Effect of the Fabrication Parameters on the Performance of Embroidered Antennas.

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Abstract.

Simulated and measured microstrip patch antennas produced using embroidery techniques have been presented. The antennas use a standard microwave substrate material. The effect of stitch direction and stitch density is described and a clear requirement to understand how the currents flow in an antenna so that the stitch direction can be correctly chosen is shown. Two different simulation approaches for these antennas are discussed and one is linked to measurement results, pointing to a simplified model for simulating embroidered patch antennas.

1. Introduction.

This paper reports findings on the effect of fabrication parameters, such as stitch direction and stitch spacing on the performance of embroidered patch antennas working in the region of 2GHz. Embroidery was chosen as a production technique because modern embroidery machines are fast and flexible in terms of pattern generation and facilitate the integration of high frequency systems into clothing. The underlying interest in the project is an investigation of possible routes to manufacture of fabric based antenna systems [1].

Industries are continuously seeking devices that are compact, robust, mobile, discreet, cost effective and easy to use. Fabric based antennas promise to meet many of these requirements in the medium term. The integration of a Fabric Antenna into the wearer's clothing ensures that it is more likely to be adopted by the end user and therefore available and operational when the circumstances require it. The Fabric Antenna's technological features respond well to current trends towards reducing size and consumption of materials. It will have multiple applications in numerous markets. For example, in healthcare it may be possible to integrate the technology into a 'monitoring vest' which when worn next to a patient's skin can remotely transmit vital readings to a health care professional thus enabling patients to be cared for at home, reducing costs and aiding recuperation. Other target areas include sport/leisure and military/emergency services.

There is, consequently, considerable interest in the development of textile based antenna systems, along with their associated feed networks. Various advantages for these systems include ease of fabrication, with the ability to change the fabrication

process easily, and conformal systems that give security or safety advantages where non conformal antennas may be damaged or cause damage, viz. a wire monopole may injure a user in an accident or even puncture a life raft.

A number papers of papers are in print providing substantial reviews of various aspects of wearable and fabric based antenna systems. For general reviews see [2], [3] and [4]. A detailed investigation of body-centric communications between multiple wearable antennas on the same person may be found in [5]. A review of different manufacturing techniques is presented in [6]. Lilja et al. have investigated the need for these antennas to function in harsh environments [7]

Copper based systems provide a conductive surface that is continuous, with a high conductivity, yielding higher efficiency antennas. It is not so easy to find high efficiency fabric based antennas, although some authors do report antenna efficiency, for example, Locher et al. [8] report an efficiency of 45% for a knitted fabric antenna and Ouyang and Chappell [9] report a 78% efficiency for a fabric antenna, involving conducting wire woven into the fabric, on microwave substrate.

There are fundamentally two ways of producing a conductive fabric component. In the first, a non-conductive fabric may be plated with a conductor. One such example of this is Noradell [10]. The other approach is to use a conductive yarn on a non-conductive substrate [11]. This approach uses knitting, embroidery or weaving as the most common fabrication techniques. Common conductive yarns include X-Static [12], Shieldex [13] and Amberstrand [14]. Figure 1 shows an Scanning Electron Microscope (SEM) image of unbraided Amberstrand Silver yarn showing individual fibres. Measurements using pictures obtained by this method show the individual fibres to be around 17μm in diameter.

Because fabric based antennas will normally have conductive yarns aligned in a preferred direction defined by the fabrication process it is important to understand the desired current flow in the antenna at its operation frequency and the way the conductive yarns distort this current flow. The yarns will not be in contact along their full lengths, generally, and the structure may have a significant percentage of air voids, see Figure 2. Because of these limitations, it is not easy to define an EM model that accurately describes the properties of the fabric antenna while maintaining a clear link with the structure of the fabricated antenna. Several approaches are possible and two of these are discussed in this paper along with some findings on this topic.

Recent literature [15-30] focuses mainly on embroidery and the performance of the finished devices, either in terms of antenna gain or, in the case of lower frequency RF-ID devices, receive distance or gain. A few of these papers refer to stitch density [16,21,25] or stitch type [15] and only [15] alludes to the effect of the stitch direction in terms of RF-ID performance at 900MHz but little is made of this topic. [29] reports the effect of stitch direction on embroidered patch antennas while [16] suggests that the stitching technique may be used to control antenna impedance. It also reports antenna gain and read range for four different stitch densities. [21] reports using double layer embroidery for high conductivity radiators and transmission lines. Moradi, et al. [26] discuss the effect of the sewing pattern on the performance of RF-ID Tag Antennas and suggest a means to produce an electromagnetic model for electro-textiles.

This paper reports on embroidered antennas in the low GHz range and shows that both the stitch density and the stitch direction can be very important in defining a high frequency system and how it functions. The project has focused on the Lock

Stitch as a standard stitch, both for its simplicity and the fact that it tends to produce fabric conductors with lower resistance than other stitch types considered. While there are many different stitch types available it has been found that conductive yarns do not normally have the same tensile strength as non-conductive yarns. This is exacerbated by the fact that they also tend to have a higher surface roughness than non-conductive yarns, making the embroidery process more challenging. Experience has shown that yarns such as Amberstrand break moderately easily in the embroider process and they can also damage the embroider machinery [15]. Care must be taken to select correct yarn tensions and machine speed. In addition, oil is used as a lubricant to aid the process. A simple stitch such as the Lock Stitch is beneficial in these circumstances. The embroidery software has a set of CAD/CAM tools providing fast, flexible and efficient productivity. Images can be scanned or imported for use as a backdrop for digitising as a guide or required shapes can be created manually. These designs are composed of what is known as 'embroidery objects'. These objects can be manipulated independently. Each object has a set of defining characteristics such as colour, dimension and arrangement; however the most essential consideration is the stitch type. This has been discussed, in this context, above. In relation to the outcome required digitising can be done manually in a point-and-stitch manner or through the use of fill stitches that automatically transform shapes into 'embroidery objects' filled with the desired stitch type.

