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Technical Support Package

Making Complex Electrically Conductive Patterns on Cloth

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National Aeronautics and
Space Administration

Technical Support Package

for

MAKING COMPLEX ELECTRICALLY CONDUCTIVE PATTERNS ON CLOTH

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NASA Tech Briefs

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Making Complex Electrically Conductive Patterns on Cloth

Brief Abstract

The technology disclosed herein provides for an automated method of creating complex fabric-based circuits and antennas. Previous attempts by others have resulted in marginalized success and have underscored the difficulties associated with fabric-based RF/microwave circuits and antennas. Several types of RF antennas constructed from fabric have been reported. However, in these cases, the construction was either very labor intensive or the geometric construction of the circuit was very simple. The disclosed methods prescribe development processes that are distinguished by at least 5 important characteristics:

1. the electronic layout of the circuit mirrors the methods used for the fabrication of conventional rigid printed circuit board (PCB) and printed antennas, thus promoting automation of the development,
2. the prescribed methods permit use of materials that enable traces characterized by high surface conductivity
3. the prescribed methods permit sufficient control of line characteristic impedance for application over a wide part of the electromagnetic spectrum,
4. the prescribed methods permit the automated realization of complex single- and multi-layered circuits; i.e., circuits with high degrees of geometric complexity, and
5. the setup cost to implement the prescribed methods is reasonable compared to setup of a wet-etch procedure commonly used for flexible and conventional rigid PCBs.

We believe that these 5 characteristics associated with the prescribed methods will likely result in adoption of these methods for development of fabric-based circuits and antennas. The range of applications could range from small, but important, niches in dedicated high-speed circuitry, RF/microwave circuits and antennas, to widespread applications in digital and RF microwave circuits. Two important qualities that have not been established for the prescribed methods include ultimate realizable circuit density and integration of active devices. These qualities of the prescribed methods are currently being investigated.

Section I — Description of the Problem

Attention to fabric circuit, or 'E-textile', technology has grown rapidly over the last decade. Two major, general application areas include flexible circuits and circuits integrated into clothing or textile apparel. The flexible circuit technology category encompasses a very wide range of specific applications requiring a high degree of conformability and, or, a high degree of adaptability. A 1996 reference states the U.S. market for flexible circuitry at $500 million and 1.8 billion worldwide [1]. The second general application area is often referred to as "wearable computer" technology. See [2] for a brief history of this technology. Specific applications in this area include clothing-embedded electronic systems for wireless system networking, cellular communications, and digital battlefield applications, as well as advanced spacesuit electronics and antennas. Examples are given in [2-4].

We believe that the methods described herein offer significant advantages compared to other published methods in both general categories discussed above, namely, flexible circuits and "wearable computer" technology. First, fabric-based flexible circuits for high-speed digital and RF applications require additional considerations, including Ohmic losses, impedance control, and unintentional radiation. Some methods for automated fabrication for digital circuits have been identified, but have had limited applications due, in part, to high Ohmic line losses associated with the traces (IBM/MIT article). In the referenced case, high Ohmic losses limited the resulting circuits to applications involving low current flow, and hence, lower circuit speeds. Other publications of fabric antennas have identified successful attempts to obtain fabric antennas that display good gain and impedance performance [5]. However, these have been limited to fairly simple constructs, such as rectangular microstrip patches, that do not involve intricate geometric patterns associated with other types of antennas and microwave circuits, such as directional couplers.

With respect to the second category of flexible circuits, we believe, but have not verified, that the methods described herein offer at least two advantages compared to conventional and new flexible circuits using non-fabric materials (e.g., laminate-based):

(1) we believe, although have not verified, that the minimum bend radius of these laminate constructions is probably much higher than those resulting from the methods described herein, and

(2) the laminate-based flexible circuits will not endure washing as well. However, it should be noted that, at this time, conventional flexible laminates offer a number of advantages over the fabric-based circuits described here, so the latter, at most, will occupy a small, but potentially important, niche of the larger flexible circuit market."

Another advancement for fabric circuits and antennas was established as part of a DARPA effort. In this effort, the investigators were successful in creating fabric circuits with complex geometrical features by deposition of metals on fabric. We believe that the methods described herein are more feasible economically and more versatile.

[1] "Flexible Printed Circuitry", Thomas H. Steams, McGraw-Hill, copyright 1996 (ISBN 0-07-061032-0)
http://www.textileworld.com/News.htm?CD=1294&ID=341
[2] http://www.wearable.ethz.ch/vision.0.html
[3] http://www.textileworld.com/News.htm?CD=1294&ID=34
[4] http://www.computerworld.com/mobiletopics/mobile/handhelds/story/0,10801,98693,00.html
[5] "Fabric antennas for mobile telephony integrated within clothing," P.J. Massey, Phillips Research Laboratories, Redhill, U.K.

