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A Modular Textile Antenna Design using Snap-on Buttons for Wearable Applications

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Abstract—An antenna design concept with detachable radiation elements offering modular geometry reconfigurabilities for wearable applications is presented. By utilizing snap-on buttons both as the radio frequency (RF) connection and mechanical holding mechanism, different modularly interchangeable microstrip patches are employed to demonstrate geometry reconfigurabilities in terms of polarization and resonance frequency. The uniqueness of the design arises from the fact that all configurations share one common feed structure which consists of a two-layered substrate including snap-on buttons, a ground plane and a proximity coupled feed. To show the concept, modular realizations with different functionalities in terms of polarization or resonance frequency are demonstrated in this paper. Firstly, a detachable patch offering interchangeable right hand circular polarization (RHCP) and left hand circular polarization (LHCP) at 5 GHz is proposed. Secondly, a demonstration of a planar inverted-F antenna (PIFA) concept offering interchangeable resonance frequencies for the 2.4- and 5.3-GHz bands of wireless local area networks (WLAN) is given. Finally a patch module designed for 8 GHz operation is presented to show the versatility in frequency modularity. Experimental results of the fabricated antennas in free-space, worn by a torso phantom and in bending conditions, validate the concept and prove that this type of modular design offers convenient, passive, low cost and versatile system reconfigurabilities which can benefit wearable applications.

Index Terms—Modular antennas, wearable antennas, textile antennas, snap-on button.

I. INTRODUCTION

In recent years, flexible and wearable antenna designs have received significant attention due to the dramatically increasing demands in various wearable electronic systems [1], [2]. Applications include mobile communications, wireless medical monitoring/diagnosing and military applications [3], [4]. Besides conventional antenna requirements, wearable antennas are expected to be flexible, lightweight, low-cost and garment-integratable [5], [6]. As a result, conductive textiles have been emerging as one of the most promising conducting materials [7], [8]. Many wearable devices made from conductive textiles such as patch antennas [9]–[11] and arrays [12], ultra-wideband [13], [14] and ultra-wideband-notched [15] antennas, as well as antennas based on fundamental mode [16] and half-mode [17], [18] substrate-integrated waveguides have been reported. Moreover, clothing closure accessories have been exploited as support for antenna design. For example, metallic buttons for textiles have been designed as wearable antennas [19], [20], and commercial metallic snap-on buttons also have been proposed as a practical and economical radio frequency (RF) connection solution for wearable systems, since they can form detachable RF connection with suitable RF performance [21]–[23]. This leads to the idea of making specific radiation elements detachable with snap-on buttons to achieve modular antenna designs, thus enabling passive reconfigurability of the overall system. Although this requires manual operation, passive reconfiguration promotes ease of antenna design [24] and versatile wearable antenna integration since no active components and bias circuits are needed.

Modular antenna designs have been proposed in various wireless communication systems such as mobile phones [25], cellular communication base-stations [26] and avionics systems [27]. They can be categorized into two main groups according to their modular antenna elements, namely identical and different modular antenna elements. Typically, identical modular antenna elements are employed as building blocks for antenna array designs [26], [28]. With such modular designs, the array dimensions can be easily reconfigured. On the other hand, modular designs with different antenna modules can be found in systems featuring interchangeable antennas which share one common feed design [25], [27], [29]. These antenna modules are usually of same outline geometry to satisfy the requirements of same fitting and feeding, even if they are serving different functionalities. Such modular antenna designs bring valuable advantages including low manufacturing cost, easy maintenance and most importantly passive system reconfigurability.

