional CPW-fed antenna to demonstrate the significance of the proposed design. A parametric study is first performed on the feed of the proposed design to achieve the desired impedance matching. Next, a prototype is fabricated; measurement results show good agreement with the simulated model. Moreover, the antenna demonstrates a very low susceptibility to performance degradation due to bending effects in terms of impedance matching and far-field radiation patterns, which makes it suitable for integration within modern flexible electronic devices.**

***Index Terms*—Coplanar waveguide (CPW), flexible electronics, polyimide, ultrawideband (UWB).**

I. Introduction

ULTRAWIDEBAND (UWB) technology has recently become one of the most promising solutions in indoor wireless communication systems. UWB has the advantages of high data rate, low power, as well as simpler hardware configuration compared to conventional wireless systems. A UWB system can be integrated within electronic devices and used in various applications such as: wireless PC peripherals and multimedia connectivity, network access for mobile computing devices, and wireless body area networks (WBANs) [1]. On the other hand, the past few years have witnessed increased research activities focused on the development and optimization of flexible electronics in response to the market trends that report a growing interest in portable, lightweight, low-profile, and flexible electronic devices [2]. Consequently, the integration of flexible UWB antennas with such devices is ultimately needed for wireless connectivity. In response to such demands, several design approaches of flexible and conformal UWB antennas based on flexible substrates were reported in the literature [3]–[6].

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In [3], a 58×58-mm^2 flexible UWB antenna based on an organic paper substrate is proposed. Although the design offers a flexible low-profile solution, paper-based substrates tend to lack robustness and introduce discontinuities when used in applications that require high levels of bending and twisting. Moreover, they have a high loss factor [loss tangent ($\tan\delta$) is around 0.07 at 2.45 GHz] that compromises the antenna's efficiency [7]. In [4], a stretchable UWB antenna based on an elastic substrate is presented. The design offers a good solution in terms of flexibility and stretchability. However, it involves a complex manufacturing process where the conductors are realized by injecting a room-temperature liquid metal alloy into molded microstructured channels on an elastic dielectric material followed by channel encapsulation. In [5], a conformal exponentially tapered slot antenna based on a 200-μ m liquid crystal polymer (LCP) substrate is reported. The design exhibits excellent radiation characteristics. However, the dimensions (130×66 mm^2) are too large for integration within modern compact and flexible electronics.

In this letter, we present a compact elliptical-shaped UWB monopole antenna for flexible/wearable/conformal applications. The antenna is printed on a 50.8-μmm Kapton polyimide substrate, which is known for its flexibility, robustness, low dielectric loss, and thermal endurance. The antenna is fed by a linearly tapered coplanar waveguide (CPW) to further improve the impedance matching. Moreover, both radiating element and ground plane are printed on the same side of the substrate, which promotes low fabrication cost and complexity in addition to roll-to-roll production. In Section II, we present the description for the proposed design, feed parametric study, fabrication process, radiation characteristics, and comparison to conventional straight CPW-fed design. In Section III, we discuss the performance of the proposed antenna under bending conditions. Finally, conclusions are given in Section IV.

II. Antenna Design and Parametric Study

The design and parametric study of the proposed antenna have been carried out using the full-wave simulation software CST Microwave Studio, which is based on the finite integration technique (FIT) [8]; the final design is further verified using HFSS, which is based on the finite element method (FEM) [9].

A. Choice of Substrate

To comply with flexible technologies, constituent elements need to express high flexibility and robustness and exhibit high tolerance against bending and twisting repeatability. The

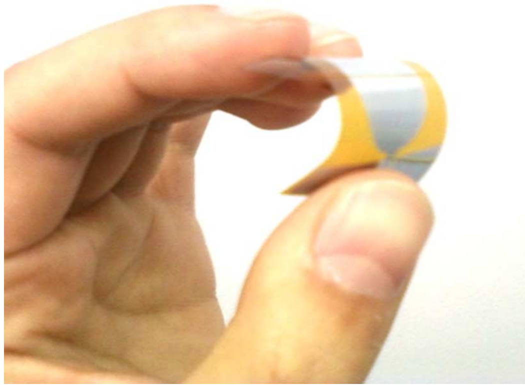

Fig. 1. Polyimide-based ultrawideband flexible antenna.

