Wearable Dual-Polarized Antenna Array for In-Body to On-Body UWB Communication

Qiong Wang
Chair for RF Engineering,
Communication Laboratory
Dresden University of Technology,
Dresden, Germany
+49 351 463-42387
qiong.wang@tu-dresden.de

Ronny Hahnel
Chair for RF Engineering,
Communication Laboratory
Dresden University of Technology,
Dresden, Germany
+49 351 463-32284
ronny.hahnel@tu-dresden.de

Dirk Plettemeier
Chair for RF Engineering,
Communication Laboratory
Dresden University of Technology,
Dresden, Germany
+49 351 463-33203
dirk.plettemeier@tu-dresden.de

ABSTRACT

In this paper, ultra wideband (UWB) low band wearable dual-polarized antenna array designs have been proposed for in-body to on-body communication channel of wireless capsule endoscope (WCE) application. Single element antenna, dual elements, four elements array are designed and compared in free space and in body proximity. Conformal design has been focused. Wilkinson power combiner has been employed with optimized designed substrate. Near field pattern measurement has verified that the proposed 1by2 antenna can achieve a good near field directivity as well as a dual-polarized performance compared with the standard monopole reference antenna in the near field transmission measurements with the circular polarized capsule antenna.

Keywords

Dual-polarized antenna, antenna array, near field pattern, UWB, Vivaldi antenna, wearable antenna, in-body to on-body communications, WCE.

1. INTRODUCTION

These years have witnessed a great research interest in the wireless body area communications for medical and healthcare services. The ever-advancing miniaturization of electronic devices is leading to the creation of various personal information and communication appliances which can be attached to or implanted inside the bodies of patients. UWB solution has emerged for wireless body area communication interface with high data rate in the future telemedicine systems, such as the medical wireless capsule endoscopy for real-time video imaging of the digestive tract in gastrointestinal diagnosis. The authors have proposed an UWB capsule endoscope antenna design for implanted communication in the UWB low band 3.1-4.8 GHz [1], which acts as a transmitting antenna in the proposed one-way communication link. To establish effective and efficient wireless links with the implanted capsule, the corresponding on-body wearable receiver antenna should be designed with unidirectional radiation characteristics, dual-polarization, high gain, low sidelobe, small size and low profile.

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A planar Vivaldi UWB antenna design has been proposed as the on-body wearable receiver antenna for medical in-body wireless communications in [2]. The proposed antenna connects two opposite Vivaldi variants on one side of the substrate and is fed by a radial stub microstrip on the other side. With a metallic reflector at the Vivaldi side, a strong broadside radiation can be obtained from two opposite end-fire radiations resulting from two opposite planar Vivaldi variants. Based on the original Vivaldi element design, this paper will describe the conformal dual-polarized 1by2 and 1by4 antenna array with optimized Wilkinson power combiner design. Far field and near field pattern will be given to describe the radiation and coupling/transmission performance.

2. ANTENNA DESIGN AND MEASUREMENT

2.1 Return Loss in Free Space

Taking the favorable flexibility of the wearable antenna on body torso surface into account, the antenna substrate should be in low profile and very flexible so that it can be conformal on body torso surface. On the other hand, the substrate should be chosen with a relative large permittivity as well as low dielectric loss in the UWB low band so that the designed antenna can be compact and in low loss in the array design. Several chosen candidates of the substrates are FR4 by Isola Group (http://www.isola-group.com), Akaflex by Krempel Group (http://www.krempel-group.com) and RO4003C by Rogers Group (http://www.rogerscorp.com). FR4 is with a relative large permittivity value 4.4 but the dielectric loss tangent is also large, ie., 0.02, which will be unfavorable in the array formation with power combiner. Akaflex is with good flexibility but the dielectric property in the UWB band is not so clear. RO4003C is with a relative permittivity value 3.55 and the loss tangent is 0.0027. RO4003C could be a good substrate candidate in terms of flexibility, permittivity as well as propagation loss and has chosen to be used in the wearable antenna design.

