Investigation on material variants and fabrication methods for microstrip textile antennas: A review based on conventional and novel concepts of weaving, knitting and embroidery

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Abstract: Wearable electronics sector is a fast-growing industry due to the rapid progress gained by developing textile-based conductive materials and conductive yarns. The demand for wireless communication in smart textiles has been increasing progressively, and therefore textile antennas will create potential benefits for wireless applications. Microstrip patch antennas play a major role in the field of textile antennas due to their low profile, conformal nature, compatible dimensions, and manufacturing feasibility. The performance of the microstrip patch antenna depends on the antenna dimensions, fabrication techniques and materials, which determine the antenna input impedance, gain, radiation efficiency, and bandwidth. The selection of correct materials, fabrication methods, and topology are very crucial for textile antennas. The heterogeneities in the textile material affect the quality factor and hence degrade the antenna performance. This article reviews conventional and novel fabrication techniques and material variants of each antenna component based on knitting, weaving, and embroidery in order to provide background information and application ideas for designing and developing microstrip patch antennas.

Subjects: Manufacturing Engineering; Materials Science; Electrical & Electronic Engineering; Electronic Devices & Materials

Keywords: Conductive textiles; conductive yarns; electric resistance; microstrip patch antenna; textile fabrication

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I am currently working as a R&D Engineer and doing research on multifaceted textile applications in the wearable electronic sector. My current research interests include Smart Textiles applications, Textile-based TENGs, Textile Antennas and Textile-based RFID technology. In recent years, microstrip textile antennas have become a topic of pivotal importance in smart textile applications and have been widely studied due to their versatile applications in diverse fields. Despite advantages, such as flexibility in manufacturing, secure integration, compatibility, and flexibility, the anisotropic nature of textile-based antennas limits electromagnetic wave propagation, compromising antenna performance. This article reviews conventional and novel fabrication techniques and material variants of each antenna component based on weaving, and embroidery in order to provide a full extent of technical information to enhance antenna performance in terms of gain, radiation efficiency, and bandwidth and application ideas for designing and developing of microstrip patch antennas by selecting correct materials, fabrication methods, and antenna topologies.
1. Introduction

With the fast development in the wearable electronics sector, textile-based antennas play a vital role. Unlike conventional inlay antennas, the anisotropic nature of textile-based antennas limits electromagnetic wave propagation, compromising antenna performance. However, wearable antennas have many advantages over conventional antennas, such as flexibility in manufacturing, secure integration, compatibility, and flexibility. In recent years, wearable antennas have become a topic of pivotal importance in smart wireless devices and have been widely studied due to their versatile applications in many sectors such as military, health, fashion, sportswear, security, and material resource planning.

In terms of wearable antennas, microstrip antennas have gained potential benefits over other designs due to the pertaining anisotropic nature of textile materials. The advantages of microstrip patch antennas over other antenna designs can be classified as conformal nature, repeatable production at low cost, low profile, and compatible dimensions for manufacturing. These advantages are particularly important from the perspective of RF (Radio Frequency) properties. Kirtania et al. (2020) pointed out that RF properties of microstrip antennas do not change substantially in unpredictable environments surrounded by metal and liquid, and this characteristic of microstrip antennas is much more reliable than dipole antennas. Despite many advantages, microstrip antennas suffer from limitations with higher frequency applications due to their narrow bandwidth, low gain, and high surface wave losses. UHF (Ultra High Frequency) antennas have recently attracted potential benefits in the textile industry with the progress in RFID (Radio Frequency Identification) systems. This technology is starting to be used in practice in applications related to product traceability, supply chain, and life cycle management, authentication of final products, and prevention in counterfeiting, etc. This represents an important topic to study because microstrip antennas have great potential to be used in textile applications when optimized for higher BW (Bandwidth) and gain values. Several methods for optimizing textile microstrip antenna performance have been reported in the literature by increasing the height of dielectric substrate (Alonso-Gonzalez et al., 2019), designing slotted structures in the design (Alonso-Gonzalez et al., 2019; Singh et al., 2018; Virkki et al., 2017), reducing parasitic capacitance (Y. Liu et al., 2019), using double-loop inductive feed structures (Mo & Li, 2019), and designing antenna arrays (Chin et al., 2018; Mao et al., 2020).

