Patch Antenna Bending Effects for Wearable Applications: Guidelines and Design Curves

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***Abstract*—This paper presents a systematic investigation on the bending effects of wearable rectangular patch antennas. Design curves are generated for the resonant frequency variations and radiation pattern variations by simulating patch antennas that are bent on cylindrical surfaces by different angles. A frequency shift vs. bending radius plot has been generated to target on antennas for varies wearable applications.**

I. Introduction

The emerging applications for wearable electronics have experienced enormous market growth over the last decade [1]. Antennas, being one of the critical components in modern wireless devices, need to be specifically designed to function while being worn and bent.

In this study, we present a systematic and comprehensive investigation of the bending effects of wearable rectangular patch antennas. The resonant frequency and radiation pattern variations have been studied by simulating patch antennas in a full-wave model. A frequency shift vs. bending radius plot has been generated to target antennas for various wearable applications. It has been shown that the bending angle vs. normalized frequency shift is a universal criterion that remains consistent over frequency scaling, and is thus suitable for comparing the bending robustness among various types of antennas. One of the main objectives of this work is to generate useful design curves to help antenna engineers for wearable applications to incorporate the effects of bending more efficiently.

II. Modeling of Patch Antenna Bending

We characterize the antenna bending by the bending angle, which is defined as the angle of arc formed by bending one dimension of the patch over a cylinder with radius of R, as illustrated in Fig. 1 (a). An antenna model has been built in full-wave simulator HFSS, in which the bending angle is varied from $0°$ (flat) to $90°$ (severely curved). The patch antenna studied in this work is a simple $\lambda/2$ (corresponding to wavelength in the substrate) rectangular patch antenna at the frequency of $f = 2.49$ GHz, with the patch dimensions L = 39.5 mm and W = 50 mm. The substrate of the patch antenna has been modeled with dielectric constant of $\epsilon_r = 2.1$ and thickness of h = 1 mm, corresponding to the material properties of cotton substrate. Two types of bending in the two principle planes are identified as E plane bending (bent along the length dimension) and H plane bending (bent along width dimension), as illustrated in Fig. 1 (b) and (c), respectively.

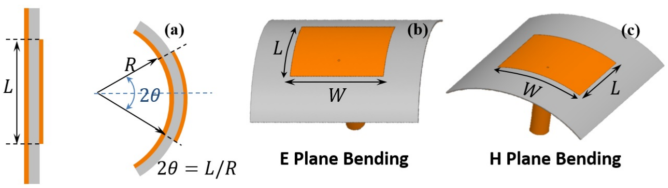

Fig. 1. Characterization of rectangular patch antenna bending effects. (a) The illustration of bending angle 2θ and bending radius R. The E plane bending and H plane bending cases are shown in (b) and (c), respectively. The patch dimensions L and W are kept constant as 2θ and R are varied throughout the study.

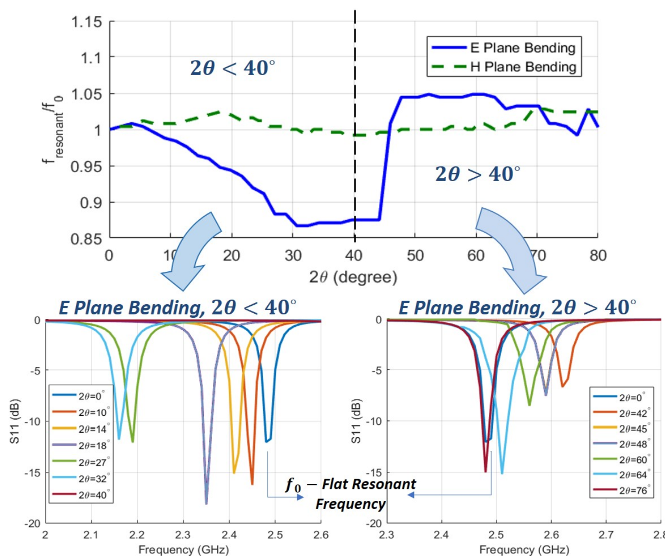

Fig. 2. Frequency variations of the bending effects on both E and H plane. The normalized frequency shift is plotted with respect to bending angles for the rectangular patch antennas. The E plane frequency shift due to bending splits into two regions, with left shift on slightly bent region ($2\theta < 40°$), and right shift on severely bent region ($2\theta > 40°$).

III. Frequency Variations of Bending Effects

Fig. 2 illustrates the effects on the resonant frequency shift as the antenna being bent by different angles 2θ along E and H planes. The bending angle has been varied from $0°$ (flat case) to $90°$, and resonant frequency f_{res} has been normalized by the flat condition resonant frequency f_0 and plotted for

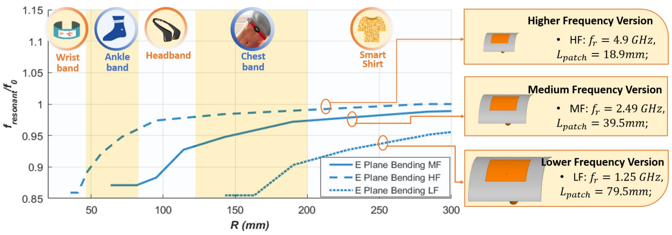

Fig. 3. Normalized frequency shift (f_{res}/f_o) with respect to bending radius R, targeting at various potential wearable applications.