2. D.C. Resistance measurements on transmission lines.

There are many conductive yarns to consider. Many of these are produced with Electromagnetic Compatibility (EMC) applications in mind. A lower conductivity is often acceptable for this application but this can make some yarns unsuitable for

high frequency electronics. Resistance measurements on individual fibres, using a digital multimeter, were undertaken as a preliminary indicator of the fibres' applicability to high frequency circuits and systems. The need for a possible set of such indicators is felt, by the authors to be important in terms of cost and time saving in the decision making process when choosing a particular yarn and stitching technique to use for a particular application. These measurement results, shown in Table 1, clearly suggest that Amberstrand has a place in wearable high frequency electronics. There was little difference between the Amberstrand thread and a copper wire using the multimeter available. A more accurate measurement using more sophisticated equipment with a four-wire technique was not deemed necessary as the differences between the fibres being measured was clear from these results.

2.1. <u>Resistance Measurements of Patch Antennas.</u>

A digital multimeter was used. Brass bars were connected to the ends of the measurement cables to apply an even pressure and good contact over the length/width of the patches. Connecting the bars together gave zero ohms resistance. Based on this, and the D.C. measurements, in the previous section it was, once again, deemed unnecessary to use a four wire method. Measurement repeatability was good.

The embroidered patches were 37mm x 29mm and were embroidered using silver coated Amberstrand yarn with different stitch directions, vertical, horizontal and diagonal, as well as with different stitch spacing (0.4mm, 0.6mm, 0.8mm and 1mm). The definition of the stitch directions may be seen in Figure 3. It should be noted, in this context, that the diagonal stitching aligns with the corner to corner diagonal. The stitch used was the Lock Stitch. Measured resistance values are shown in Table 2.

The influence of the stitch direction is clear and, in many cases, intuitive. It is clear that the current prefers to follow the stitch direction rather than jump between yarns, particularly at higher stitch spacing. However, at D.C. there is no clear pattern to be seen for the effect of stitch spacing.

3. Antenna Measurements.

Three different embroidered antennas were used, as described in Section 2.1. The antennas conformed to the dimensions given above and were placed on Taconic RF - 45 (ε_r = 4.5 and tanδ = 0.0037) substrate with a copper ground plane. A coaxial probe feed was used to obtain a good match point. The measured results are summarised in Table 3. An etched copper patch is included in the table as a comparison standard. A fully fabric patch antenna was fabricated as a comparison. This used an Amberstrand vertical embroidered patch affixed to a denim substrate with a thickness of close to 1.5mm. The ground plane was a knitted conductive sheet using using Shieldex. Connection to the patch was made using a via feed a U.FL miniature connector sewn to the fabric using conductive threads. This gave an efficiency of 31% against 53% for an Amberstrand patch on an FR-45 substrate. The fine feed cable connecting to the U.FL connector had close to 0.33dB extra loss in comparison with the semi-rigid coaxial cable connecting to the FR-45 substrate. This loss difference gives close to 7% difference in the efficiency measurement. It is possible to conclude that the fabric antenna is within 13% of an FR-45 based antenna in terms of efficiency.   The vertical thread orientation is the preferred direction for the first radiation mode and the results show the best performance for higher stitch density antennas. The diagonal stitch direction antennas tend to

perform better than the horizontal ones. It is likely that this is because there is a component of the current flowing in the preferred direction. The resonant frequencies for the horizontal and diagonal patches are lower than those for the vertical stitch direction. One can point to increased current path lengths and possible increased inductance and capacitances caused by the anisotropic nature of the conductors as possible causes for this effect. The efficiencies quoted were obtained in an anechoic chamber with a full three dimensional scan of the radiated fields giving values for directivity and gain, and hence the efficiency.

In all but three cases in Table 3 the S_{11} values for Amberstrand show a better match than for the etched copper patch. This is most likely because the fabric patches were placed against a pad where the feed via emerged from the substrate and the position was adjusted to give, as far as possible, optimum match. This was not the case with the etched copper patch.

Figure 4.a to Figure 4.c shows the E_θ field cut for three patch antennas with a stitch spacing of 0.4mm using silver coated Amberstrand. Each of these has a different stitch direction. Figure 4.d shows a similar radiation cut for an etched copper antenna. For the TM_{10} mode, which is accepted as the normal radiation mode of a patch antenna, the vertical stitch direction places the conductive fibres in line with the accepted current flow. The polarisation purity for this antenna is in excess of 27dB on boresight. This is significantly worse than the etched copper antenna (35 dB). The polarisation purity for the horizontal stitch direction is degraded to around 23dB. The diagonal stitch direction yields a patch with around 8dB polarisation purity. It is possible to surmise that this is caused by current flowing along the diagonal threads and then crossing between them, causing the two polarisations to come close together in terms of magnitude.

