A low profile wideband unidirectional antenna for wearable device

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Abstract—In this paper, a wideband wristband antenna for wearable device, characterized by low profile and unidirectional radiation property, is proposed. First, the Theory of Characteristic Mode (TCM) is employed to expound the operation principle of the generation of unidirectional radiation. Then, an appropriate feeding structure is chosen to excite the desired modes. As a result, the corresponding modes are excited and the unidirectional radiation is obtained. Moreover, the desired cellular operation bands (from 1710 MHz to 2155 MHz) are achieved. The total efficiency accompanied with flatness feature are at the levels of -1.5 dB and -6.5 dB in free space and with phantom respectively.

Index Terms—wideband antenna, Theory of Characteristic Mode, wearable antenna.

I. INTRODUCTION

In recent years, two new narrow-band technologies, namely Enhanced Machine Type Communication (eMTC, also referred to as LTE-M) and Narrow Band-Internet of Things (NB-IoT), are emerging based on the conventional cellular data network. With the advent of these new standards, it enables the cellular IoT for low cost, low power and wide area deployment [1]. Increasingly more portable devices, therefore, are allowed to access to cellular network with more functionalities and freedom of interconnection. Among those numerous applications, wearable devices such as smartwatch is one outstanding candidate for data access.

The design difficulty of antenna for smartwatch is defined by the limited space into the device and the lossy human tissue very close to the antenna. Most of the existing antenna solutions are dedicated to 2.4 GHz wireless body area network (WBAN) applications. Conventional antenna types for small terminals such as planar inverted-F antenna (PIFA) [2], monopole antenna [3] and loop antenna [4] are investigated. These antennas are integrated into the housing of watch. However, when the frequency goes down to cellular bands e.g. LTE Band 3 and 4 from 1710 MHz to 2155 MHz (23% bandwidth), the increase of electrical length makes the antenna difficult to be embedded into the housing of a smartwatch. Although in [5] a miniaturized PIFA is implemented, the high quality factor makes the operating bandwidth quite narrow, which is not suitable for wideband cellular communication. Instead of placing the antenna into the casing, though narrowband performance is observed, patch antennas using textile substrate provide more degree of freedom of design, by which the antenna is capable of integrating with thin wristband of the smartwatch. Meanwhile, the textile- or fabric-based antenna is able to be conformal to any shape of surface. A wristband antenna of dipole type proposed in [8] is implemented for LTE cellular bands. Despite wide bandwidth is achieved, the total efficiency is degraded caused by absorption from lossy body tissue due to the omnidirectional property of dipole antenna. Thus, contrary to the requirement of low-power cellular IoT, more power will be consumed if such an antenna is employed. As a result, for off-body communication, a wideband unidirectional antenna is appreciated in smartwatch where the space is constrained by the housing. In [9], a compact unidirectional antenna for WBAN applications is presented. Though both wideband operation and low back radiation are achieved, the antenna has a relatively high profile, roughly λ/8, which means a physical height of 18.75 mm at 2 GHz. To accommodate the antenna into the thin wristband of watch, a low profile planar flat loop [10] based on cardboard substrate with a height of 3 mm is proposed. As presented, when widening the width of loop, the antenna can achieve more than 30% bandwidth potential and unidirectional radiation feature while the profile is kept at low, which is a promising candidate for wearable device.

In this paper, a wideband unidirectional wristband antenna for smartwatch application, covering operation bands from 1710 MHz to 2155 MHz, is investigated on the basis of the study in [10]. Computed in CST Microwave Studio, the antenna is co-simulated with CST Design Studio (DS) and Optenni Lab. Furthermore, a matching circuit is applied to the proposed antenna so as to obtain the wideband operation. The simulated and measured results are both provided.

II. OPERATION MECHANISM

To better understand the operation mechanism of the proposed antenna, the Theory of Characteristic Modes (TCM) is performed first to obtain the insight of mode behavior of the radiator. As studied in depth, the characteristic angle indicate the mode behavior near resonance[11] that when the characteristic angle is 180° the corresponding mode is at resonance while the associated mode is inductive when the angle is within 90° and 180° and capacitive when the angle is within 90° and 180°. A planar version of the proposed low profile radiator is employed to examine the characteristic mode, shown in Fig. 1 with its dimensions. Note that the material of the metallic structure is set as PEC in computation.
by Method of Moment and no external excitation is applied. The characteristic angles of the first five modes are depicted in Fig. 2. As can be seen, there are three resonant modes below 3.5 GHz which are around the frequency of interest: mode 1, mode 4 and mode 5 with their resonance at 1.8 GHz, 3.2 GHz and 2.8 GHz respectively. Although the resonance frequencies in characteristic mode analysis are a bit higher than the desired frequency band, the resonance will shift to lower when the radiator is integrated with the wristband of watch. Also, there are two non-resonant modes within the observation range, an inductive mode 3 and a capacitive mode 2, which are out of the interest of this work.