Section II — Technical Description

The purpose of the innovation is to provide a method to fabricate, in an automated fashion, circuits from fabrics that overcome many of the limitations of existing methods. One prior art consists of the use of an embroidery machine and conductive thread to directly embroider the trace with the conductive thread. The resulting circuits were characterized by high Ohmic losses and therefore limited to lower-speed circuits with low currents. Another limitation of that method is the ability to control the characteristic impedance, a characteristic important for high-speed digital and RF circuits, as well as antennas. The innovation disclosed herein consists of methods and processes to create fabric circuits that overcome the many limitations characterizing the prior arts. The simplified process flow that characterizes the technology in this report is as follows:

1. Create 1st layout of circuit/antenna and targets (fiducials) using conventional CAD software and save as 1st circuit file
2. Create 2nd circuit file with outline of metal boundaries slightly reduced (i.e., inset) relative to 1st circuit file
3. Transfer 2nd circuit layout file to embroidery machine using common file format (e.g., Gerber, DXF, IGES)
4. Place layered circuit construction, consisting of substantially planar layers of conductive and non-conductive fabric on hoop to secure layers. For example, 1 conductive layer for ground, 1 insulating layer, and 1 conductive layer for traces.
5. Place hoop with layered fabrics in position to embroider
6. Using non-conductive thread, embroider the circuit traces defined by 2nd circuit file. The metal to be retained is fastened to the other layers by stitches outlining the circuit trace, or traversing the interior of the trace or conductive pattern.
7. Remove embroider layered construct from embroidery machine and place into automated PCB milling machine (a.k.a., "rapid prototype machine")
8. Use target registration (fiducials) to align circuit coordinates and milling machine coordinates using video camera integrated with milling machine. If the camera is not available, align coordinates by manual inspection and alignment of milling bit with targets.
9. Using 1st circuit file, instruct milling machine to cut the layered construct, thus separating the desired metal of the circuit/antenna and the undesired metal that corresponds to metal etched in an etch process.

Although this list describes one of the primary methods of the disclosed innovation, there are a number of embodiments and alternative steps. For example, laser cutout of the circuit has been demonstrated as an alternative to milling machine cutout. (See attached pictures below in NASA JSC Conductive Fabric Circuits and Antennas: Illustrations of Constructed Devices and Results).

Section III — Unique or Novel Features

Using the prescribed methods, we have successfully demonstrated the ability to develop low-loss fabric microwave transmission lines and geometrically complex antenna designs. Compared to published work, we believe the transmission lines created with this method rival or surpass other published results in terms of insertion loss, and, moreover, can be created in an automated fashion. To the best of our knowledge, the use of the combination embroidery machine/automated milling machine to develop fabric-based circuits is novel. We also believe an alternate embodiment, which entails creating the layered construct using a permanent or temporary adhesive and machining the circuit on the conductive (top) layer, with an optional step of post-cut embroidery to permanently fasten the layers, to be unique. We believe this latter embodiment may have an advantage in creating higher density circuits than the 1st embodiment described.

The described method has several important advantages relative to other published methods, including the "e-broidery" technique:

1. The method described herein achieves higher line surface conductivity since the conductive surface is tightly woven, whereas the "e-broidery" technique relies upon continuity of adjacent threads to achieve surface conductivity. This advantage enables circuits with lower Ohmic loss and hence faster, higher-speed circuits.
2. Owing to the tight weave of the conductive fabric, we believe the method described herein is better-suited to achieving good impedance control when compared to the "e-broidery" approach
3. The embroidery thread employed in the methods described herein can be chosen from the set of all threads for best overall strength and thread size, whereas the requirements on the conductive thread, as described in [6], are often severely restrictive.
4. Some published methods for fabric circuits and fabric antennas do not prescribe techniques for controlling trace, circuit, or printed antenna geometric tolerances.
5. Some published methods for fabric circuits and fabric antennas do not prescribe techniques for creating circuits and antennas with complex geometrical shapes.
6. Other researchers are attempting to construct fabric circuits by weaving the circuit traces directly into the pattern. Based on vendor information, the setup for a single circuit is extremely high (e.g., $10,000.00 for a run). In mass production, this may not be a barrier. However, in contrast, single runs using the proposed method are relatively inexpensive, making design iterations affordable.

Also see attached NASA JSC Conductive Fabric Circuits and Antennas: Illustrations of Constructed Devices and Results

Section IV — Potential Commercial Applications

There are numerous potential commercial applications. For example, see links [2-4] above, as well as [6], which describes electronics built into ski Jackets (we believe these to be conventional electronics integrated into the fabric, although eventual use of fabric circuits offers significant advantages). Fabric RF antennas and circuits could be employed in clothing and textile apparel for wireless networking, cellular, RFID, sensors, and GPS applications. See especially [7-9] below for additional commercial applications of fabric circuits. Other potential applications Include deployable fabric antennas and fabric antennas for fabric skin aircraft and UAVs.