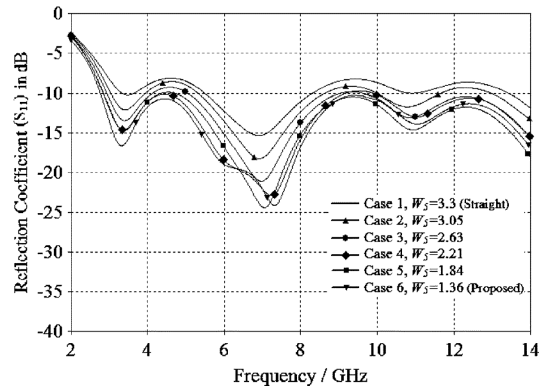

Fig. 2. Parametric study of the CPW feed tapering.

choice of polyimide Kapton as the antenna's substrate (prototype shown in Fig. 1) was due to its good balance of physical, chemical, and electrical properties, which is characterized by a low loss factor over a wide frequency range. Moreover, Kapton polyimide offers a very low profile (50.8 μm), yet is very robust with a tensile strength of 165 MPa at 73°F, a dielectric strength of 3500–7000 V/mil, and a temperature rating of -65°C to 150°C [10].

B. Antenna Design and Numerical Investigation

The radiation mechanism of planar UWB monopoles is a widely studied subject and has been extensively investigated [11]. As is well known, the operation of these antennas can be explained by the overlapping of closely spaced resonances. The proposed antenna is based on an elliptical-shaped radiating element. By tuning the major axis of the radiator, the resonant frequency of the dominant mode can be constrained to cover the 2.45-GHz Industrial Scientific Medical (ISM) band to provide extra band usability in addition to the standard (3.1–10.6 GHz) UWB frequency range. The proposed antenna is fed using a CPW, which adds a merit of fabrication simplicity since the radiating element and ground plane are printed on the same side of the substrate.

A good impedance matching in UWB antennas can be a challenging task in practice. It should be noted that there are several factors that control the impedance matching, such as the ground plane and feed line configuration, substrate thickness, and dielectric properties. In general, elliptical and circular radiating elements can be thought to operate as a frequency-dependent load in series with the transmission line. In [6], two microstrip transitions between a 50-Ω feed and a circular radiating element are introduced to improve both the impedance matching and bandwidth of a UWB antenna. The high real part of the input impedance accompanied by small reactances that alternate sign with frequency are responsible for achieving a good impedance match. This controlled resonance was attained by the added matching transitions. However, the design reported in [6] is based on a partially grounded microstrip line. Such transitions have also been proved to minimize the return loss and improve the bandwidth in microwave circuits [12]. A variation of this technique is used in this letter, where the central conductor of the CPW is linearly tapered to provide a smooth impedance transition that exhibits a reduction in the return loss compared to a straight CPW feed. It should be noted that partial tapering to the CPW feed line would not be effective and would lead to degradation in the impedance matching. For example, in [13], only the upper part of the central CPW conductor is tapered, which degraded the matching around the center of the (3.1–10.6 GHz) UWB range.

First, we started with the conventional (straight) case as a reference. Next, a parametric study is performed on the dimension of W_5, which controls the tapering degree. The parameters L_2 (ground plane length) and G_1 and G_2 (radiating element and feed gaps) are maintained fixed after obtaining best matching in the original case. As can be inferred from Fig. 2, optimal width of W_5 leads to a minimized return loss. It should be noted that further width reduction gives rise to a new resonance minimum accompanied by a matching degradation in the 5-GHz region.