A range of techniques have been proposed in the literature for fabricating textile-based antennas. For example, knitting, weaving, embroidery, and metallization on fabric surfaces. Microstrip antennas consist of three main components: dielectric substrate known as antenna substrate, ground plane, and radiating patch. The choice of conductive materials for antenna patch and ground plane critically affects the antenna performance. It is generally agreed that conductive materials in antennas should possess a low electrical resistance to minimize conduction losses. However, this is a matter of ongoing discussion with textile antennas due to the anisotropic electrical resistance. The existing evidence supports that textile conductors possess a higher electrical resistance than their metal counterparts because of fabric heterogeneities that create electric current discontinuities. A typical area of interest found in the literature for addressing this issue is dealt with the stitch direction. Several researchers have proven that if the discontinuities are parallel to the flow of the current, they will not interfere with the electromagnetic field and wave propagation, and if the discontinuities impede the current flow, the increase in resistance will interfere with electromagnetic field and wave propagation (Koski et al., 2014, 2013; Ouyang & Chappell, 2008; Tokarska, 2019; Tokarska & Orpel, 2019). The dielectric substrate creates an insulation layer between the ground plane and the radiating patch. The dielectric properties of the substrate and its height determine the antenna dimensions and hence the input impedance. The quality factor of the antenna explains the power loss and relates
the antenna’s performance concerning gain, bandwidth, and radiation efficiency. It is therefore important to understand the full extent of textile antennas and examine how parameters associated with the material variants and construction methods influence the antenna performance.

In this paper, we discuss how material variants and construction methods affect the selection of antenna components based on theoretical, empirical and experimental results in the literature. The remainder of this paper consists of eight sections. Section 2 illustrates the different parts of the microstrip patch antenna and Section 3 describes the three main fabrication parameters of wearable antennas: weaving, knitting, and embroidery. In Section 4, the importance of Q factor analysis based on material composition and construction methods has been discussed. A more detailed analysis of power losses in textile antennas is presented in terms of conduction, dielectric, surface wave, and radiation losses. The techniques proposed in the literature to improve the Q factor of conventional microstrip antennas are inspirational for subsequent improvements in textile antennas. An up-to-date overview of these techniques to improve the quality of textile microstrip antennas is presented considering design improvements and construction changes. Section 5 outlines the material and construction characteristics of textile dielectric substrates. This section concludes by providing an emphasis on 3D composite dielectric substrates and their pertinence in achieving a lower dielectric constant and lower dielectric loss. In Section 6, the methods used to fabricate the textile radiation patch and ground plane are explained in detail. This section outlines specific methods to fabricate composite woven and knitted microstrip antennas through a single-step manufacturing process. The effect of physical deformation, applications in the communication sector, composite antennas, merits and demerits of each construction method, comparison of woven, knit, and embroidered antennas are discussed under sub-sections of Section 6. Section 7 provides a concrete overview of the conductive yarns used for textile antennas. Details about conductive yarn manufacturing methods, material variants for improved antenna performance, and novel manufacturing methods are also highlighted in this section. Section 8 summarizes material and construction variants of textile microstrip antennas that have been discussed in previous sections. Future directions are suggested since several issues remain unaddressed in areas of design resolution and volume fraction of conductive material.

2. Microstrip patch antenna

Microstrip patch antennas belong to the class of planar antenna structures. The microstrip patch antenna shown in Figure 1 is fed by a transmission line. The radiating patch, transmission line, and the ground plane are made of a highly conductive metal-like copper. The radiating patch is of length L and width W, and sits on top of a dielectric substrate of thickness h with permittivity ε, or dielectric constant. The radiating patch may be square, rectangular, circular, elliptical, triangular, or any other configuration: Figure 1 represents a square radiating patch. The dielectric substrate is of length Ls and Ws, and sits on top of a ground plane of the same dimensions. The thickness of the ground plane or of the microstrip is not critically important. Typically, the height h is much smaller than the wavelength of operation, but should not be much smaller than 0.025 of a wavelength (1/40th of a wavelength) or the antenna efficiency will be degraded. In the remainder of the paper, the performance of the microstrip antenna is discussed in terms of gain, efficiency, return loss (S11), bandwidth, antenna input impedance, and Q factor.