[6] http://www.computerworld.com/mobiletopics/mobile/handhelds/story/0,10801,98693,00.html
[7] http://web.media.mit.edu/~rehmi/fabric/
[8] http://www.research.ibm.com/journal/sj/393/part3/post.html
[9] http://www.media.mit.edu/wearables/lizzy/
[10] http://www.cs.bris.ac.uk/Publications/Papers/1000636.pdf
[11] http://www.newscientist.com/article.ns7idzdn1427

NASA JSC Conductive Fabric Circuits and Antennas: Illustrations of Constructed Devices and Results

The computerized embroidery machine used in the preferred embodiment is shown below in Figure 1. Figure 2 shows a microstrip transmission line with a conductive fabric trace, a nylon belt insulator, and a conductive fabric ground plane. This transmission line was constructed manually prior to the procurement of the embroidery machine or the automated milling machine. However, since then, identical lines have been embroidered and cut as described in the embodiments. Figure 3 shows the insertion loss per cm for the NASA JSC microstrip line and a co-planar waveguide line appearing in open literature. The intention of this comparison is to impart the difficulties in achieving low-loss lines at RF and microwave frequencies. NASA JSC has since expanded the test results through 2.5 GHz, which encompasses the 2.4 GHz ISM/wireless Ethernet band, which is of interest in both the commercial and governmental sectors. Figure 4 shows an example of the prior art, a fairly simple, fabric microstrip patch. Figure 5 shows a NASA JSC fabric equiangular spiral antenna. This antenna demonstrates the ability to construct conductive fabric patterns with nontrivial, geometric complexity.

Figure 1. Computer-driven embroidery machine.

Figure 2. Fabric microstrip circuit with conductive fabric on nylon belt.

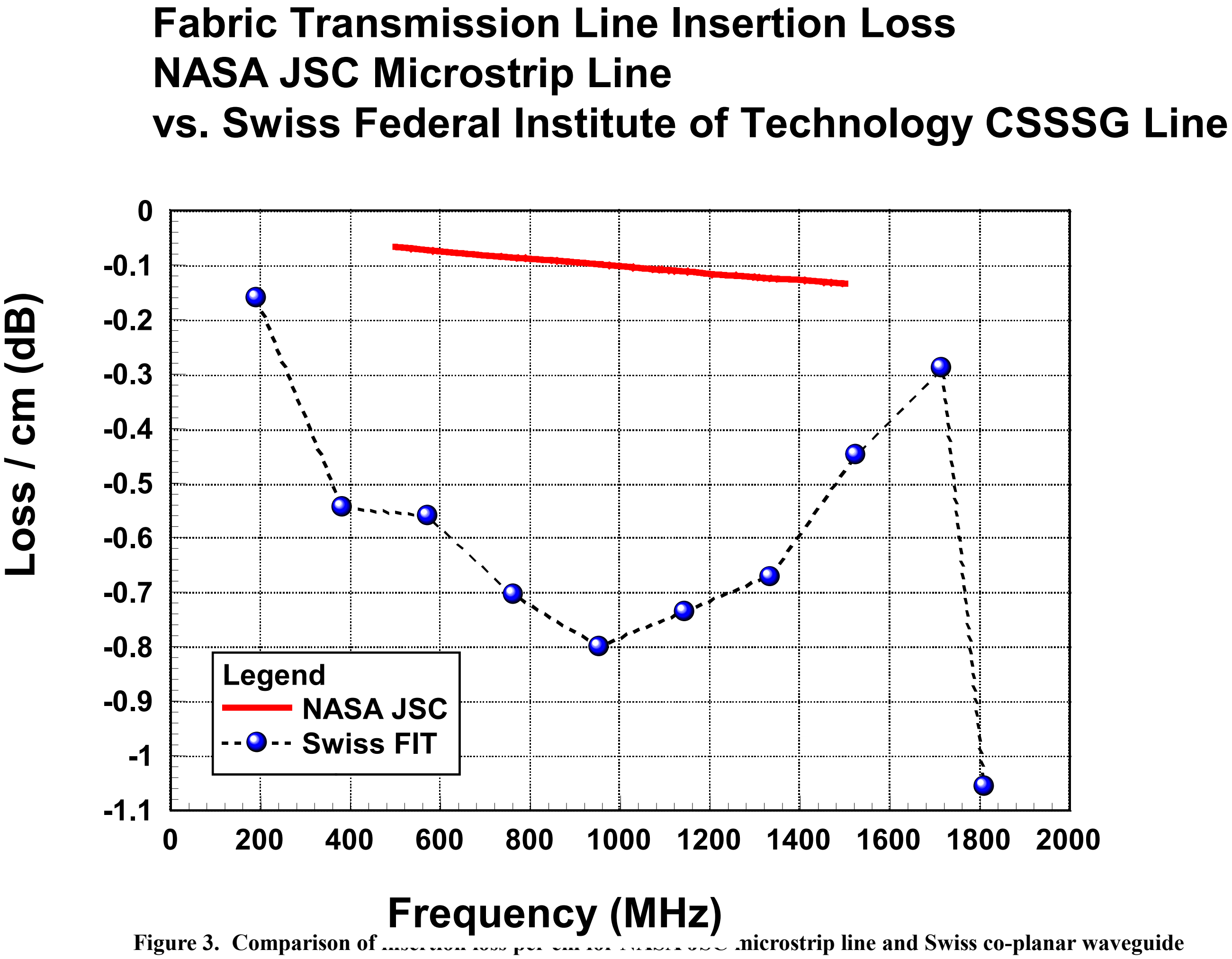

Figure 3. Comparison of insertion loss per cm for NASA JSC microstrip line and Swiss co-planar waveguide line.