It is worth mentioning that we have investigated the same geometry proposed in this letter but based on a partially grounded microstrip line. It was found that this technique is not practical with such low thicknesses since the impedance matching of this type of feeding is highly dependent on the trace width/substrate thickness ratio as can inferred from [14]

$$Z_{\mathrm{o}} = \frac{120\pi}{\sqrt{\varepsilon_{\mathrm{eff}}\left\{\frac{w}{h} + 1.393 + 0.677 \times \ln\left(\frac{w}{h} + 1.444\right)\right\}}} \qquad (1)$$

where Z_{o} is the characteristic impedance, w is the trace width, and h is the substrate height. For example, to achieve a 50-Ω impedance on a 50.8-μm substrate and a dielectric constant of 3.4, the line width is required to be 140 μm, which obviously is impractical to implement/utilize in addition to the partially added thickness to the antenna structure and fabrication/printing complexity since it involves both sides of the substrate. Dimensions of the proposed antenna are as follows (all in millimeters): $L_1 = 34$, $L_2 = 13$, $W_1 = 33$, $W_2 = 14$, $W_3 = 15.2$, $W_4 = 3.3$, $W_5 = 1.1$, $G_1 = 0.85$, $G_2 = 1.2$, $D_{\mathrm{maj}} = 33$, $D_{\mathrm{min}} = 22$. The geometry of the final design is depicted in Fig. 3.

C. Fabrication

The radiating element along with the CPW was printed on a 50.8-μm flexible Kapton polyimide substrate with a dielectric constant of 3.4 and a loss tangent of 0.002. A conductive

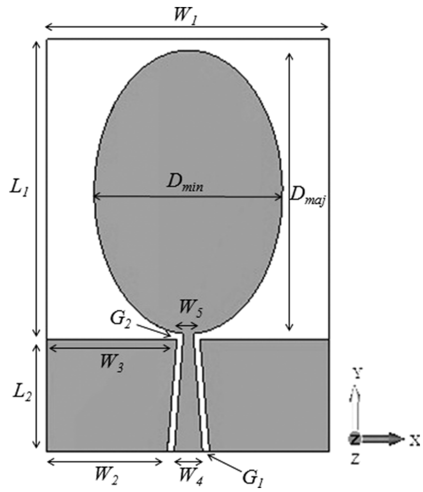

Fig. 3. Geometry and dimensions of the proposed elliptical monopole-based UWB antenna.

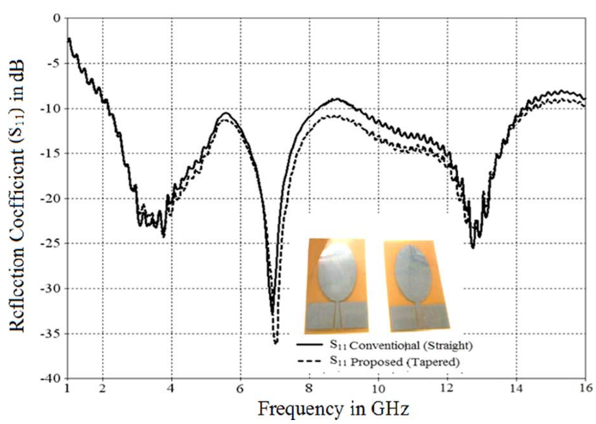

Fig. 4. Measured S_{11} for the proposed tapered CPW-fed antenna and the conventional one based on straight CPW feed line.

ink based on sliver nanoparticles is deposited over the substrate by a Dimatix DMP 2831 inkjet material printer followed by a thermal annealing at 100°C for 9 h by an LPKF Protoflow industrial oven. It should be noted that three layers of ink were jetted on the substrate to achieve a robust and continuous pattern. The three CPW conductors were affixed to an SMA connecter.

D. Performance and Comparison

For comparison purposes, the return loss/impedance matching of the proposed antenna is compared to an identical geometry fed with a straight CPW feed. The antennas' S-parameters were obtained using an Agilent PNA-X series N5242A Vector Network Analyzer (VNA).

As expected from the numerical investigations, an improved impedance matching over the 2.2–14.3-GHz frequency range is observed as seen in Fig. 4, while on the other hand, the conventional antenna design exhibits a matching degradation around the 8.2–9.6-GHz region in which the return loss exceeds the 10-dB standard limit.