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Figure 5 shows the S_{11} values for the four antennas described in the previous paragraph. The "traditional" copper antenna has the highest Q from this figure. The vertical stitch direction follows this. Both of these two antennas show a very good impedance match (Copper: -14 dB S_{11} at 2.38 GHz and Vertical: -27.6 dB S_{11} at 2.47 GHz respectively). The horizontal stitch direction yields a reduced resonant frequency too but still has an acceptable impedance match (-16 dB at 2.2 GHz). The diagonal stitch direction does not produce a good match, at the TM_{10} frequency and it resonates at 2.16 GHz with S_{11} at -5 dB.

There is a back lobe that is larger than would be desirable. It is believed that this is partly caused by the small ground plane (90mm x 70mm) and partly by the measurement tower in the chamber. Simulations, including a model of the measurement tower, support the latter part of this assertion. However, for the antennas measured here, the size of the backlobe increases as the fibre directions distort the current flow. The vertical stitch direction shows as the best of the three embroidered antennas and the diagonal stitch direction is the worst of the three. A note of caution must be sounded here as the groundplane will appear to have a slightly different size for each measurement as the frequencies are different.

4. Simulations.

There are several ways of modelling this problem. This study uses IMST EMPIRE XCcel (Finite Difference Time Domain method) to model the problem. Two different approaches have been taken. The first is to intersperse good conductive "threads" with areas of lower conductivity to provide a model for the higher resistance paths between adjacent threads. A range of lower conductivity values have been considered. The conductive thread models the embroidered thread in that it forms a

zig-zag pattern across the patch area. At the ends of the run of thread, alternate pairs are connected together so there is a continuous run of conductor laid down on the substrate to form the conductive region (see Figure 6). Clearly this is a simplified model as the interconnection between the yarns is not continuous. Simulations suggest that the balance between the conductive track width and the low conductivity area width is very important for accurate measurements.

A second approach is to use both measurements and a knowledge of the structure to obtain an equivalent solid surface conductivity. This approach has been used by other workers, including Ouyang and Chappell [31]. The use of knowledge of the embroidery parameters to obtain an equivalent solid surface conductivity is being pursued in this research project and the modelling results for equivalent surface conductivities are presented in the section on antenna results.

The complicating factor is in understanding the way that current flows. This is crucial for good fabric antenna design. It has been seen in simulations that current flow can cause unwanted higher order modes to dominate, switching an antenna to a different frequency of operation. The different current directions can also affect polarisation purity. The interconnection between adjacent strands is problematic to model and understand.

Figure 6 shows simulated surface currents for patches (dimensions as described above on a low loss Taconic substrate as described in the previous section) with horizontal (6a) and vertical (6b) conducting "fibres" (0.8mm wide) separated by a low conductivity material (0.2mm wide) with $\sigma = 1x10^4 \ Sm^{-1}$. The widths used were estimated from microscope images. The conductivity was chosen as simulations

suggest that this is the lower limit of usable effective surface conductivities. The different current patterns and different directions can be seen in these figures.

Figure 7 shows a comparison of the calculated total efficiencies for antennas modelled using a continuous, effective conductivity, surface and the vertical and horizontal "fibre" models for a range of conductivities. It is clear that the higher conductivity "fibres" yield a better efficiency leading to a requirement for a calculation of an effective conductivity that takes the stitch direction and the stitch density into account. This will allow a decision to be made as to the stitch density that will meet the requirements for a particular application, which can be used in considering the cost against performance compromise.

5. Discussion and Conclusions.

This paper has focused on the issues arising from the fabrication of fabric based high frequency circuit components using embroidery. The work presented here considers patch antennas although many other antennas will lend themselves to textile and flexible systems. The results presented here point to the fact that fabric based antennas are approaching practicality. One of the patch antennas, using Amberstrand Silver coated thread, reported here has been measured to show an efficiency of 52.5%, compared to 70% for an equivalent copper patch. This compares very well with other fabric based antennas reported in the literature. Amberstrand was chosen as the yarn of choice because of its low D.C. resistance both as a fibre and when embroidered into patches. Its high frequency measurements confirmed this decision.

It is clear from the results in this paper that the stitch direction can influence the performance of a high frequency system significantly. At D.C. the resistances

measured for patches support this and this approach can be used as a quick performance indicator. At the same time it should also be noted that these measurements are on individual samples and some perceived variability points towards the need for a fabrication parameter study using more samples. This has been initiated.

The antenna measurements reinforce the conclusions being drawn out of the D.C. results with respect to stitch density. Stitch density has an effect on antenna efficiency and the challenge is to balance the required efficiency with the cost of fabricating the antennas. Currently, at sample levels Amberstrand Silver costs close to £1 per metre. Clearly, in production quantities the costs will reduce. A patch antenna may have close to 5.5m of fibre for a 0.8mm stitch density. This figure will be close to double that for a 0.4mm stitch density.

For the patches, an etched copper patch was measured to have an efficiency of 70%. At the corresponding TM_{10} mode frequency, the vertical stitch direction patch had an efficiency of 52.5% while the efficiency for the horizontal stitch direction patch drops to 15%. Both of these patches exhibit reasonable polarisation purity, better than 20dB. The diagonal stitch direction antenna shows a 30% efficiency with polarisation purity around 9dB. Clearly, there is better current flow in the preferred direction, albeit mainly diagonally with resultant vertical and horizontal directed components, producing the high cross polar content.