Antenna gain: The ability of the antenna to radiate more or less in any direction compared to a theoretical antenna

S11(Return Loss): S11 represents the power reflected from the antenna. If S11 = 0 dB, then all the power is reflected from the antenna and the power of antenna radiation is zero

Antenna efficiency: The ratio of the power radiated from the antenna to the power supplied to the antenna
Antenna Bandwidth: The range of frequencies at which an antenna can operate precisely

Antenna input impedance: Impedance of the antenna at its terminals

Q factor of antenna: The ratio between the power stored in the reactive field and the radiated power

3. Fabrication techniques of wearable antennas

3.1. Weaving

Woven fabrics are composed of two sets of yarns, namely warp and weft, which are interlaced to form a fabric. A weaving machine is a device that causes interlacements between two sets of yarns. Figure 2a shows the basic structure of a weaving machine. The warp yarns are unrolled from the warp beam during the let-off mechanism and guided through the weaving machine along the longitudinal direction. Each warp yarn is threaded through the heddle eyes that are mounted on the heddle frames and guided through the weaving machine in longitudinal direction. The number of heddle frames is determined by the complexity of the woven structure. During the shedding mechanism, the heddle frames move the warp yarns in the vertical direction in order to create a shed: at maximum displacement, the shed is called as open shed. Subsequently, the weft yarn is inserted at the right angle to the warp yarns. After the weft insertion, the reed performs the beat-up action and beats the weft yarn against the cloth fell. The heddle frames switch position to interlace the weft yarn and create a new open shed for the second weft insertion. The take-up roll takes the fabric and wind up onto the woven cloth. In antenna fabrication, the weaving ratio and thread density are important parameters that determine the effective conductive length for a minimal conduction loss. Thread density is defined by the number of warp(end) and weft(pick) yarns per inch of woven fabric: denoted by EPI (End per Inch/Ends Spacing) and PPI (Picks per Inch/Picks Spacing). Figure 2b illustrates 1/1, 2/1, 3/1, and 4/1 weaving ratios: A 3/1 twill is a ‘warp faced ‘weave, where the warp yarns will be more visible in the pattern than the weft yarns. The name 3/1, therefore, represents 3 warp yarns and 1 weft yarn are being used to construct the diagonal stripe. Figure 2c represents the conductive grid structure of a woven microstrip patch antenna using copper yarns. Figure 2d represents the warp and weft arrangement of satin conductive fabric (4/1 weaving ratio). Three-dimensional composite woven antennas are the newest research field in textile antennas. These antennas can be developed in a single step without any further assembling process. Figure 2e represents a 3D woven ultrawideband antenna developed through 3D orthogonal weaving technique, and Figure 2f represents multilayer woven antennas developed through jacquard weaving technique. In both techniques, the radiating patch and ground plane are bound using a separate binding yarn, referred as Z yarn. Figure 2g schematically represents the 3D orthogonal weaving process of microstrip antennas. In
3D orthogonal weaving, firstly, weft yarns are inserted into the sheds formed by warp yarns in the top and bottom layers. The warp yarns are then interlaced with each other to form plain patterns. Finally, both top and bottom layers are bound by spacer yarns by interlacing (moving up and down) along the warp direction over the copper weft yarns.