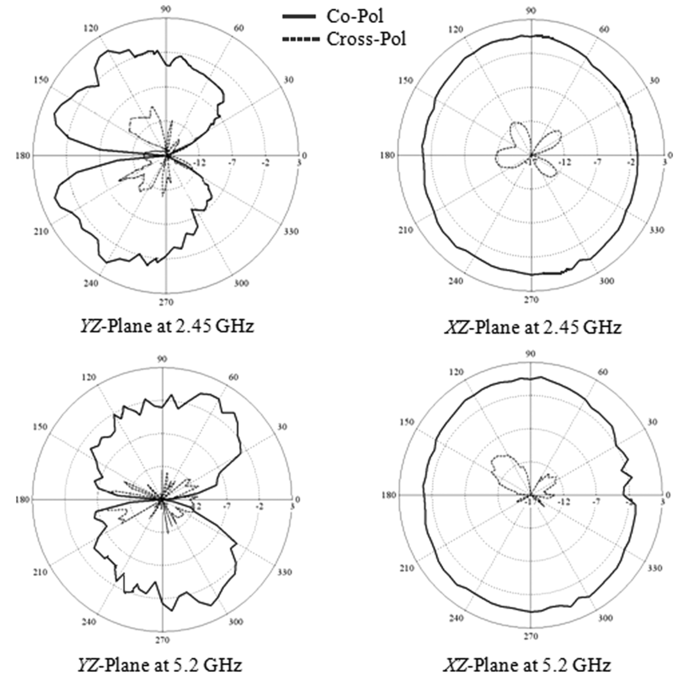

Fig. 5. Measured co- and cross-polarization far-field radiation patterns in the yz- and xz-planes at 2.45 and 5.2 GHz, respectively.

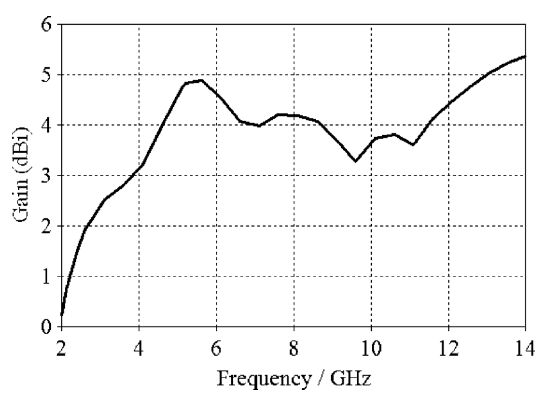

Fig. 6. Peak gain across the operational bandwidth of the proposed antenna.

E. Radiation Characteristics

The far-field radiation patterns of the principal planes (E- and H-) were measured inside the University of Arkansas at Little Rock's anechoic chamber. The antenna under test (AUT) is placed on an ETS Lindgren 2090 positioner and aligned to a horn antenna with an adjustable polarization where both co- and cross-polarization patterns can be obtained. Radiation patterns of the proposed antenna at 2.45 and 5.2 GHz in the yz-plane (E-plane) and xz-plane (H-plane) are depicted in Fig. 5. It can be observed that the antenna retains a reasonable omnidirectional radiation patterns at both frequencies.

The simulated gain versus the operational frequency of the proposed antenna is illustrated in Fig. 6. It is found that the gain variation is within 2 dB in the standard UWB 3.1–10.6-GHz band. Gain values are around 1.7 dB in the 2.45-GHz ISM band.