In this paper, a modular antenna design based on metallized fabric and flexible low-permittivity foam substrate is presented for wearable applications, providing possible system reconfigurabilities for polarization and resonance frequency. Commercial snap-on buttons are employed as RF connectors and mechanical fixtures to enable easy detachability of the modular antenna radiating elements. Various types of antenna functions can be conveniently achieved by flipping-over, interchanging or ground-shorting the patch modules. To demonstrate the concept, three patch modules offering interchangeable circular polarizations and resonance frequencies for 5 GHz, WLAN 2.4-GHz, 5.3-GHz (IEEE 802.11) bands and 8 GHz in the X-band have been designed, realized and tested. These frequencies are chosen as representative examples, but the...
Figure 1. The proposed modular antenna and its configuration. The antenna includes a common antenna base and an interchangeable patch module designed for a specific functionality. The patch module is mounted on a common base which consists of a ground plane, two layers of substrates, an open-end microstrip proximity coupled feed and five snap-on buttons. Four snap-on buttons are used as mechanical fixtures for the various patch modules, whereas the fifth optional button is utilized as RF connector to create a short in a PIFA configuration. Various functionalities are fulfilled with dedicated patch modules.

Interchangeable modular radiating patch dedicated to a specific application and a common base which includes a microstrip proximity coupled feed, a two-layered substrate and five commercial snap-on button connectors. In this paper, 5 GHz, WLAN 2.4- and 5.3-GHz (IEEE 802.11) bands as well as 8 GHz in the X-band have been chosen as the designed antenna operation frequencies for illustration. But it is emphasized that the concept is not limited to these frequencies.

A. Antenna Structure and Material

To obtain flexibility without sacrificing conductivity, the radiating patch elements, the microstrip feed and the ground plane are made from a silver-coated nylon RIPSTOP fabric (commonly denoted as silver fabric) with a dc sheet resistance of 0.01 Ω/□ and a thickness of approximately 100 µm. The various patches can be fixed on top of the common base with four pairs of engaged snap-on buttons which provides detachability and consequently interchangeability. For the same reason, a proximity-coupled feed is adopted for the generic design since the physical separation between feed and radiating element permits a free-standing detachable patch. The substrate contains two layers of 1.6-mm-thick highly flexible Cuming Microwave C-Foam PF-4 foams with relative permittivity $\varepsilon_r = 1.06$ and loss tangent $\tan \delta = 0.0001$. This two-layer structure serves two functionalities including antenna elements separation and strict immobilization of snap-on buttons. An open-ended microstrip line serving as the antenna feed and four male snap-on buttons serving as the patch fixtures are embedded between the top- and bottom-layer substrate. Note that the top-layer substrate is cut with four holes for the snap-on button male pin to go through. A fifth female snap-on button placed to provide a shorting post for a proposed planar inverted-F antenna (PIFA) configuration is sewed onto the ground plane using conductive threads and thus a hole is individually trimmed through both substrate layers to accommodate it.

B. Snap-on Buttons

The snap-on buttons are the key components which mechanically and electrically enable low-cost and practical detachability and interchangeability for the patch modules. The chosen commercial snap-on buttons and their main dimensions are both included in Fig. 2. On the one hand, they are selected as mechanical fixtures since their size are appropriate for the patch modules, and more importantly, they offer solid mechanical performance. A dedicated test done in [23] indicates that

![Table I: Dimensions of the common antenna base and the outlined dimensions of the radiating patch modules.](image)
C. Patch Modules

Since the radiation element is detachable and interchangeable, different patch modules can be designed to serve various functionalities. Moreover, this feature can benefit a low maintenance cost since easy servicing and economical repair can be achieved by direct component replacement. For illustration purpose, three different types of patch modules are designed to achieve five interchangeable functionalities in terms of polarization and resonance frequency respectively. The first two modules are single-layer structures and can serve two functionalities individually: As shown in Fig. 3-(a), the first patch module aims at providing RHCP or LHCP at 5 GHz, depending on the orientation of the diagonal slot. The second patch module shown in Fig. 3-(b) can resonate either at 2.45 or 5.3 GHz which is controlled by its orientation and the engagement of a shorting button to create a PIFA operation (Fig. 1). In contrast, the third patch module only provides a single functionality but with a higher degree of freedom in terms of module design: An illustrative example is designed for operation at 8 GHz and requires a two-layered structure, as shown in Fig. 3-(c). This last arrangement structure offers more freedom in module design, however, at the cost of additional complexity.