3.2. Knitting
Knit fabrics are composed of interloping loops of yarns. The two major types of knits are weft knits and warp knits (Figure 3ai). In weft knits, as illustrated in Figure 3ai, each course yarn lies at right angles to the direction in which the fabric is produced (wale direction) and the interloping course yarn traverses the fabric widthwise direction. Three fundamental stitches in weft knitting are plain-
knit, purl, and rib. Weft knitting machines can produce both flat (Figure 3biv) and circular fabrics (Figure 3bi, bii). As illustrated in Figure 3aii (left), the individual yarn is fed one or more needles at a time, however, multiple yarns can also be fed. On the other hand, in warp knits, the interloping course yarn traverses the fabric in a lengthwise direction. The needles produce parallel rows of loops that are simultaneously interlocked in a zigzag pattern (Figure 3aii (right)). One or more set of warp yarns are fed through swinging yarn guides to a row of needles extending across the width of the machine (biiFigure 3aiii). Two common types of warp knitting machines are the Tricot and Raschel machines. Figure 3aiii represents a schematic of knitting mechanism of a tricot knitting machine. Unlike typical knit structures, however, a separate conductive yarn (metal coated textile yarn) is interloped with the knit structure while producing antenna conductive components, as illustrated in Figure 3c, to create a set of intermeshing conductive loops.
Figure 4. Embroidery fabrication method: (a) a schematic of computerized embroidery machine, (b) embroidering FSS on top of a dielectric substrate, (c) Different patterns of embroidery stitches (from top left: Satin, Tatamin, double layer Tatamin, running stitch, triple Running stitch, Hotfill, Back Stitch, and Stem), (d) sketch of the lock stitches representing the stitch length, (e) embroidered microstrip patch antenna, (f) stitch spacings(s) of (i) parallel stitch and (ii) perpendicular stitch with a stitch length of Ls. Figures (a), (b), and (e) reprinted with permission from Tsolis et al. (2014), 2014 CC-BY 4.0 license, MDPI Publishing: Basel, Switzerland. Figures (c), (d), and (f) reprinted with permission from Zhang (2014), 2014 CC BY-NC 4.0 license, Loughborough University, UK.

3.3. Embroidery

Embroidery is a promising technique to produce repeatable, reliable, compact, and reusable antenna geometries. Figure 4a represents a computerized embroidery machine used for conformal and intricate designs. The main advantage of embroidery technique over weaving and knitting is that sheet resistance can be adjusted by controlling the stitch spacing (distance between two stitches), stitch length, and stitch direction (horizontal, diagonal, vertical, zig zag, etc.) and stitch pattern (Figure 4c). Figure 4f represents stitch spacing (s) and stitch length (Ls) of parallel (Figure 4fi) and perpendicular (Figure 4fii) stitch direction. Furthermore, embroidery patterns can be directly transferred onto the fabric surface, avoiding an additional assembling process (Figure 4b). Besides, without controlling complex parameters, a homogeneous sheet resistance can be achieved for intricate designs by designing through a CAD (Computer-aided design) software. In embroidery techniques, the most common technique for fixturing conductive yarn onto the base fabric is lock stitch (Figure 4d). Figure 4e represents an embroidered microstrip patch antenna using lock stitch. The lock stitch is formed using two individual threads, a top thread and a looper thread, which are interlocked during the embroidery process. The conductive layer is embroidered by the conductive thread (top thread) which runs through a tension system and the eye of the embroidery needle. The non-conductive thread (looper thread) interlocks the conductive thread via the needle holes in the fabric. This non-conductive thread is wound onto a bobbin and inserted into a bobbin casing, which is located in the lower half of the embroidery machine.

4. Quality factor of the antenna

The Q factor analysis of textile-based antennas is essential since power losses of textile antennas are higher than their metallic counterparts due to the anisotropic nature of textile materials and fabrication limitations. Therefore, material variants and fabrication variants should be considered based on power losses as mentioned in Equation (1) while fabricating each component of the textile antenna.
The Q factor is the ratio between electric energy stored and radiated by the conductive material, which is a measure of power loss in a microwave system. The Q-factor determines the bandwidth of the microstrip antennas. The total Q-factor ($Q_t$) is a combination of Q-factor due to lateral radiation loss ($Q_{lateral}$), Q-factor due to space wave radiation loss ($Q_{space}$), Q-factor due to conduction loss ($Q_c$), Q-factor due to dielectric loss ($Q_d$) and the Q-factor due to surface wave propagation loss ($Q_s$). The total Quality factor in terms of these Q factors is given below in Equation (1).

$$Q_{lateral} = \frac{W_e}{P_{lateral}} , Q_c = \frac{W_e}{P_c} , Q_d = \frac{W_e}{P_d} , Q_s = \frac{W_e}{P_s} , Q_{space} = \frac{W_e}{P_{space}} , Q_t = \frac{W_e}{P_{lateral} + P_c + P_d + P_s + P_{space}} \quad (1)$$

The energy stored on the antenna is the same for each Q factor and independent of the mechanism of power loss. $P_{lateral}$ is the power loss associated with lateral radiation, $P_c$ is the power loss associated with conduction, $P_d$ is the dielectric power loss, $P_s$ is the surface wave power loss, and $P_{space}$ is the desired power loss due to space radiation, which determines the radiation efficiency and gain of the antenna.