Figure 1 shows the conformal antenna structure for single element, 1by2 and 1by4 configurations. Planar structure views are omitted here. The single element design is based on the former published research [2]. The current design is based on RO4003C substrate with a dimension of 17x8 cm for single element and thickness of 0.2 mm. The whole antenna design is with a high flexibility. The conformation is based on a body torso cylinder phantom dimension with radius of 18 cm and height of 40 cm. This phantom is designed based on an averaged torso dimension. The 1by2 configuration design with dual polarizations is proposed as also shown in Figure 1. The dual elements are combined through the Wilkinson combiner. The UWB Wilkinson power combiner has been optimized on Rogers 4003C. The relative low-loss, suitable permittivity properties of the Rogers 4003C plays an important role in compromising etching limitation and substrate dimension as well as substrate loss in UWB band. Figure 2 shows the simulated insertion loss of the designed 1by4 UWB Wilkinson power combiner (dimension 400x81 mm). The resulting variance of the insertion loss from -6 dB is due to the inevitable substrate loss although it has already been the optimized substrate. But the performance is already much better than that of the design based on FR4 substrate in UWB band. Based on the optimized UWB power combiner design, a four-element dual-polarized array is shown in Figure 1. The prototypes of the single element, 1by2 and 1by4 arrays are also shown in the same figure. They are also in conformal configuration with the same conformation structure.

The measured return loss performance of the three configurations are shown and compared in Figure 3. They have given the similar performance. With more antenna elements, the wideband matching performance would be better in UWB low band with the inter-influence of the mutual impedance. Single element antenna has relatively narrow band matching performance in UWB low band, while 1by2 and 1by4 arrays broaden the matched band with more resonance ripples. The measured S11 for 1by2 and 1by4 arrays do not show much big difference.

Moreover, in fact, the conformal design does not change a lot the return loss performance of the three antenna configurations, although the performance of the planar designs of the three antennas is not listed here due to page limitation.

2.2 Radiation in Free Space

The far field radiation patterns of the three conformal antenna prototypes are first measured in free space. Figure 4 shows the simulated and measured radiation pattern comparison of single element antenna at the central frequency 4 GHz. As expected, the maximum radiation direction is vertical to the reflector plane and good linearity of the single element brings about the big difference for the co-polarized component and the cross-polarized component. Measured results agree well with the simulated results. The similar conclusions can be drawn at 3 GHz and 5 GHz. The measured maximum total gains in the main lobe are 5, 8, 6 dBi for 3, 4, 5 GHz respectively.

Figure 5 shows the measured far field normalized radiation patterns at 3, 4, 5 GHz for 1by2 array antenna. Only the results on horizontal plane are shown since that on vertical plane present the similar characteristics. As expected, dual-polarized structure brings about comparable co-polarized and cross-polarized components. Moreover, with higher frequency in the UWB low band, wide radiation pattern beam performance can be observed in the main radiation domain. The ripples in the main lobe are due to the phase delay of different radiation rays in the main half sphere. Back lobe locates in the other half sphere beyond the reflector plane and it is therefore negligible. The higher central observation frequency, the more ripples in the main lobe. The measured maximum total gains in the main lobe are 5, 4.5, 3 dBi for 3, 4, 5 GHz respectively. Compared to the gains of single element, around 3 dB reduction is observed at the maximal radiation direction. 1by2 array brings about safer communication link with dual polarizations as well as a cost of reduced gain.

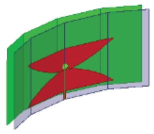
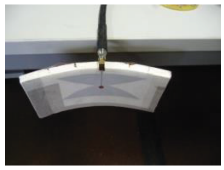
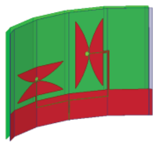
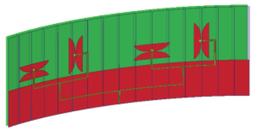
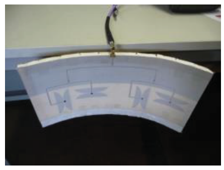
Config.	Simulation	Measurement
Single		
1by2		
1by4		

Figure 1. Conformal antenna structure for single element, 1by2 and 1by4 configurations in simulation and in measurement respectively.