The alignment and the attaching/detaching repeatability of these patch modules are critical for the antenna performance and thus particular attention is required with regard to the module design. Firstly, the silver fabric is chosen for the module materials as it is conductive, flexible and, more importantly in this case, robust enough to remain undistorted for numerous interchange of modules. Secondly, four positioning holes are created in the modular patches to ensure an accurate module alignment with the male buttons embedded in the top substrate layer. These holes are precisely cut using a laser milling machine. To tightly confine the module alignment with the button fixtures, the hole radius is determined to be 0.7 mm which corresponds to the exact dimension of the neck of the male pin. Very stable alignment and attaching/detaching repeatability have been observed during the measurement campaign for the most-frequently-used modules.

The outlined geometry and the other dimensions of these patch modules can be found in Table I and II, respectively. All simulations are performed with CST Microwave Studio 2014 (CST). The design process starts with the circularly polarized patch modules, since matching to the feeding structure is the most challenging to achieve compared to the other modules.

1) Patch module for 5-GHz orthogonal circular polarization: Initially, as expected for a rectangular microstrip antenna design on unit permittivity substrate, the patch dimensions are set to be a half of the wavelength at the chosen operating frequency. The patch is then tuned to obtain approximately a 5% higher resonance frequency which will compensate the influence from the diagonal slot introduced later. To achieve circular polarization, the method using a diagonal slot perturbation is selected and initial dimensions of the slot are determined using formula (8.20) given in [30]

$$\left| \frac{\Delta A}{A} \right| = \frac{1}{2Q_0}.$$  \tag{1}$$

This formula is utilized to find out the initial slot dimensions, where $\Delta A$ is the slot area ($L5 \times W5$), $A$ is patch area ($L2 \times W2$) and $Q_0$ is the antenna unloaded quality factor. The value of $Q_0$ is estimated through the fractional bandwidth ($\Delta f/f_0$) and the voltage standing wave ratio (VSWR) obtained from simulation results using the relationship [31]

$$\frac{\Delta f}{f_0} = \frac{VSWR-1}{Q_0 \sqrt{VSWR}}.$$  \tag{2}$$

Consequently the only unknown $\Delta A$ can be determined accordingly as a starting value. An optimal slot dimension combination which yields a nearly 0-dB axial ratio (AR) is then gained through parameter sweeps in CST. Because of the introduction of the diagonal slot, the resonance frequency is now lower and consequently closer to 5 GHz. Subsequent tuning of $L1$ and $W1$ is required to achieve a maximum
impedance bandwidth and an AR below 1 dB, both centered at 5 GHz. Finally, the length of the open microstrip feed is adjusted for best impedance matching. It is worth mentioning that since the microstrip feed line is fixed from this point on, matching techniques for all subsequently designed patch modules will require extra effort. The antenna loaded with the designed patch, as shown in Fig. 4-(a), provides RHCP while in contrast the one shown in Fig. 4-(b) provides LHCP. The circular polarization is easily interchangeable by flipping the patch accordingly.

2) Patch module for 2.45- and 5-GHz WLAN operation: As illustrated in Fig. 1 and Fig. 4-(c), a fifth female snap-on button sewed onto the ground plane can be engaged to a male counterpart to form a patch-to-ground electrical shorting. As a consequence, the antenna operates then as a PIFA antenna (quarter-wavelength patch), as shown in Fig. 4-(c), instead of the standard half-wave microstrip patch configuration as shown in Fig. 4-(d). The two resonance frequencies are generally both inversely proportional to the patch length $L_2$ and the lower resonance frequency (PIFA) is also additionally dependent on the shorting button’s vertical position $S$. It is worth to mention that once the circular module design is completed, the outline ($L_2$ and $W_2$) is determined for all other patch modules which are made of a single layer structure, in contrast to the two-layered 8-GHz module. Therefore, $S$ is utilized to tune the lower resonance frequency. Furthermore, transverse slots can be introduced within the patch to individually adjust the higher resonance frequency. Since the resonance frequency tunability is important for obtaining various system reconfigurability, three of this module variations with different transverse slots have been fabricated and tested to verify the prediction. As displayed in Fig. 5, a 2-mm wide slot with different length of 6, 10 and 14 mm was introduced in three identical modules respectively.