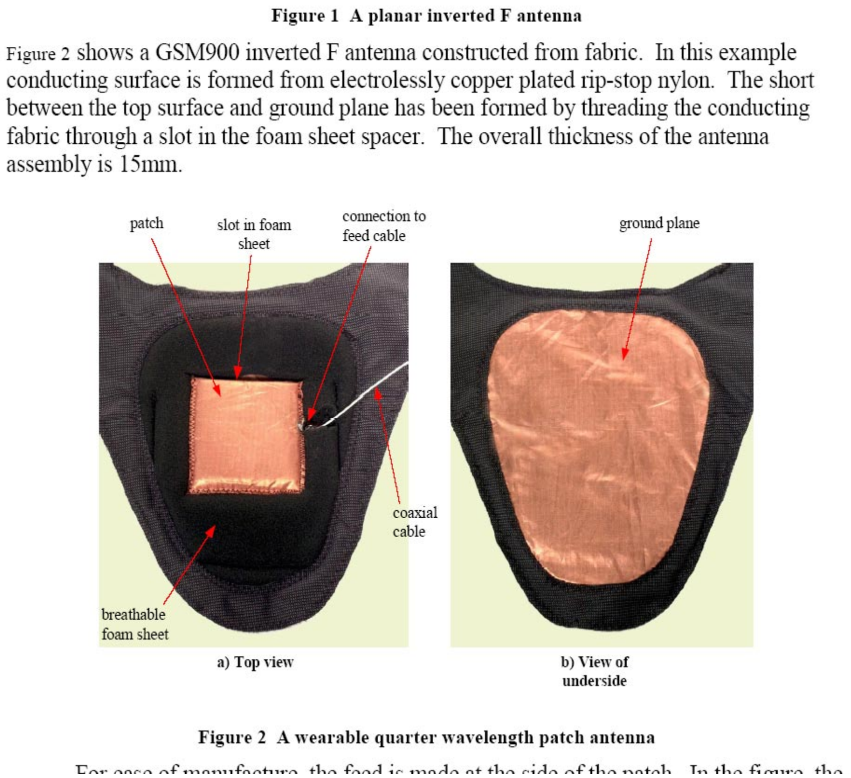

Figure 1 A planar inverted F antenna

Figure 2 shows a GSM900 inverted F antenna constructed from fabric. In this example conducting surface is formed from electrolessly copper plated rip-stop nylon. The short between the top surface and ground plane has been formed by threading the conducting fabric through a slot in the foam sheet spacer. The overall thickness of the antenna assembly is 15mm.

a) Top view

b) View of underside

Figure 2 A wearable quarter wavelength patch antenna

For ease of manufacture, the feed is made at the side of the patch. In the figure, the

Figure 4. Prior Art- simple fabric microstrip patch antenna (excerpt from “Fabric Antennas for Mobile Telephony Integrated with Clothing”).

Figure 5. NASA JSC Fabric Equiangular Spiral Using Preferred Embodiment.

Disclosure 5/24/2005

I. First Method and Process for Automated Creation of Circuits and Antennas from Layered Conductive and Nonconductive Fabrics

1. Create circuit traces on computer using conventional circuit layout CAD software.
2. Create fiducials on the same plan as the circuit traces.
3. Export or save circuit layout to standard or custom format for printed circuit boards (PCB).
4. From PCB layout (Step 3), create reduced-size embroidery machine layout; that is, digitized machine instructions for embroidery machine stitch runs. This layout should be trace outlines slightly smaller than the original circuit by an amount, delta (See Fig. 1). Additional fill stitches can be included to aid in holding circuit to fabric.
5. Place conductive fabric layer on top of non-conductive fabric layer, and optional third bottom layer of conductive fabric, so that all layers are flat and relatively free of wrinkles.
6. Place layered construction in hoop that secures layers together.
7. Using the embroider machine instructions created in Step 4, embroider the circuit trace outlines, fill stitches, and fiducials on the layered circuit construction in hoop using nonconductive thread for the stitches. The stitches secure the conductive fabric layer to the nonconductive fabric layer.
    a. Traces could be secured with single stitch in middle of trace (see Fig. 2)
    b. Traces could be held with 2 stitch runs, one on each side along the length of a trace (see Fig. 3)
    c. Traces could be secured with an arbitrary pattern of stitches within the interior of the trace.
8. Remove layered fabric construction from hoop and secure on table of automated milling machine.
9. Export or save PCB layout (Step 3) to format recognized by the automated milling machine.
10. Send the circuit pattern file (Step 9) to the automated milling machine.
11. Use fiducials to align the circuit layout coordinates and the coordinates of the automated milling machine.
12. Instruct the automated milling machine to cut traces as indicated in the circuit pattern file.

13. Remove the separated conductive fabric layer that is external to all circuit traces, leaving the circuit formed of conductive fabric (Fig. 1) with embroidered fill and trace outline stitches.