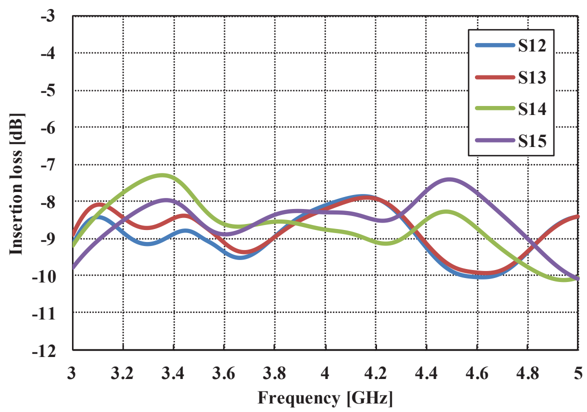


Figure 2. The simulated insertion loss of the 1by4 Wilkinson power combiner

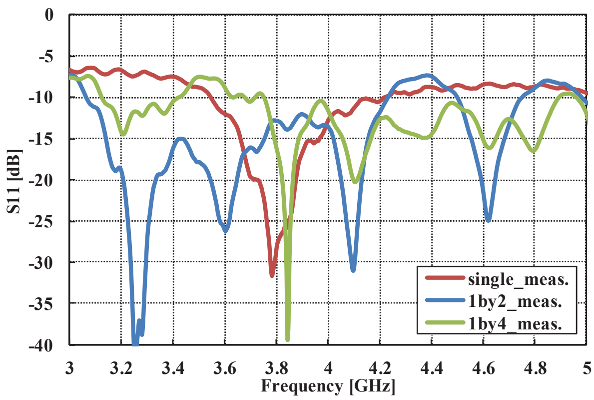
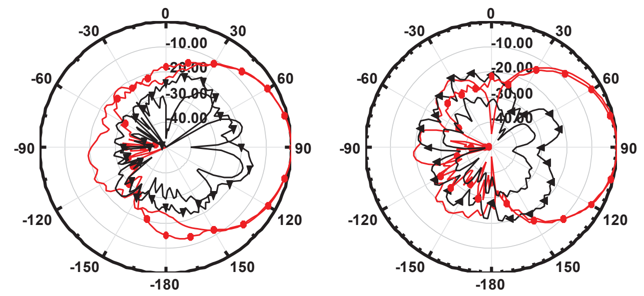


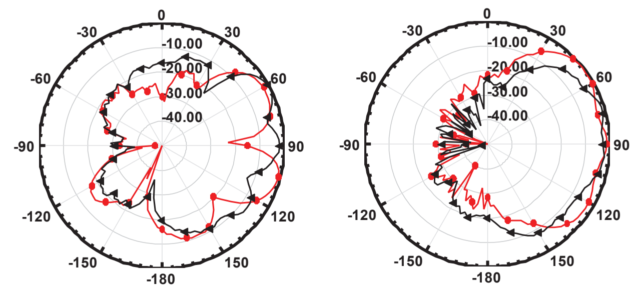
Figure 3. Measured return losses of the conformal single element, 1by2 and 1by4 configurations in free space.



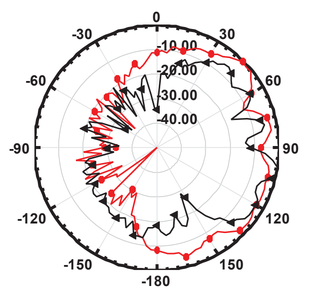
(a) Horizontal pattern (b) Vertical pattern

Figure 4. Simulated and measured far field normalized radiation patterns at 4 GHz for single element antenna (sim.: without marker; meas.: with marker; red: co-polarized; black: cross-polarized) with measured total gain of 8 dBi at the maximal radiation direction.

In fact, the measured far field normalized radiation patterns of 1by4 array are similar to that of the 1by2 array, where the co-polarized components are comparable with the cross-polarized components. But for 1by4 array, more ripples can be observed in the horizontal plane due to more phase delays of different radiation rays from more antenna elements. Moreover, much wider radiation beam can be obtained due to the extended antenna accommodation area. The measured maximum total gains in the main lobe are 5, 6.5, 4 dBi for 3, 4, 5 GHz respectively. A bit improvement at higher frequencies within UWB low band can be obtained. Therefore, if the required covering region for the capsule communication is large, the 1by4 array can be expected to be competent with favorable covering domain. Otherwise, 1by2 array may be sufficient with more compact design.