Fig. 3 shows the characteristic currents associated to modes 1, 4 and 5 of the investigated radiator. Mode 1, the fundamental mode, behaves like a transmission line mode with the modal currents flow out of phase in top and bottom plates (see Fig. 3a) whilst the currents in [9] are in phase in both layers. This difference may be caused by the low profile of the structure and the asymmetry between the upper and lower plates. In addition, the current intensity in the top plate is much weaker than that in bottom plate, which is analogous to the fundamental mode of a planar rectangular chassis if the proposed structure is folded back to a planar plate. Similar to the odd symmetry at XZ-plane in mode 1, the modal current of mode 4 shown in Fig. 3b has the same reflection plane. However, the currents in the middle of the lower plate are reversed. Moreover, the current intensity in the upper layer are stronger that that in the lower layer. On the contrary to the aforementioned two modes, a even symmetry along XZ-plane with equal current intensity on the top and bottom layers is observed in mode 5 as seen from Fig. 3c.

The corresponding modal radiation patterns (directivity) are given in Fig. 4. As predicted from characteristic currents, modes 1 and 4 have a donut-like pattern while the mode 5 radiates towards ±x-axis as the horizontal currents in the top and bottom cancel out. After the characteristic modes are analyzed, the excitation method could be determined. According to the symmetry properties, a voltage source is selected at gap of the top plate so that the odd mode currents are excited. Consequently, this feeding configuration not only excites mode 1 but also mode 4. However, it is worthy to note that over the desired operation band (1710 MHz - 2155 MHz), there is an approximately 90° phase shift between mode 1 and mode 4 so that the complex sum of these two modes results in an unidirectional pattern (shown in Fig. 5) instead of a donut-shape one. As
explained in [9], the radiations of two modes are constructively and destructively superposed in the +Z axis and -Z axis respectively by making use the 90° phase shift.

III. WIDEBAND UNIDIRECTIONAL ANTENNA DESIGN ANTENNA STRUCTURE

Based on the operation principle abovementioned in Section II, the antenna featuring low profile, wideband operation and conformality is proposed (shown in Fig. 6 with detailed dimensions) and its matching circuit topology is revealed in Fig. 7. The antenna is bent to be conformal to the surface of wrist with 1 mm gap and placed about 10 mm away from the casing of the smartwatch. For the ease of fabrication and demonstration, an ABS plastic, with a permittivity of 2.7 and a loss tangent of 0.005, is applied as the carrier of the antenna (the bracelet or wristband) due to similar dielectric constant to a rubber wristband. The antenna metallic structure is simulated with copper (5.96e+007 S/m). Furthermore, a CTIA-Certification-Standard-based wrist phantom [12] with a radius of 31.5 mm is also employed under the watch to evaluate the impact of lossy body tissue. The prototype of the strap antenna with its matching circuit (calculated by Optenni Lab) are given in Fig. 8. The carrier (ABS plastic) of the antenna is made by 3D printing technology and copper foil tape is used as the antenna metallic structure. In addition, the wristband is connected to the casing via a metal bridge. Note that the materials of carrier and antenna can be flexible textile and conductive fabrics to make the antenna more applicable to wearable case.

Fig. 9 indicates the reflection coefficients of the proposed antenna including both simulated and measured ones. It can be seen that the matched antenna can meet the desired operation bands (-6 dB reference level of impedance matching for mobile terminals) for both cases with and without user impact.
Moreover, the user proximity degrades the matching in either matched or unmatched antenna. The corresponding radiation and total efficiencies are provided in Fig. 10. The measured total efficiencies in free space and with wrist phantom both manifest a flat behavior over the operating frequencies: from -1.5 dB to -1.9 dB and from -6.5 dB to -7 dB respectively. Again, as displayed, to place the antenna at the vicinity of lossy body tissue deteriorates the efficiency performance due to the coupling from the antenna to user resulting in the absorption of power leaked from near field of antenna to body tissue. A 5 dB decrease caused by user effect is observed in radiation and total efficiencies. Compared to the optimal total efficiency of the antenna solutions presented in [8], the levels are improved by roughly 2 dB and 4 dB in this work than those of monopole and dipole antenna proposals in previous works respectively.

An unidirectional radiation characteristic is obtained as seen in simulated 3D radiation patterns (directivity) shown in Fig. 11. However, it is noticed that the excited 3D radiation pattern generated by the proposed low profile wearable antenna is narrower than the complex sum of modal radiation patterns discussed in previous section. This most probably results from the bending of the antenna to embedded into the wristband such that the launched modes are not kept the same as those in characteristic mode analysis. Besides, the filling material (ABS plastic) in between the top and bottom plates have shifted the intended characteristic modes because of dielectric loading effect so that the phase difference between two modes may not be 90° any more.
IV. CONCLUSION

In this paper, a low profile unidirectional broadband antenna with 23% bandwidth, covering the LTE bands from 1710 MHz to 2155 MHz, is proposed. The operation mechanism of the folded structure is first investigated by using Theory of Characteristic Mode to acquire insights into the mode resonance behavior. Since the appropriate feeding configuration is used, the associated modes are excited which leads to the required unidirectional radiation by taking advantage of 90° phase shift between two excited modes. Simulated and measured results are given, indicating antenna’s applicability in wearable devices. In contrast to previous studies, the averaged total efficiency under the user case has been improved to -6.5 dB.

ACKNOWLEDGMENT

This work was supported in part by the Academy of Finland 6Genesis Flagship (grant no. 318927).

REFERENCES