$$\frac{1}{Q_t} = \frac{1}{Q_{lateral}} + \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_s} + \frac{1}{Q_{space}} \quad (2)$$

4.1. Conduction loss ($Q_c$)

$Q_c$ is a measure of conduction loss that quantifies the conductivity of the antenna. In the case of conductive textiles, the fundamental parameters that govern the conductivity are material composition, material construction method, and product dimensions. A detailed presentation of such parameters can be linked to several variables: yarn linear density, the surface volume fraction of conductive material, number of layers, skin effect of the conductive yarn, etc. Textile materials possess an anisotropic electric resistance, and the conductivity of electro-textiles is determined by the effective electric length. This leads to an important aspect to be considered for textile antennas since fabrication methods largely contribute to the effective electric length - this will be duly discussed below. Prospective studies in the literature have focused on the primary variables of fabrication methods that govern the conductivity of the radiator and ground plane: loop length, loop density, and bulkiness in knitting; ends spacing, pick spacing, weaving ratio, and surface volume fraction of conductive material in weaving; stitch density, and stitch direction in embroiding.

Tokarska and Orpel (2019) proposed an approach to measure the anisotropic electrical resistance of knitted fabrics. In line with the findings of this study, the author observed the largest resistance values when the line connecting the voltage electrodes was parallel to the course direction and the smallest resistance values when the line connecting the voltage electrodes was parallel to the wale direction. The resistance increased as the electrode moved toward the sample edge. Furthermore, Tokarska (2019) experimentally demonstrated an approach to characterize woven and knitted electro-textile materials by their resistivity and biaxial anisotropy coefficient—an indication to determine whether material property depends on its testing direction, concerning the principal axes. It was found that resistance and biaxial anisotropic coefficient of electro-woven fabrics were better than electro-knitted fabrics. The findings supported that higher course and wales density increased both resistance and biaxial anisotropy coefficient due to many contact points. However, the literature on the performance of knitted antennas is less consistent because several studies have reported better antenna performance with increased loop density (Section 6.2). Though an increase in weft/warp density increased the resistance, a strong cross-link was observed between the anisotropy coefficient and the weave pattern. Ouyang and Chappell (2008) achieved similar results by using different woven
patterns, and the findings of this study will be further discussed in detail later in Section 6.3. A number of studies have examined the anisotropic resistance of embroidered electro-textiles based on stitch direction and stitch density (Koski et al., 2013; E. Moradi et al., 2012; Song et al., 2019). This paper further analyzes the anisotropic resistance of embroidered and knitted antennas by simplifying the unit cells into an equivalent circuit: a resistor network. The point interactions among adjacent conductive unit cells of knit and embroidery patterns are significantly higher than the point interactions of woven patterns. Consequently, the pick spacing (d) should be reduced with the increase in the weaving ratio to improve the optimum interconnections between conductive threads (Figure 5c).

There are several models to calculate the effective resistance of woven structures based on the unit model and the single yarn model. However, existing models cannot be used to determine the effective electric length of asymmetric weaves considering the contact resistance. In knitting, conductive loops are interlaced through each other, and the resistance of each unit cell depends on the loop geometry in terms of Rc, RLa and Rlb by considering the simplest form, single jersey structure. Figure 5a represents an equivalent circuit model for knit structures by considering symmetric and uniform loop geometry, and Rc, RLa, and Rlb represent stitch resistance of the contact interlaced segments. As illustrated in Figure 5a, considering the symmetry of the loop, the equivalent circuit of a loop resembles a hexagonal circuit and is composed of two Rc, two RLa, and two Rlb. However, it is important to understand what factors may impact the loop geometry of knit structures since a uniform loop geometry is a critical parameter in determining antenna performance. A uniform loop geometry within the structure is a challenging goal since it depends on a combination of several parameters, such as take-down tension, feeding tension, knit structure, loop density, linear yarn density, etc. Consequently, the geometry of adjacent loops deviates from the symmetric and uniform loop geometry although controlled. This is backed up by evidence from Tokarska (2019) in which the author concluded that knitted E-textiles possess a higher conduction loss with a higher effective resistance than woven E-textiles. In the embroidery technique, stitches are embroidered adjacent to each other, which forms an equivalent circuit in terms of single stitch resistance (Rs) and contact
resistance (Rc; Figure 1b). Due to the symmetry and precise geometry of each unit cell, the difference in Rs and Rc between adjacent cells can be considered negligible in embroidered antenna radiators. The shortest electrical path or lowest conduction loss can be experienced in parallel stitch direction because major current flows in the stitch direction across Rs, and current flows across Rc is negligible due to the symmetric circuit. In line with the equivalent circuit model, it can be concluded that embroidery stitches in the parallel direction create a lower resistance and lower conduction loss than stitches in the perpendicular direction. This comparison in conduction loss shows a good agreement between parallel embroidery stitches and lower insertion loss for textile antennas. In this section, the embroidery technique is a promising technique to fabricate textile antennas because of homogeneous sheet resistance and short electrical length compared to woven and knitted antenna radiators.