Disclosure 5/24/2005

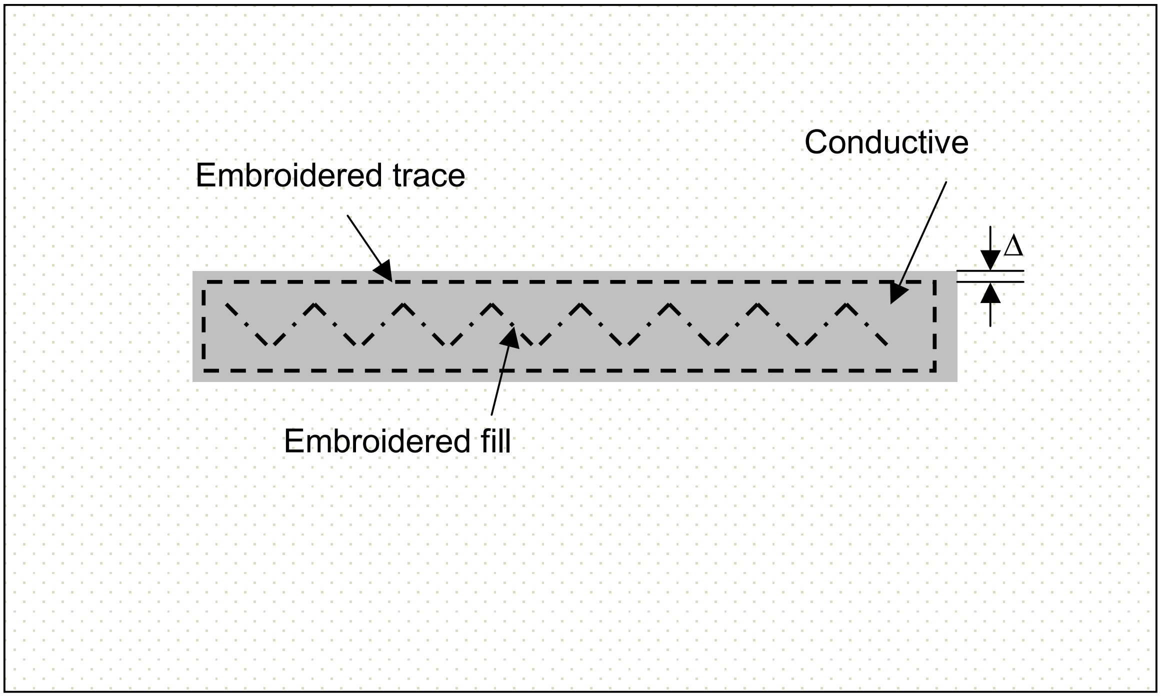

Figure 1. Fabric Circuit with Embroidered Outline Trace and Fill Stitches. The darker rectangular shade region is the desired conductive circuit. The sparsely shaded region is the nonconductive surface with top conductive layer cut and removed. An optional ground plane (not shown) may be placed beneath the nonconductive layer.

Disclosure 7/14/2005

II. Second Method and Process for Automated Creation of Electromagnetic Systems from Layered Conductive and Nonconductive Fabrics

1. Create circuit traces and conductive regions on computer using conventional circuit layout CAD software.
    a. Optionally, circuit traces can comprise voids in conductive regions, also referred to as "complementary elements".
    b. The phrase "circuit traces and conductive regions" is used herein to represent waveguides, transmission lines, antennas, frequency selective surfaces, and digital lines.

2. Create fiducials on the same layer as the circuit traces.

    a. Fiducials may optionally be created on a separate virtual layer.

3. Export or save circuit layout to standard or custom format for printed circuit boards (PCB).

4. Attach conductive fabric layer on top of non-conductive fabric layer using adhesive, keeping all layers flat and relatively free of wrinkles.

    a. Optionally, the adhesive may be heat-activated to permanently bond the circuit to the substrate prior to cutting the conductive fabric circuit. Automated hot-tip or laser machines can be used to heat-activate the localized area confined to traces and metal regions that form the circuits and/or antennas. The process outline for this is as follows:
        i. Send the PCB layout (Step 3) to the automated hot-tip or laser machine.
        ii. Instruct the automated hot-tip or laser machine to heat-activate the adhesive in circuit regions.
        iii. Fiducials may be generated by heating to make a visible mark. Alternatively, the fiducials may be marked on the conductive fabric prior to heat-activating the adhesive. In this case, the coordinate systems for the hot-tip or laser machine should be aligned with the pre-marked fiducials.
        iv. A hot-tip may be a tool in the automated milling machine so that material repositioning and fiducials are not required.

5. Secure layered fabric construction on table of automated milling machine.

    a. Table of automated milling machine may incorporate the use of a vacuum table to assist in securing the layered fabric construction.

6. Export or save PCB layout (Step 3) to a format recognized by the automated milling machine.

7. Send the circuit pattern file (Step 6) to the automated milling machine.

8. Instruct the automated milling machine to cut traces and, optionally, fiducials in the top conductive fabric layer as indicated in the circuit pattern file.

9. Remove the separated conductive fabric layer that is external to all circuit traces, leaving the circuits, and optional fiducials, formed of conductive fabric.