As mentioned previously, the microstrip feed has been optimized for the circularly-polarized patch and thus cannot be changed. Therefore, matching technique needs to be applied to the patch modules in this case. To match the antenna in PIFA configuration, a rectangular notch with dimensions $L_6 \times W_6$ is required, as shown in Fig. 3-(b). This notch reduces the capacitance between the patch and the microstrip feed and hence compensates the capacitance decrease in the patch input impedance due to the ground shorting. For the half-wave configuration, a satisfactory matching is achieved by a rotation of the patch module bringing the edge without notch down, and thus leading to a similar input impedance as the circularly polarized module. The antenna in quarter-wave and half-wave configurations are illustrated in Fig. 4-(c) and (d) individually. Switching between two resonance frequencies, 2.45 GHz and 5.3 GHz, is accomplished via a simple rotation of the patch and engaging (or disengaging) the shorting snap-on button. In addition, the antenna loaded with the half-wave patch with a transverse slot of length of 10 mm is shown in Fig. 4-(e).

3) Patch module for 8-GHz X-band operation: This module consists of one layer of non-conductive fabric as a support with
the same outline geometry as the other patches and one layer of silver fabric as a radiation element resonating at 8 GHz. This two-layered arrangement provides a more adaptable way for patch module design since the radiating element has more freedom in terms of size and shape selection, while the non-conductive fabric ensures mechanical fixture. The supporting fabric was chosen as cotton textile commonly used for embroidery. The fabric has a measured thickness of approximately 200 μm, as well as a relative permittivity $\varepsilon_r = 2$ and a loss tangent $\tan \delta = 0.01$ both estimated based on fitted simulation results, which broadly agree with the measured values for cotton textiles in [32], [33].

As anticipated, the vertical length $L7$ of the radiating element is inversely proportional to the resonance frequency. The bottom of the radiating element is tapered as a triangle to get a satisfactory matching. The antenna loaded with this patch is illustrated in Fig. 4-(f). Owing to the vicinity to the radiating element, coupling to the snap-on buttons should be taken into account in the design. This can be done with simulation tools and complicated current distributions have been observed in simulated results. Moreover, the radiating patch is facing down towards the substrate to avoid galvanic contact with the two closest female buttons.

4) Other possible functionalities: With a two-layer structure like the 8-GHz patch module, more functionalities can be fulfilled. For instance, an array of small patches can be possibly designed using this type of structure. Other patch module designs offering multiple-band or wide-band performance as well as switchable skewed beam directions can be designed through additions of slots and snap-on shorting posts. Various such further possibilities have been explored through simulations, but have not been validated experimentally and thus are not presented here for the sake of brevity. The possibilities of this modular antenna design are wide ranging in terms of variety of achievable antenna characteristics.

III. Experimental Results

For validation of the modular concept, the proposed antenna designs have been fabricated and experimentally characterized. Since the devices are designed for wearable applications, the impacts of human body proximity and bending have been investigated as well. In particular, the antenna loaded with the 5-GHz LHCP patch was utilized for a bending study as well as for the characterization on a human torso phantom, as this design is the most sensitive to tolerances.

To achieve accurate patterning of the geometry, the patch modules and microstrip feed are cut with a laser milling machine (LPKF: Protolaser S). A dedicated fixture is used to trim holes in the substrates and align the feed line and snap-on buttons onto the bottom substrate. Machine-washable fabric glue, Wash N Wear Glue White from Helmar®, is applied to attach the ground plane to the substrate, the microstrip feed/buttons to the bottom substrate, the top substrate to the bottom substrate, and the radiation patch to its fabric substrate. As only a very thin layer of the glue is required to form a permanent and solid bond, its influence on the antenna performance is deemed negligible and can be best taken into account as a slight increase in the conductor loss of the metalized textile. Conductive epoxy is adopted to mechanically and electrically connect a SMA connector to the microstrip feed. The conductive epoxy applied is the CW2400 from CircuitWorks® which offers high strength bond and excellent electrical connection with a very low volume resistivity of 0.1 $\Omega\cdot m$.