4.2. Surface wave loss (Qs)
Microstrip antennas excite dominant TM0 surface wave field. This surface wave field decays more slowly than the space wave field and will disturb the radiation pattern through reflection and diffraction from the edges of the ground plane. Furthermore, TM0 surface waves can result in mutual coupling between distant antenna elements. Therefore, surface wave excitation from microstrip patch antennas is undesirable and should be minimized to increase Qs and hence OT. This subject has been considerably explored in the literature with limited research in textile antennas. These studies have shown a good agreement between substrate height and surface wave loss. Studies have shown that surface wave loss is negligible for very thin dielectric substrates but have experienced a trade-off between the thickness of the dielectric substrate and antenna input impedance (Agbor et al., 2018; Jackson, 2016; Mishra et al., 2015)—reducing the substrate’s thickness increases the antenna’s dimensions and, hence, increases the antenna input impedance. The effect of the height of the dielectric substrate on radiation efficiency and surface wave losses is discussed under Section 3.3.

The concept of RSW (Reduced Surface Wave) microstrip antenna is a promising technique to prevent the excitation of the dominant TM0 surface wave mode (Agbor et al., 2018). RSW excitation is beneficial for three main reasons. First, the reduction in surface wave excitation increases the radiation efficiency of the antenna. Second, less diffraction from the edges of the ground plane and dielectric substrate reduces back radiation and hence interference with the main radiation pattern. Third, reduced surface wave excitation reduces the coupling with adjacent antenna elements. Techniques for reducing surface waves in textile antennas have been experimented with via-loaded RSW antennas (Paraskevopoulos et al., 2016), substrate–superstrate RSW antennas (Mukherjee et al., 2020), Electromagnetic Band Gap (EBG) metamaterials as superstrate (Manikonda et al., 2018), introducing parasitic elements within the dielectric substrate, etc. However, most of the previous studies have focused on via loaded RSW, and substrate-superstrate RSW textile antennas for microwave applications. Therefore, there is a huge gap in this area to study other RSW techniques to extend the knowledge of RSW textile antennas. In via-loaded RSW microstrip antennas, the radiator cavity is loaded with an array of shorting pins between the radiator patch and the ground plane (Figure 6a). The number of shorting pins, the diameter of shorting pin, the spacing between the shorting pins are designed such that the inductive currents on the shorting pins are canceled out the capacitive polarization currents at the design frequency, thus resulting in an effective permittivity of the patch cavity closer to the permittivity of air. Paraskevopoulos et al. (2016) developed the first higher-mode microstrip embroidered patch antenna based on the via-loaded RSW microstrip antenna concept for on-body communications (Figure 6b). The authors analyzed six different embroidered patterns to obtain the exact diameter and distance measurement between shorting pins and subsequently selected a circular stitch type—stitch type 6 (Figure 6c). The S11 (return loss) results of the embroidered RSW antenna by Paraskevopoulos et al. (2016) showed better performance in bandwidth to cover the entire 2.4 GHz ISM, which exhibited a three-time larger BW of 150 MHz ranging from 2.36 GHz to 2.51 GHz instead of 50 MHz BW of the copper antenna (Figure 6d).
Figure 6. Via loaded RSW textile microstrip antenna: (a) Via loaded RSW concept; (b) Embroidered and Copper Higher-mode microstrip patch antenna (HMMPA); (c) Embroidery process for side vias and central vias, stitch density and stitch method; (d): Comparison of on-body and free-space performance of embroidered and copper antenna, S11, gain and radiation efficiency; (e) A schematic of Orthogonal Woven composite concept for via loaded RSW antennas (f) A schematic of cavity RSW antenna. Figures (b-d), adopted with permissions from Paraskevopoulos et al. (2016), 2016 CC BY-NC-4.0 license, Loughborough University, UK.