10. Additional conductive and non-conductive layers may be added to the construct, using adhesive.

    a. New circuit files may be created to define traces and conductive regions on new layers.
    b. Optionally, needles or thin rods may be inserted through multiple layers to align circuits of various layers when applying adhesive.
    c. The new circuit traces and regions may be separated from the surrounding conductive layer by the automated milling machine as described above.
    d. This step may be iterated to create an arbitrary number of circuit and ground/shielding layers.

Optional Steps

The intent of the following steps is to provide for attachment means in addition to the adhesive used above.

Optional Method A

11. Create holding stitch file to sew or embroider non-conductive stitches to fasten the conductive fabric circuit to the non-conductive fabric substrate layer.

    a. The stitch pattern may consist of embroidered trace boundaries inset from the original circuit boundaries by a small amount, Δ, and embroidered fill stitches (See Figure 1).
    b. A non-conductive cover layer may be placed on the top conductive layer in order to secure the circuits of the conductive layer. In this case, the stitch pattern may consist of a cross-stitch pattern to secure the non-conducting cover layer over the circuit.

12. Optionally, create an attachment stitch file that establishes stitch patterns used for fastening multiple layered constructions, where stitches in addition to those defined in the holding stitch file are required.

    a. Attachment stitch file and holding stitch file of previous step may exist as a single file.

13. Optionally, create a layer interconnect stitch file that establishes stitch patterns used to electrically connect circuits on different layers using conductive thread (See Figure 2).

  a. Layer interconnect stitch file and attachment stitch file and holding stitch file of previous steps may exist as a single file.

14. Store holding stitch file, and optional attachment stitch file and layer interconnect stitch file, in a format compatible with computer-controlled embroidery machine.

15. Place layered circuit construction, with circuits and fiducials cut with automated milling machine as described above, in hoop to secure.

    a. This could constitute a complete layered construct.
    b. Alternatively, it could constitute the inner layer of a multiple layer construction.
        i. An example could be conductive layer i, conductive layer i+1, and conductive layer i+2 and the two or more insulating layers between them (see Figure 2).
        ii. Another example could be conductive layer i+1 and the insulating layer below it.
    c. Optionally, needles or thin rods may be inserted through multiple layers to align circuits of various layers when hooping.

16. Place hoop with layered circuit construction in computer-controlled embroidery machine.

17. Optional fiducials on the layered construct may be used to set one or more coordinate frames of the computer-controlled embroidery machine.

    a. Alignment of embroidery machine head may be accomplished by manual alignment of needle with fiducial targets.
    b. Alignment of embroidery machine head may be accomplished using video cameras integrated with the embroidery machine.
    c. Alignment of embroidery machine head may be accomplished by manual alignment of fabric in hoop.

18. Using the holding stitch file and optional attachment stitch file, instruct computer-controlled embroidery machine to create trace and/or fill stitches using non-conductive thread as a means to secure circuits and layers of the layered construct.

    a. Traces could be secured with single stitch in middle of trace (see Figure 3).
    b. Traces could be held with 2 stitch runs, one on each side along the length of a trace (see Figure 3).
    c. Traces could be secured with an arbitrary pattern of stitches within the interior of the trace (Figure 1 shows one example).
    d. Circuit-free region (e.g., layers with ground only or dielectric layers only) may be filled with variety of stitch run types.
    e. Holding stitches can either be any arbitrary pattern to fasten the entire layered construct, or, it can be targeted within select conductive regions (e.g., traces) of any layer.

19. Optionally, using the layer interconnect stitch file, instruct computer-controlled embroidery machine to electrically connect circuits between layers of a multiple layer construct using conductive thread.

20. Optional additional layers may be placed on the top or bottom of the layered construct to create a first layered group, also referred to herein as a “Layered Group”. All previous steps in Optional Method A may be repeated as needed to secure the circuit, secure the layers, and provide interconnectivity between layers as desired to fabricate a multiple layer construct.

    a. One layer may be an electrically insulating layer placed on top of a conductive layer as described above.
    b. Another layer may be an electrically insulating layer on the bottom of the construct to insulate a ground plane or bottom circuit.
    c. Other layers may be additional insulating and conductive layers as in conductive layer i+3 (Figure 2). In Figure 2, connectivity in Layered Group 1 is first established between layers i and i+2 prior to adding and connecting layer i+3 to layer i.

21. Multiple Layered Groups can be fastened and connected using previous steps to create the final Group Stack.

    a. In Figure 2, Layered Group 2 is added to Layered Group 1, and electrical connectivity between the top of Layered Group 1 and the bottom of Layered Group 2 is applied with conductive thread.

22. Adhesive used for initial attachment may be temporary so that it can be washed away following layer construction means above.

23. Active and/or passive electrical components may be attached to any one or more conductive regions on any layer(s).

Computer-controlled laser cutting

As an alternative to automated cutting of circuit traces and regions with a milling machine, a computer-controlled laser can be substituted in either Methods I or II.