The horizontal and diagonal direction antennas showed a larger back lobe than the copper antenna. While this can be controlled by increased ground plane size such a route might be an issue in wearable systems where surface area may be at a premium.

Simulations using fibre equivalent models have been presented, but it is clear that this approach requires care in selecting conductive and low conductivity ratios to get accurate results. The measured efficiency for the vertical stitch direction antenna suggests, using Figure 7, that a conductivity for the low conductivity material in the simulations of around 200 S/m yields an acceptable correlation between the measurements and simulations. This holds for the case of a 0.4mm spacing vertical stitch direction patch antenna as described in this paper. This also supports the hypothesis that the current follows the actual fibres preferentially, even when the stitch spacing is quite low. The simplified model presented here merits further attention and studies are continuing on this topic.

Acknowledgement.

References

1. High Performance Flexible, Fabric Electronics for MegaHertz Frequency Communications. http://www.lboro.ac.uk/research/iemrc/Projects pages for projectsp2new/Standard/high perf flexible fabric.pdf (Last accessed 12/12/12)

2. B. Gupta, S. Sankaralingam, and S. Dhar, "Development of wearable and implantable antennas in the last decade: A review," in *Microwave Symposium (MMS), 2010 Mediterranean*, 2010, pp. 251–267.

3. N. H. M. Rais, P. J. Soh, F. Malek, S. Ahmad, N. B. M. Hashim, and P. S. Hall, "A Review of Wearable Antenna," in *Loughborough Antennas & Propagation Conference (LAPC)*, 2009, no. November, pp. 225–228.

4. T. F. Kennedy, P. W. Fink, A. W. Chu, N. J. Champagne, G. Y. Lin, and M. A. Khayat, "Body-Worn E-Textile Antennas : The Good , the Low-Mass , and the Conformal," *IEEE Trans. Antennas and Propagation*, vol. 57, no. 4, pp. 910–918, 2009.

5. P. S. Hall and Y. Hao, *Antennas and Propagation for Body-Centric Wireless Communications*. London, UK: Artech House, 2012.

6. J. C. G. Matthews and G. Pettitt, "Development of Flexible , Wearable Antennas," in *European Conference on Antennas & Propagation (EuCAP)*, 2009, pp. 273–277.

7. J. Lilja, P. Salonen, T. Kaija, and P. de Maagt, "Design and Manufacturing of Robust Textile Antennas for Harsh Environments," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 9, pp. 4130–4140, Sep. 2012.

8. I. Locher, M. Klemm, T. Kirstein, and G. Tröster, "Design and Characterization of Purely Textile Patch Antennas," IEEE Transactions on Advanced Packaging, vol. 29, no. 4, pp. 777–788, Nov. 2006.

9. Y. Ouyang and W. J. Chappell, "High Frequency Properties of Electro-Textiles for Wearable Antenna Applications," IEEE Transactions on Antennas and Propagation, vol. 56, no. 2, pp. 381–389, 2008.

10. Noradell, see http://www.fine-silver-productsnet.com/index.html (Last accessed 12/12/12)

11. A. Chauraya, S. Zhang, W. Whittow, T. Acti, R. Seager, T. Dias, and Y. C. Vardaxoglou, "Addressing the challenges of fabricating microwave antennas using conductive threads," in Antennas and Propagation (EuCAP), 2012 Proceedings of the Sixth European Conference on, 2012, pp. 1365–1367.

12. X-Static http://www.noblebiomaterials.com/category2.asp?itemid=212 (Last accessed 12/12/12)

13. Shieldex http://www.statex.biz/?lang=en (Last accessed 12/12/12)

14. Amberstrand: http://www.metalcladfibers.com/amberstrand-fiber/ (Last accessed 18/12/12)

15. J. Choi, Y. Kim, K. Lee, and Y. C. Chung, "Various Wearable Embroidery RFID Tag Antenna Using Electro-Thread," Antennas and Propagation Society International Symposium, 2008. AP-S 2008. IEEE 2008, pp. 1–4.

16. Ukkonen, L.; Sydanheimo, L.; Rahmat-Samii, Y. "Sewed textile RFID tag and sensor antennas for on-body use " 6th European Conference on Antennas and Propagation (EUCAP), 2012 , Page(s): 3450 – 3454

17. J. L. Wang, Zheyu , Zhang, Lanlin, Bayram, Yakup, and Volakis, "Embroidered E-fiber-polymer composites for conformal and load bearing antennas," in Antennas and Propagation Society International Symposium (APSURSI) IEEE, 2010, pp. 3–6.

18. T. Maleszka and P. Kabacik, "Bandwidth properties of embroidered loop antenna for wearable applications," in European Wireless Technology Conference, September 2010, pp. 89–92.

19. V. J. L. Wang,Zheyu, Zhang,Lanlin , Bayram, Yakup, "Multilayer printing of embroidered RF circuits on polymer composites," IEEE International Symposium on Antennas and Propagation (APSURSI), 2011, pp. 278–281.

20. L. Zhang, Z. Wang, D. Psychoudakis, and J. L. Volakis, "E-fiber Electronics for Body-Worn Devices," 6th European Antennas and Propagation (EUCAP), 2012 pp. 760–761.

21. Z. Wang, L. Zhang, D. Psychoudakis, and J. L. Volakis, "GSM and Wi-Fi textile antenna for high data rate communications," Proceedings of the 2012 IEEE International Symposium on Antennas and Propagation, vol. 3, pp. 1–2, Jul. 2012.