(a) 3 GHz (b) 4 GHz

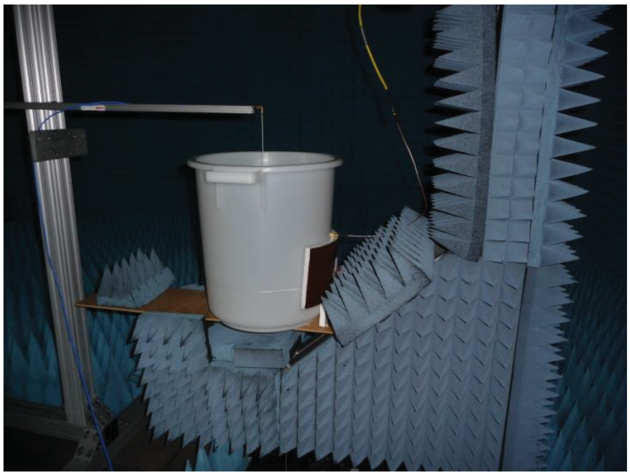


(c) 5 GHz

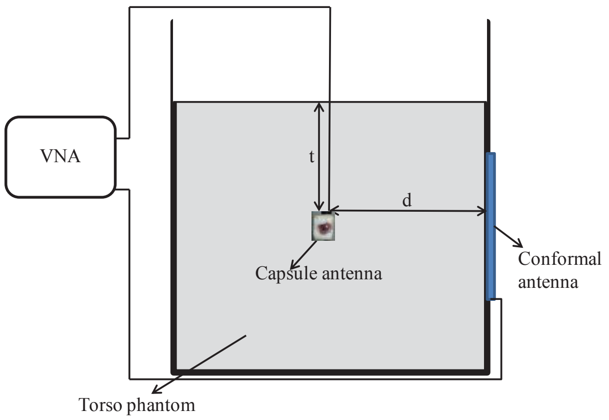
Figure 5. Measured far field normalized radiation patterns at 3, 4, 5 GHz for 1by2 array antenna on horizontal plane (red: co-polarized; black: cross-polarized) with measured total gain of 5, 4.5, 3 dBi at the maximal radiation direction.

2.3 Near field in body proximity

The dielectric characteristics of human body torso tissues in UWB low band can be approximated using average muscle tissue. The average dielectric parameters for human torso tissue in UWB low band can be concluded as average dielectric constant of 51.5 and average conductivity of 3.2 S/m [1]. A tissue-simulating fluid based on the Sucrose ($C_{12}H_{22}O_{11}$) recipe solution with 342.30 g/mol molar mass [3] is employed to simulate the average tissue dielectric characteristics in 3.1-4.8 GHz. As shown in Figure 6, the tissue-simulating fluid is accommodated inside a PVC cylinder (with an average radius 18 cm and height of 40 cm) to mimic the body torso. The antenna 1by2 array is conformal and fixed on the cylinder surface and the measurement capsule helix antenna with circular polarization is inside the phantom. The distance between the capsule antenna and the conformal antenna is set to be "d" and the distance of the capsule antenna to the liquid surface is set to be "t". Both antennas are connected with the vector network analyzer as shown in Figure 6. The whole measurement platform (phantom cylinder and together with the conformal antenna) can be rotated on the horizontal plane in the range of [0^0, 360^0] around the conformal antenna axis. The capsule antenna is fixed with no rotation inside the phantom.



(a) Near field measurement setup in anechoic chamber



(b) Side view of the measurement setup

Figure 6. Near field measurement setup in anechoic chamber with capsule antenna inside the phantom cylinder and the conformal 1by2 array on cylinder surface.

The near field pattern measurements were first carried out with different "t" and "d" distances. The sweeping of the distance of the capsule antenna to the liquid surface "t" did not show a significant influence on the near field pattern. While different spacing distance between the capsule antenna and the conformal antenna has a great influence on the horizontal near field pattern. Figure 7 gives the normalized near field pattern at the central frequency 4 GHz on the horizontal plane with the capsule antenna moving towards the conformal antenna direction. In the horizontal plane angular range [240^0, 330^0], the directional ability of the conformal 1by2 antenna becomes self-evident. The maximum near field coupling can be observed around 280^0 which is the direction vertical to the conformal antenna plane. That agrees with the maximum radiation direction of the 1by2 antenna in free space due to the utilization of the metallic reflector. The transmission difference compared to the pattern in the opposite direction with horizontal angular around 90^0 for d=10 cm is around 10 dB, which is much smaller than the pure transmission loss difference due to distance difference (to be at least larger than 80 dB at 4 GHz with 16 cm distance difference without antenna effect [4]). This verifies again the transmission directivity of the proposed 1by2 antenna. Besides, with near spacing distance between the capsule antenna and the conformal antenna, the antenna directivity becomes more apparent. The antenna directivity in near field can be successfully achieved with spacing distance of at least 10 cm.