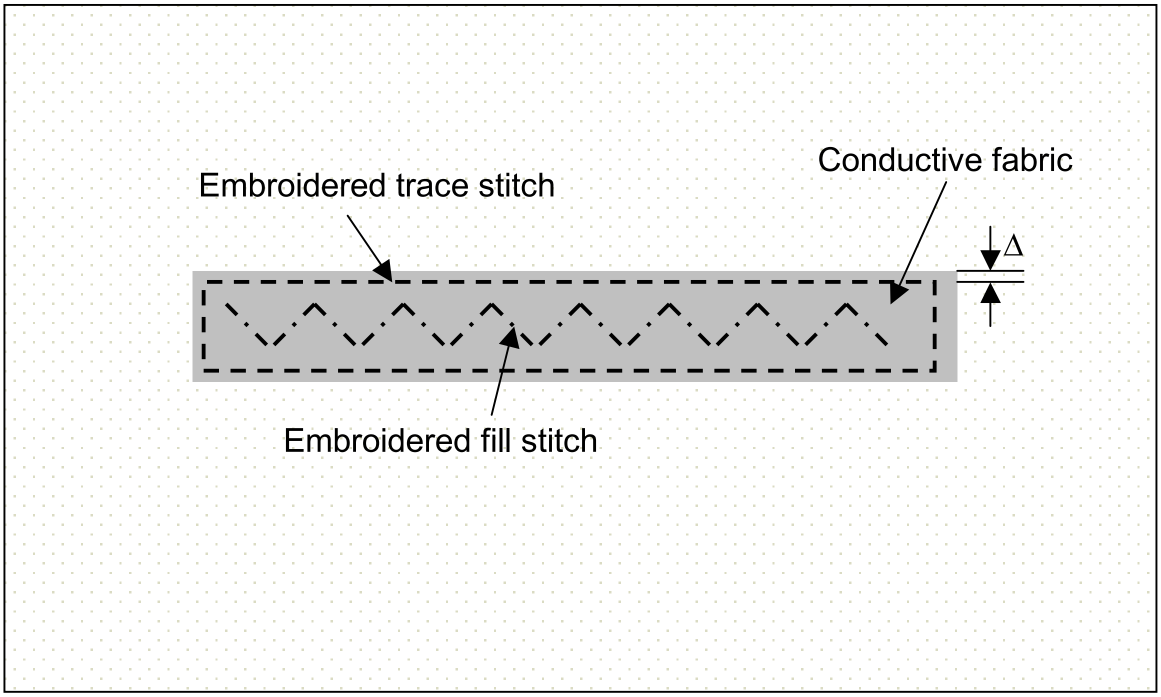

Figure 1a. Fabric Circuit with Embroidered Outline Trace and Fill Stitches. The darker rectangular shade region is the desired conductive circuit. The sparsely shaded region is the nonconductive surface with top conductive layer cut and removed. An optional ground plane (not shown) may be placed beneath the nonconductive layer.