22. Zheyu Wang, Lanlin Zhang, Bayram, Y. Volakis, J.L. "Embroidered Conductive Fibers on Polymer Composite for Conformal Antennas", IEEE Transactions on Antennas and Propagation, Volume: 60 , Issue: 9 , 2012 , Page(s): 4141 – 4147

23. J.L. Volakis; Lanlin Zhang; Zheyu Wang; Y. Bayram, "Embroidered flexible RF electronics", IEEE International Workshop on Antenna Technology (iWAT), 2012 , Page(s): 8 - 11

24. Zheyu Wang; Lanlin Zhang; D. Psychoudakis,; J.L.Volakis, "Flexible textile antennas for body-worn communication" , IEEE International Workshop on Antenna Technology (iWAT), 2012, Page(s): 205 – 208

25. Lanlin Zhang; Zheyu Wang; J.L. Volakis, "Embroidered textile circuits for microwave devices", IEEE Antennas and Propagation Society International Symposium (APSURSI), 2012.

26. E.Moradi, T. Bjorninen, L. Ukkonen, Y. Rahmat-Samii, "Effects of Sewing Pattern on the Performance of Embroidered Dipole-Type RFID Tag Antennas", IEEE Antennas and Wireless Propagation Letters, 2012 , Vol. 11, Page(s): 1482 – 1485

27. K.Koski, E.Koski, T Bjorninen, A.A Babar, L. Ukkonen, L. Sydanheimo, and Y. Rahmat-Samii. "Practical read range evaluation of wearable embroidered UHF RFID tag", IEEE Antennas and Propagation Society International Symposium (APS/URSI), 2012.

28. E.Koski, K. Koski, T. Bjorninen, A.A. Babar, L. Sydanheimo, L. Ukkonen and Y. Rahmat-Samii., "Fabrication of embroidered UHF RFID tags" IEEE Antennas and Propagation Society International Symposium (APSURSI), 2012, Page(s): 1 – 2

29. Shiyu Zhang, Alford Chauraya, William Whittow, Rob Seager, Tessa Acti, Tilak Dias and Yiannis Vardaxoglou. "Embroidered wearable antennas using conductive threads with different stitch spacings," Loughborough Antennas and Propagation Conference, November 2012.

30. T. Acti, S. Zhang, and A. Chauraya, "High performance flexible fabric electronics for megahertz frequency communications," in Loughborough Antennas and Propagation Conference, 2011, November.

31. Y. Ouyang and W. Chappell, "Measurement of electrotextiles for high frequency applications," Symposium Digest, 2005 IEEE MTT-S, 2005, pp. 1679–1682.

Figures and Tables.
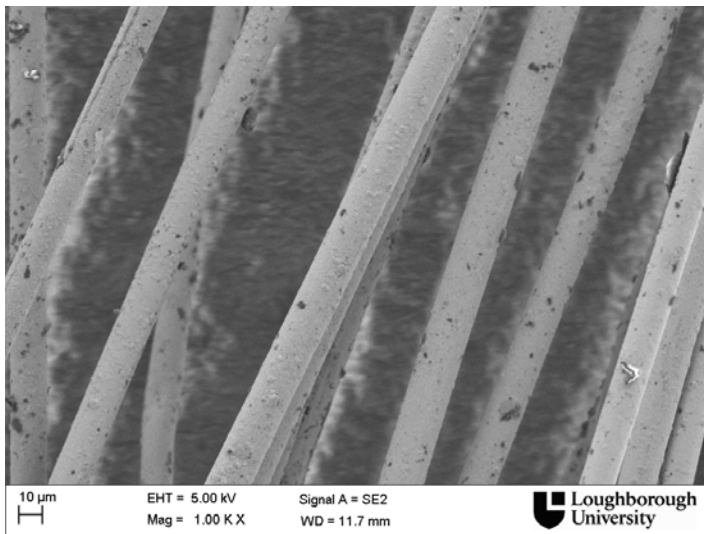
Figure 1 SEM micrograph of Unbraided Amberstrand Silver.
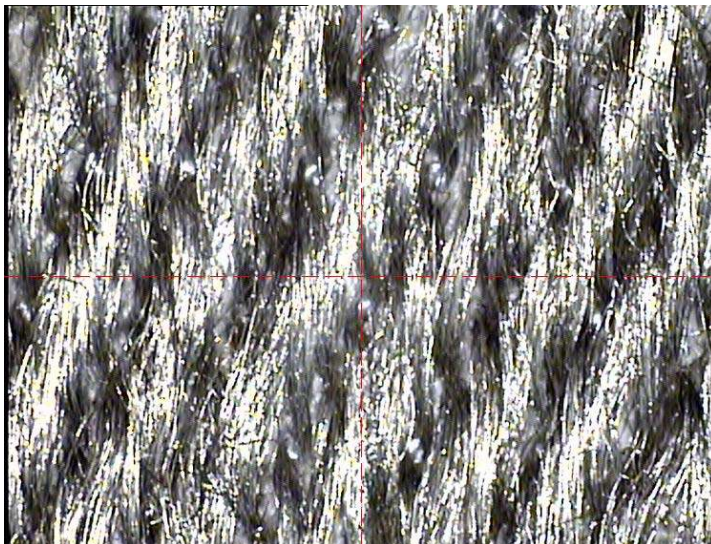
Figure 2 Micrograph of 0.4mm spacing embroidered silver coated Amberstrand Silver.