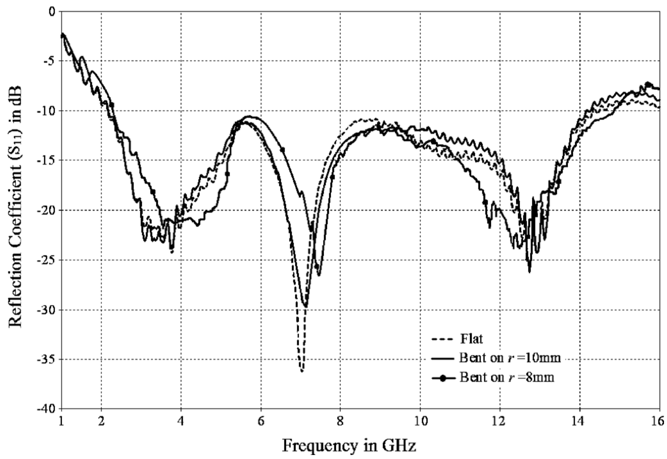

Fig. 7. Measured S_{11} for the proposed antenna bent on a foam cylinder with two different radii compared to the flat case.

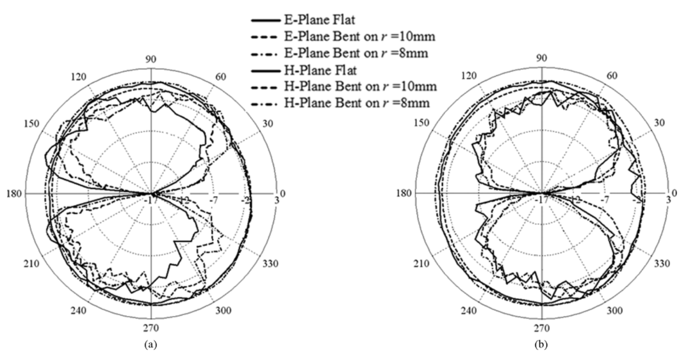

Fig. 8. Measured E-plane (yz-cut) and H-plane (xz-cut) far-field radiation patterns at (a) 2.45 and (b) 5.2 GHz, under bending conditions.

III. Flexibility Tests

Since the antenna is expected to be bent and rolled when integrated within flexible electronic devices, bending tests are performed to ensure practical operability. To test the performance of the antenna under different bending extents, the AUT was rolled on foam cylinders with two radii ($r = 10$ mm and $r = 8$ mm) to emulate different extents of bending. The proposed antenna exhibits a very low susceptibility to impedance mismatch and resonant frequency shift due to bending effects. The reflection coefficient S_{11} is maintained below -10 dB in both cases, while a shift of less than 50 MHz ($< 0.4\%$) in the resonant frequency is experienced in the first resonance crossing (2.2-GHz region). Fig. 7 depicts the reflection coefficient of the bent antenna compared to the flat case.

Furthermore, the effect of bending on the far-field radiation pattern is also investigated. Fig. 8 shows the effect of bending on the radiation patterns of the proposed antenna for both bending extents and frequencies under consideration.

It is evident that the antenna maintains its omnidirectional radiation pattern despite being conformed on the foam cylinders.

The flexibility performance of the proposed antenna is compared to the designs reported in [15]–[17]. In [15], a band-notch UWB antenna printed on a Polyethylene Terephthalate (PET) film experiences a notch shift of 28% to a higher resonant frequency when the antenna is bent on a cylinder of 10 mm radius. In [16], the performance of a broadband flexible comb-shaped antenna is investigated; a 14% shift in the resonant frequency is experienced when it is rolled. In [17], a flexible folded slot planar dipole encounters a shift to a lower resonance when subjected to bending. However, the bandwidth is maintained the same. Obviously, the design proposed in this letter exhibits a very low susceptibility to performance degradation due to bending in terms impedance mismatch, shift in resonant frequency, and distortion in radiation pattern.

IV. Conclusion

In this letter, a flexible low-profile UWB antenna is presented. The proposed design is based on a Kapton polyimide substrate that is known for its flexibility, robustness, and low dielectric losses. The radiating element is fed by a transitional CPW feed line that enhances the impedance matching along the frequency range under consideration. Furthermore, the proposed antenna is tested under bending effects and exhibits a very low susceptibility to performance degradation in terms of impedance matching and radiation pattern. Flexibility, robustness, compactness, fabrication simplicity, along with good radiation characteristics and improved impedance matching suggest that the antenna is a reasonable candidate for the targeted application.

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