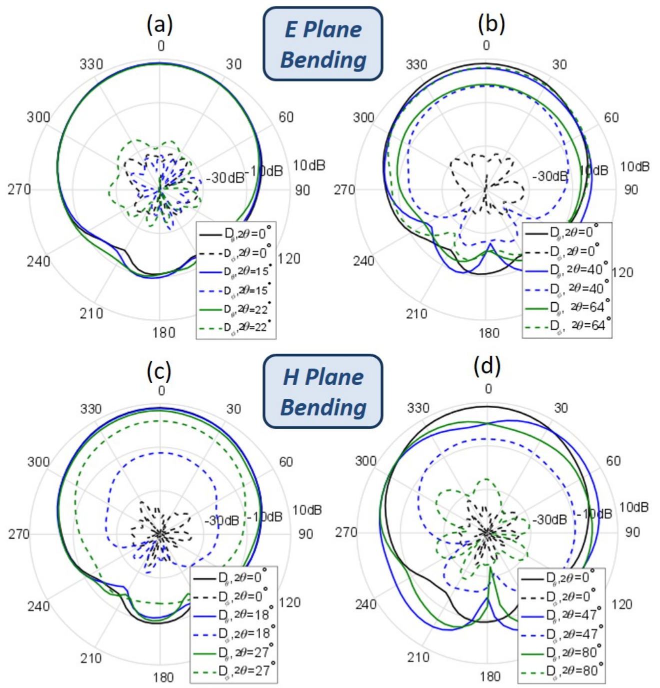

Fig. 4. Radiation pattern variations with respect to bending angles for E plane bending in (a) and (b), and H plane bending in (c) and (d).

each case. Observation of the E plane bending effect in Fig. 2 reveals that the frequency shift phenomenon splits into two regions. For bending angle $2\theta < 40°$ (slightly bent) the resonant frequency shifts left, while for bending angle $2\theta > 40°$ (severely bent) the resonant frequency shifts right (as shown in Fig. 2 (b) and (c), respectively). It also shows that E plane bending generates up to $\pm 15\%$ of normalized frequency shift, while the effect of H plane bending is less than $\pm 4\%$, since the E plane bending affects the path of resonance more significantly than H plane does [2].

To investigate the effect of bending on patch antennas operating at different frequencies in their flat condition, the original antenna topology with flat-condition resonance at 2.49 GHz has been scaled in size to create another two patches, with the resonant length corresponding to a higher frequency band (L_{patch} = 18.9mm for f_0 =4.9 GHz) and a lower frequency band(L_{patch} = 79.5mm for f_0 = 1.25 GHz). W_{patch} and thickness h are also scaled accordingly. The three different antennas which resonant at 1.25, 2.49 and 4.9 GHz are denoted as LF (low-frequency band), MF (middle-frequency band) and HF (high-frequency band), respectively.

To target the bending effect on various potential applications, the normalized resonant frequency has been generated with respect to the bending radius, as shown in Fig. 3, where the frequency shift for the antennas corresponding to three different flat-condition resonant frequency bands are separated from each other. According to results given in Fig. 3, choosing smaller antenna with higher resonant frequency is in general an effective way to enhance antenna bending robustness for applications that require severe bending. Also, for the same bending angle, the normalized frequency shift occurs almost identically for the three antennas with size and flat resonant frequency scaled accordingly. It proves that the bending angle vs. normalized frequency shift is a universal criterion that remains consistent over frequency scaling, and is thus suitable to be used to compare the bending robustness among various types of antennas.

IV. Pattern Variations of Bending Effects

Fig. 4 shows the simulated radiation pattern for the 2.49 GHz patch antenna configuration. For slight bending in E plane (Fig. 4 (a)) the co-pol radiation pattern (D_θ) is similar to the pattern in flat condition, with the cross-pol (D_ϕ component) remaining in a decent level. For severe bending in E plane (Fig. 4 (b)) the co-pol pattern deviates from the flat condition and cross-pol increases significantly, which results in poor resonance. As observed in Fig. 4 (c) and (d), although the resonant frequency is not significantly affected by H plane bending, the radiation pattern is broadened at bending angles $2\theta = 47°$ and $2\theta = 80°$, and the cross-pol arises even at small bending angles $2\theta = 18°$ and $2\theta = 27°$. We also observed a radiation efficiency degradation from 91.3% to 87.5% with 63° bending, for $h = 1$mm.

V. Conclusions and Future Works

In this work, we investigate the bending effects of wearable rectangular patch antennas by simulations with bending angles from 0° (flat) to 90° (severely curved). We scaled the patch antenna into three versions to study the effects of antenna size and original operating frequency. Shifting of the resonant frequency and variations in radiation patterns has been investigated. Future works include analytical interpretations of the simulation results, measurements for different bending angles, and investigations on the effects of materials (e.g. eletro-textiles). The main objective of the work is to generate useful design curves that provide a better understanding of the effects of bending on antenna performances.

Acknowledgement

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