Name	DC Resistance (ohms)
Shieldex Silver	30
Nickel	30
Steel thread	6.5
Amberstrand Silver	0.01
Carbon fibre	Too large to measure (TLTM)

**Table 1. D.C. Measured resistance of representative 10cm lengths of individual conductive fibres.**
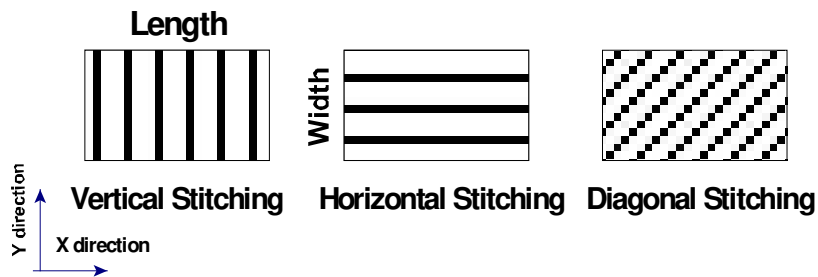
Figure 3. Sketch of Patches and the Stitch Directions.

Stitch Spacing (mm)	Stitch Direction	Measurement direction	
		Along Length x-directed in Figure 3	Across Width y-directed in Figure 3
0.4	Diagonal	0.02	0.22
	Horizontal	0.01	0.13
	Vertical	0.19	0.03
0.6	Diagonal	0.01	0.15
	Horizontal	0.00	0.11
	Vertical	0.44	0.00
0.8	Diagonal	0.01	0.23
	Horizontal	0.01	0.16
	Vertical	0.18	0.00
1.0	Diagonal	0.02	0.44
	Horizontal	0.01	0.21
	Vertical	0.26	0.01

Table 2. DC Resistance measured for different stitch spacings and directions using Amberstrand Silver. (Units are Ω)
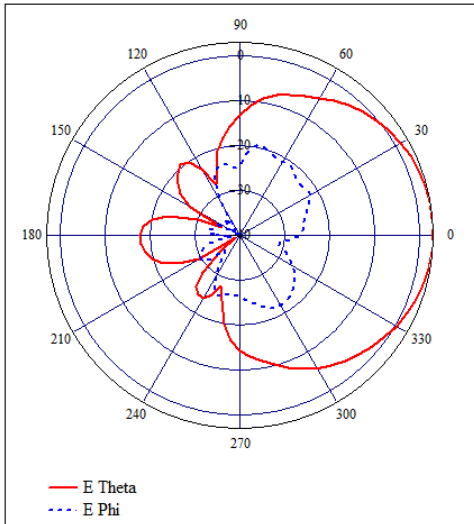
Figure 4.a. Representative Antenna Cut for 0.4mm Vertical Direction Patch Antenna at 2.465 GHz. Patch antenna faces to the right with the longer side parallel to the plane containing the cut.
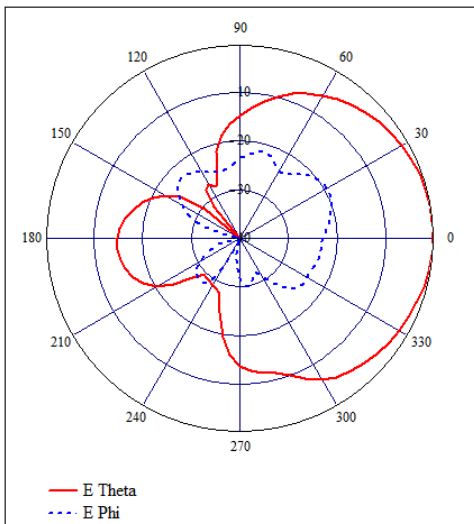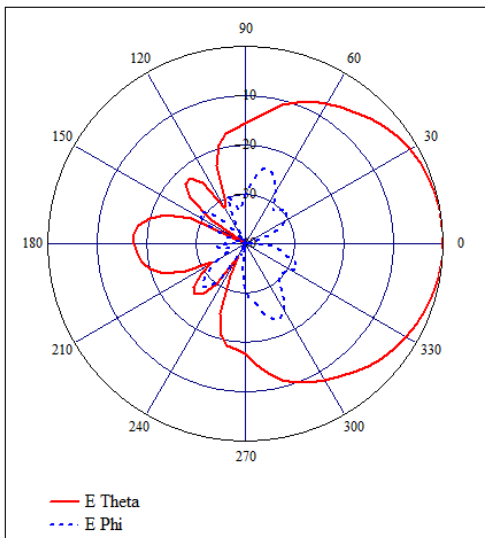

Figure 4.b. Representative Antenna Cut for 0.4mm Horizontal Direction Patch Antenna at 2.210 GHz. Patch antenna faces to the right with the longer side parallel to the plane containing the cut.
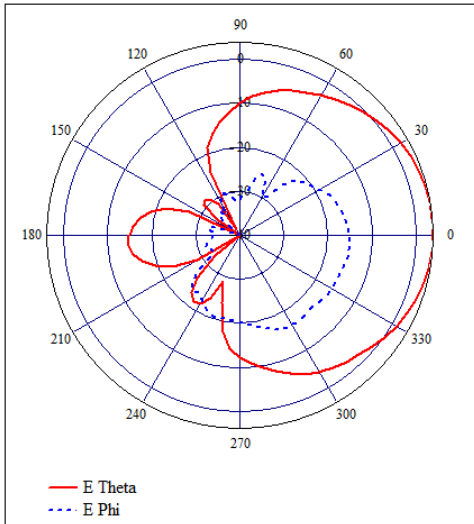
Figure 4.c. Representative Antenna Cut for 0.4mm Diagonal Direction Patch Antenna at 2.4025 GHz. Patch antenna faces to the right with the longer side parallel to the plane containing the cut.