A. Antenna loaded with circularly-polarized patch module

As illustrated in Fig. 6, the measured reflection coefficients for the antenna loaded with the circularly polarized modules show a reasonable agreement with the simulated values. The measured $|S_{11}|$ parameter of the antenna yields a -10-dB impedance bandwidth from 4.75 to 5.25 GHz for the LHCP configuration and from 4.80 to 5.35 GHz for the RHCP one, which covers the target center frequency of 5 GHz. The difference is indicative of fabrication tolerances.

The simulated and measured boresight axial ratios of the antenna in free space are compared in Fig. 7 and they exhibit a very good agreement. The 3-dB axial-ratio bandwidth is from 4.95 to 5.08 GHz for the LHCP configuration and from 4.95 to
5.06 GHz for the RHCP one, both centered at approximately 5.01 GHz. The whole 3-dB axial bandwidth (of 2.2%) is covered by the -10-dB impedance bandwidth (of 10%), which indicates that circular polarization is achieved as designed.

The normalized radiation patterns in xy-plane (H-plane) and yz-plane (E-plane) have been obtained through measurement in an anechoic chamber. The radiation patterns of the LHCP and RHCP antennas in free space are shown in Fig. 8. For the LHCP antenna, the desired left-handed polarization (co-polarization) has an approximately 20-dB power higher level over the unwanted right-handed polarization (cross-polarization). Due to symmetry, similar radiation patterns are obtained for the RHCP antenna configuration, but with a predominant right-handed polarization rather than the left-handed one. As anticipated for a microstrip patch antenna, all these patterns exhibit a main lobe directed in positive z direction with some small back lobes with amplitude dependent on ground plane size. In addition, a realized gain of 8.0 dBi has been measured for the LHCP antenna and this result is very close to the simulated value of 8.1 dBi.

### B. Antenna loaded with patch module for WLAN

The measured $|S_{11}|$ parameters of the antenna loaded with linearly polarized patches are largely in accord with simulations, as depicted in Fig. 9. The antenna with PIFA configuration has an impedance bandwidth of around 100 MHz centred at 2.45 GHz. The half-wave patch resonates at 5.33 GHz with an impedance bandwidth extending from 5.18 to 5.48 GHz.

Now considering the half-wave patches with an added transverse slot, their measured and simulated reflection coefficients are displayed in Fig. 10, showing reasonable agreement. As expected, the patch with the longest slot (14 mm) yields the lowest resonance frequency at 4.72 GHz while the highest resonance frequency 5.26 GHz is held by the one with the shortest slot (6 mm). The resonance frequency in the middle corresponds to the patch with a slot of length of 10 mm. Theoretically the resonance frequency can be further decreased by extending the slot length or introducing more slots [30].

The measured normalized radiation patterns are shown in Fig. 11. The patterns of the standard half-wave patch are as expected for this type of antenna, whereas the patterns of the quarter-wave patch show a degradation typical for PIFA antennas, with less directivity and increased cross-polarization. The measured antenna gain for the half-wave and quarter-wave patches are 7.8 dBi and 3.1 dBi, respectively. These values are close to the simulated results of 8.3 and 3.5 dBi.
C. Antenna loaded with patch for X-band

In contrast to the previous modules, this configuration only serves one functionality, however, it illustrates a higher degree of flexibility and an implementation at a higher operation band. The measured and simulated reflection coefficients have a good correspondence, as demonstrated in Fig. 12. The antenna resonates at 8 GHz with a bandwidth of approximately 500 MHz. The measured normalized radiation patterns are portrayed in Fig 13, and as expected, standard half-wave patch radiation patterns are observed, which is confirmed by the simulated electric field distribution of the antenna shown in the inset of Fig. 12. The measured antenna gain is approximately 8.9 dBi whereas the simulated one is 9.2 dBi.