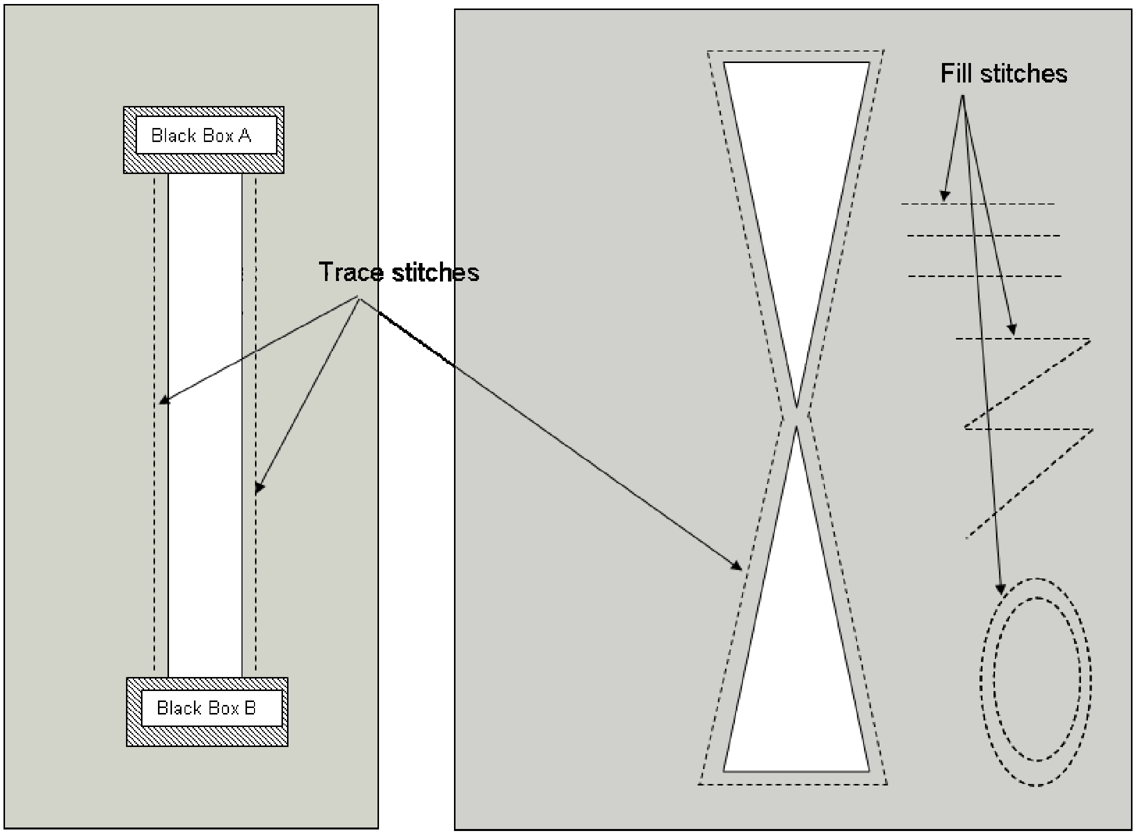

Figure 1b. Fabric Complementary Waveguide and Antenna Elements with Embroidered Outline Trace and Fill Stitches. The darker shade regions represent the desired conductive areas. The white areas represent regions in which the conductive layer has been removed. The left-hand part depicts a slotted waveguide between two arbitrary devices, while the right-hand part depicts a slotted bowtie dipole.

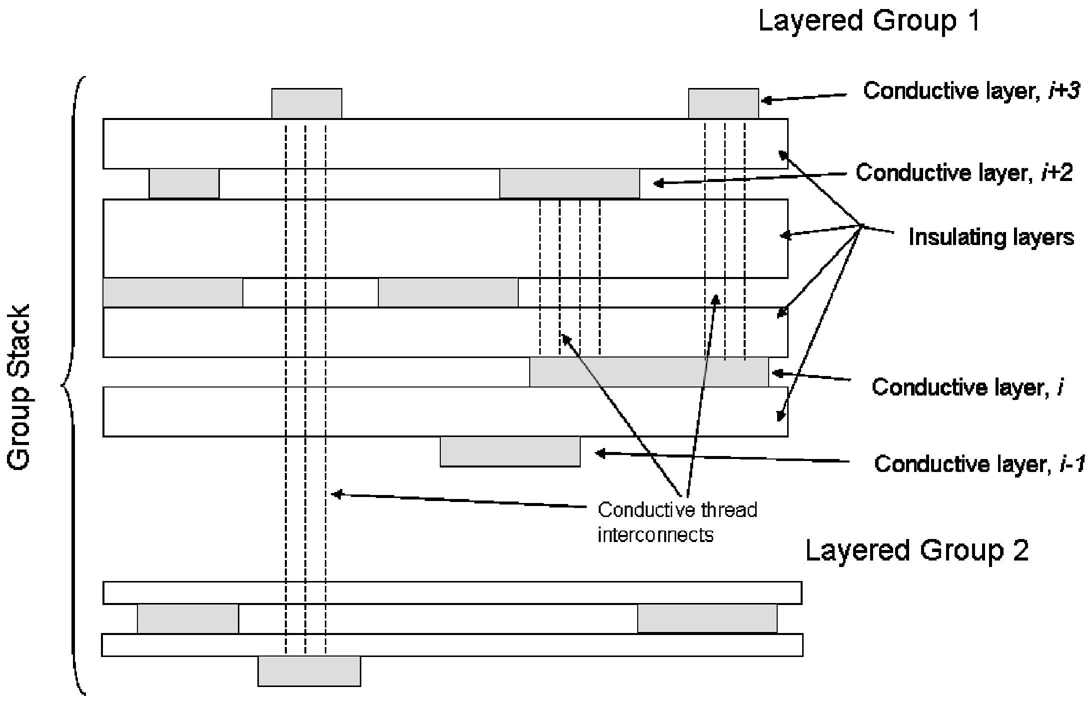

Figure 2. Multiple Layer Interconnections.

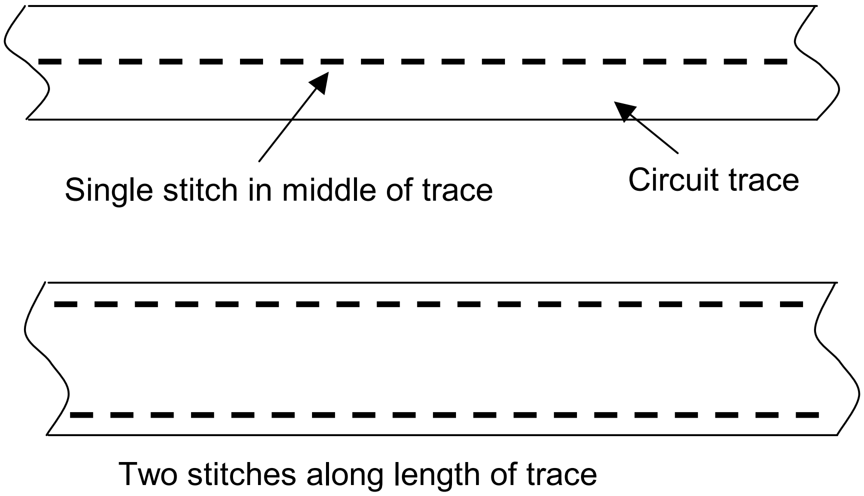

Figure 3. Single stitch or two stitches holding a trace.