Figure 4.d. Representative Antenna Cut for Etched Copper Patch Antenna at 2.3825 GHz. Patch antenna faces to the right with the longer side parallel to the plane containing the cut.
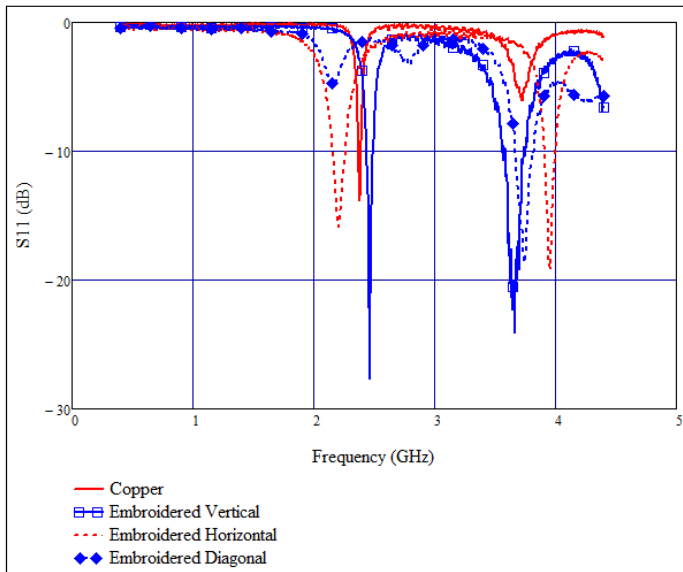
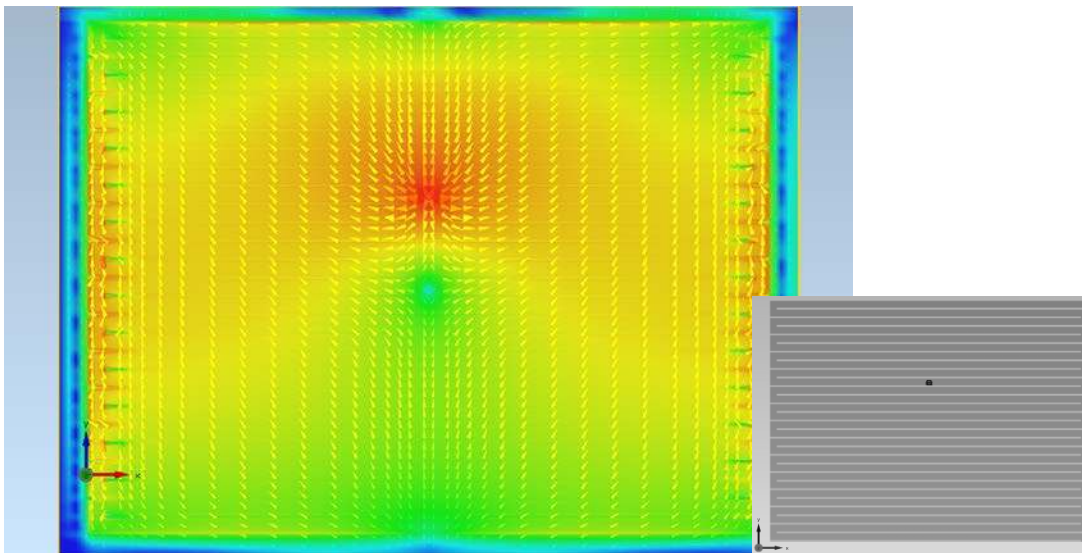**Figure 5. S_{11} Values for the four antennas in Figure 4.**