The near field pattern was then compared with a standard monopole antenna. The monopole antenna is the same fixed on cylinder outer surface, but with two different orientations, corresponding to horizontal and vertical polarizations respectively. The transmitting capsule antenna is fixed at a position with spacing distance of d=10 cm. The near field pattern at the central frequency 4 GHz is compared in Figure 8. Similarly, in the horizontal plane angular range [240^0, 330^0] we can observe the transmission directivity of the 1by2 antenna, while the monopole antenna shows a relatively small fall of the pattern in this range due to the near field influence of the human phantom. In fact, with the omnidirectional monopole antenna, the dominant propagation mechanism around the cylinder is diffraction in which the maximum transmission could be observed in the range of [90^0, 110^0] [5]. The proposed 1by2 antenna can achieve a good near field directivity as well as a dual-polarized performance compared with the standard monopole reference antenna.

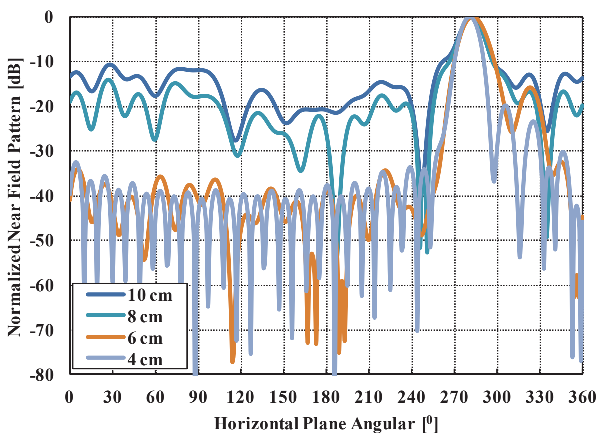


Figure 7. Normalized near field pattern at 4 GHz on the horizontal plane with different spacing distance of the capsule antenna and the conformal antenna, i.e., d=10, 8, 6, 4 cm.

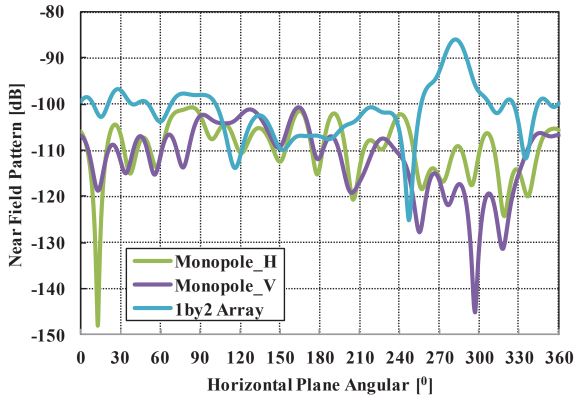


Figure 8. Near field pattern comparison of the 1by2 array and a standard monopole antenna with both horizontal and vertical polarizations at 4 GHz (spacing distance d=10 cm)

3. CONCLUSIONS

This paper proposed dual-polarized UWB low band wearable antenna array design for in-body to on-body communication channel of WCE application. Single element antenna, dual elements, four elements array are designed and compared in free space and in body proximity. Conformal design has been focused. Wilkinson power combiner has been employed with optimized designed substrate. Dual-polarized configuration with two elements and four elements show similar performance while 1by4 array can be expected to be competent with large covering domain. Otherwise, 1by2 array may be sufficient with more compact design. Near field pattern measurement system has been set up with a body torso mimic phantom cylinder. The proposed 1by2 antenna can achieve a good near field directivity as well as a dual-polarized performance compared with the standard monopole reference antenna in the near field pattern measurements with the circular polarized capsule antenna.

4. REFERENCES

[1] Wang Q., Wolf K., and Plettemeier D. 2010. An UWB capsule endoscope antenna design for biomedical communications. In *3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies* (Rome, Italy, November 07-10, 2010), ISABEL.

[2] Wang Q., Hahnel R., Zhang H., and Plettemeier D. 2012. On-body directional antenna design for in-body UWB wireless communication, In *6th European Conference on Antennas and Propagation* (Prague, Czech Republic, March 26-30, 2012), EUCAP.

[3] Y. Nishida, D. Hara, and T. Kobayashi, 'Development of Ultra Wideband Electromagnetic Phantom Materials," Technical report of IEICE. WBS2003-105, AP2003-298, RCS2003-321, MoMuC2003-111, MW2003-267(2004-03).

[4] Shi J.J., Wang J.Q. 2010. Channel characterization and diversity feasibility for in-body to on-body communication using low-band UWB signals 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL), Page(s): 1 – 4.

[5] Zasowski, T., Meyer, G., Althaus, F., Wittneben, A. 2006. UWB Signal Propagation at the Human Head. IEEE Transactions on Microwave Theory and Techniques, Volume: 54 , Issue: 4 , Part: 2.