D. Human Body Impact

As an important aspect of wearable antennas, the impact on antenna characteristics in the vicinity of a human body has been investigated with a torso phantom. The torso (TORSO-OTA-V5.1 from SPEAG) is an anthropomorphically shaped [34] shell phantom which is filled with a broadband tissue simulating gel complying with human target parameters in [35], [36] up to 6 GHz. The antenna loaded with circularly polarized patch module is chosen in this study due to its high sensitivity in terms of circularly polarized antenna performance. The measured antenna reflection coefficient and axial ratio for the LHCP antenna placed on the phantom are plotted in Fig. 6 and Fig. 7 respectively. For representation of the radiation characteristics in Fig 8, the on-body radiation patterns are normalized to the maximum values in free space, and a slight reduction in LHCP component due to the torso phantom is observed in both planes. This is confirmed with the simulated and measured realized gain of the antenna shown in Fig. 14. In most of the frequency range, there is a reasonable agreement between the antenna realized gain measured in free space and with the phantom. Only a small gain decrement (maximum 0.7 dB) due to the human body is observed in a short frequency range around 5 GHz.

All these results indicate a rather low impact on the antenna performance when worn on the human body. The resilience to degradation when worn on the body is attributed to the isolation effect of the ground plane.

E. Bending Impact

Another critical aspect of wearable antennas is the influence of bending on their performance. To assess this effect, an investigation of the LHCP-patch-loaded antenna under two bending configurations has been carried out. The bending test setup is shown in the inset of Fig. 15: namely bending along the $y$-axis with radius of 30 mm (approximately a forearm radius) and 40 mm (approximately an upper arm radius).
respectively. Practically, bending along the $x$-axis should be avoided since more significant alterations in the effective patch length ($L_2$) and consequently resonance frequency are anticipated [11], [37]. The measured reflection coefficients of the antenna under unbent and two bent configurations are illustrated in Fig. 15. There are no significant variations on the measured $|S_{11}|$ parameters introduced through the antenna bending. This is attributed to the compact size of the antenna leading to minor bending which results in only a small effective antenna length alteration. This result implies that the bending configuration should have a small influence on the impedance bandwidth of both circularly and linearly polarized modules.

In regards to the axial ratio of the bending antenna, the measured results are plotted in Fig. 16. According to the measurements, the axial ratio at 5 GHz is less than 3 dB and 5 dB for 40-mm and 30-mm bending radii, respectively. This degradation of the axial ratio bandwidth is not unexpected and can be caused by the changes in the resonance frequencies and the phase differences of both orthogonal modes [37]. A similar phenomenon for a bent circularly polarized textile antenna has been reported in [11]. These findings suggest that the axial ratio of the antenna is still within an acceptable range with small radius bending. Therefore, the study indicates that the bending effect should still allow operation of the antenna with slightly degraded axial ratio.

IV. CONCLUSION

A modular antenna design for wearable applications has been proposed utilizing commercial snap-on buttons as mechanical and electrical (RF) connectors. Different textile patch modules can be designed to serve various functionalities such as variations in antenna resonance frequency, polarization and possibly beam direction. These modules can be attached to one common proximity-feeding base consisting of ground plane, substrate and open microstrip line. Therefore, this antenna design brings advantages such as low manufacture and maintenance cost, and most importantly, provides a passive way to reconfigure system characteristics for multi-functional wearable systems. Three modules providing interchangeability in circular polarization and resonance bands have been designed, manufactured and experimentally characterized. The measurement results are in very good agreement with simulations. The impact on antenna characteristics due to human body vicinity and small radius bending have also been investigated and the results indicate only an insignificant effect on the reflection coefficient, but some degradations of the circular polarization, which is notoriously sensitive to geometry variation. In addition, other potential patch modules offering interchangeable tilt beam direction and multi-band or wideband performance can be designed. All these findings indicate that, through utilizing modular design with a single feed, a wide range of functionalities can be fulfilled for various applications.

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