Figure 6a. Surface currents for patch with horizontal conductors separated by a conductivity of 1E4 S/m. Insert shows conductor pattern.
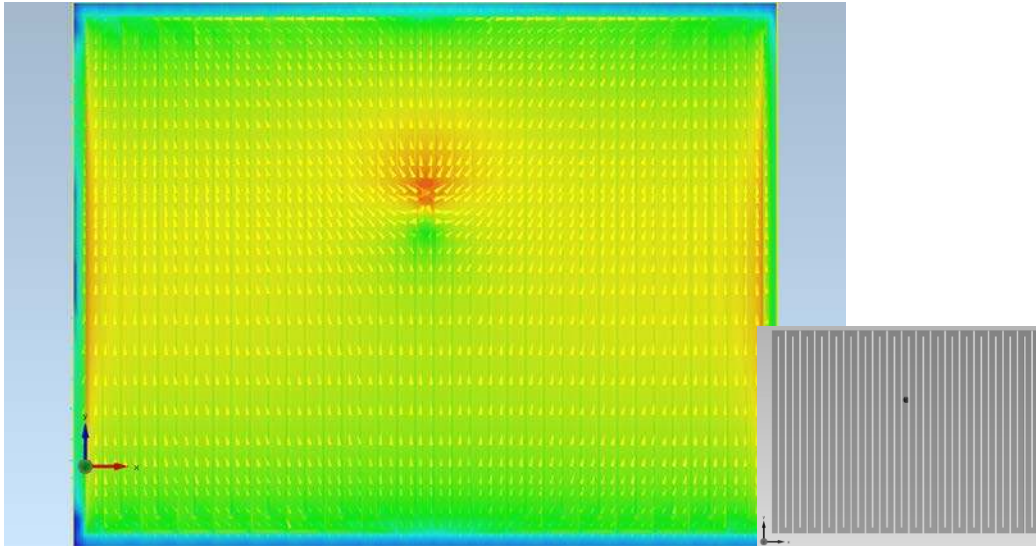
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Figure 6b. Surface currents for patch with vertical conductors separated by a conductivity of 1E4 S/m. Insert shows conductor pattern.
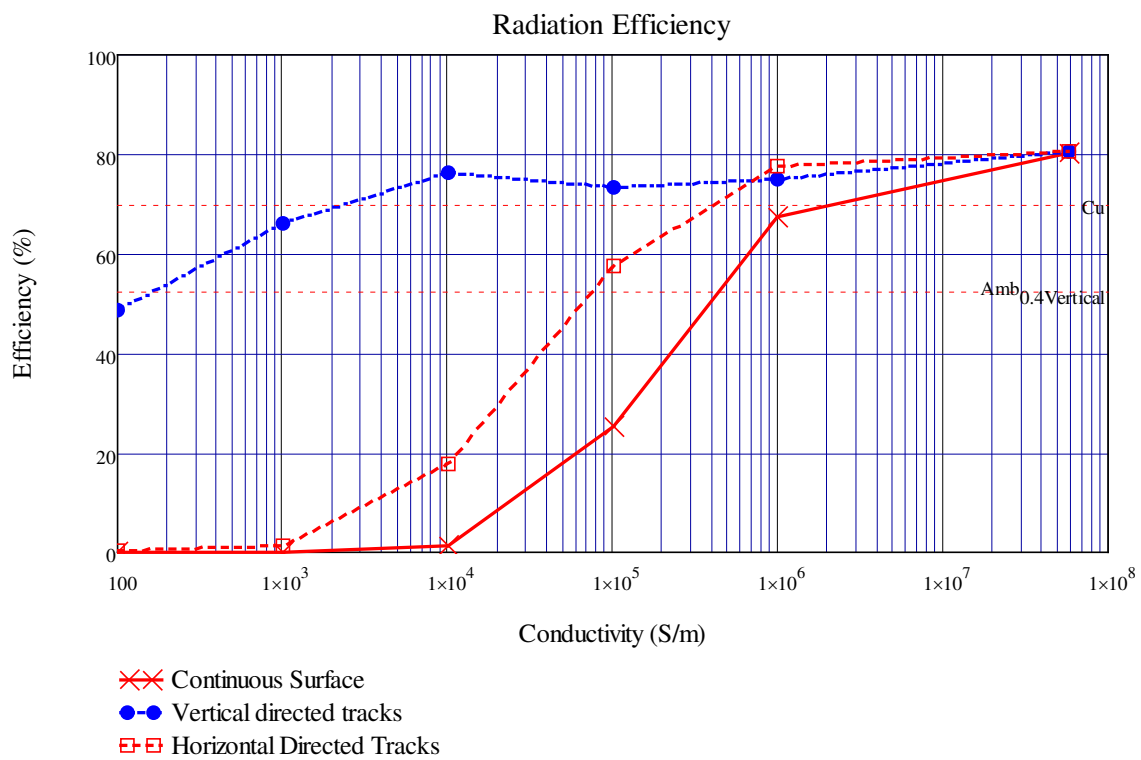

Figure 7 Comparison of simulated patch total efficiency for the three model types. Horizontal dotted lines represent measured values for a copper patch and a 0.4mm spacing vertical stitch Amberstrand patch.

Antenna	Resonant Frequency (MHz)	S11 (dB)	Gain (dBi)	Directivity (dBi)	Efficiency (%)
Etched Copper	2382.5	-13.8	6.0	7.4	70%
Amberstrand 0.4mm Vertical	2465	-27.9	4.9	7.7	52.5%
Amberstrand 0.4mm Horizontal	2210	-16.0	-1	7.1	15.4%
Amberstrand 0.4mm Diagonal	2402.5	-15.8	2.4	7.5	30.4%
Amberstrand 0.6mm Vertical	2495	-17.6	4.2	7.2	48.9%
Amberstrand 0.6mm Horizontal	2110	-12.3	-2	6.9	12.3%
Amberstrand 0.6mm Diagonal	2180	-15.9	-1.2	7.3	13.8%
Amberstrand 0.8mm Vertical	2507.5	-24.6	3.6	7.4	42.1%
Amberstrand 0.8mm Horizontal	1905	-11.0	-6.2	7.1	4.3%
Amberstrand 0.8mm Diagonal	2055	-15.6	-1.3	6.1	17.7%
Amberstrand 1.0mm Vertical	2570	-14.4	-1.6	7.1	13.2%
Amberstrand 1.0mm Horizontal	1770	-16.5	-7.8	7.5	2.9%
Amberstrand 1.0mm Diagonal	2002.5	-12.4	-1.3	6.2	16.8%

Table 3. Measured results for embroidered patch antennas on RF-45 substrate.