Even though the authors experienced a 20% reduction in gain and nearly a 30% reduction in efficiency compared to the copper antenna (Figure 6d), the on-body radiation pattern shape of the textile antenna was similar to that of the copper antenna, proposing the application feasibility of RSW microstrip antennas in the communication sector. Due to the complexity in producing composite knitted structures, via loaded RSW antenna structures may be difficult to fabricate due to shorting pins. However, based on the same concept, the effective permittivity could also be increased by creating cavities in the substrate (Figure 6f). This structure can be fabricated by 3D knitting composite structures by integrating porous unit cells such as fillet hexagonal unit structures. A typical 3D warp-knitted microstrip antenna is discussed in Section 6.2.1. The via loaded RSW concept can also be integrated with the orthogonal 3D weaving concept, where Z yarn can be used to connect the ground plane and radiator at the required distance (Figure 6e). Alonso-González et al. (2019) adopted the orthogonal 3D weaving concept to fabricate a composite multimeter waveguide. The authors analyzed the parametric characterization of woven structures to develop a TIW (Textile-Integrated Waveguide) based on the SIW (Substrate-Integrated Waveguide) concept for wearable antennas. Z-yarn interconnections between the top and bottom conductive layers were used as shortening pins.

Mukherjee et al. (2020) developed substrate–superstrate wearable antennas based on textile dielectric substrates/superstrates for body-worn applications, considering human perturbations: polyester (S11:17.89 dB, gain:4.87dBi), cordura (S11:32.27 dB, gain:3.00dBi), and Lycra (S11:-31.06 dB, Gain:3.11dBi). Manikonda et al. (2018) developed a 2.39 GHz textile microstrip antenna with an E-shaped EBG structure as the superstrate to reduce electromagnetic energy absorbed by the body. The proposed E-shape EBG array, compared to the microstrip antenna without EBG array, suppressed the surface waves: increased directivity from 0.3 dB to 1.66 dB, reduced SAR (Specific Absorption Rate) rate from 1.49 W/kg to 0.76 W/kg, and enhanced return loss on the human-body phantom model from −12.4 dB to −20.8 dB.
4.3. Space wave loss \( (Q_{r_{space}}) \)

\( Q_{r_{space}} \) is the Q-factor associated with the desired power loss due to space wave radiation \( (P_{r_{space}}) \). Figure 7 represents an illustration of space wave radiation of a microstrip antennas—both desired and undesired power losses due to radiation are also illustrated. \( Q_{r_{space}} \) determines the gain and bandwidth of the microstrip antenna, and a lower \( Q_{r_{space}} \) is desired since it relates to a higher space radiation loss \( (P_{r_{space}}) \). Equality 3 provides a theoretical expression for space wave radiation. As expressed in the equality (3), the height of the dielectric substrate (\( h \)), the relative permittivity of the dielectric substrate (\( \varepsilon_r \)), and antenna geometry (\( L \times W \)) are the primary parameters that determine the quality factor of space radiation. Therefore, the geometry accuracy with which textile antennas operate is of the utmost importance. The main practical problem that textile antennas confront is deformation under stress and strain. Deformation will affect the radiation pattern and radiation efficiency adversely since fringing effects that create space radiation occur along the width direction. The evidence is equivocal in terms of the impact of deformation since several textile antenna designs have shown both stable and unstable performances with deformation (more results in Section 6). (Locher et al., 2006) analyzed how bending radii of woven and knitted antennas affect antenna performance. The author experienced a shift in resonant frequency for linearly polarized antennas towards the lower side when the antenna is bent around \( x \)-direction and \( y \)-direction. This can be proved theoretically from Equation (6) and (5) since \( L \) and \( W \) increase when the antenna is bent around \( x \)-axis and \( y \)-axis, hence reduce \( f_r \) (resonant frequency). The results were more pronounced for knitted microstrip antennas than woven microstrip antennas since knitted antenna elongates with the bending radius. Woven antennas behave differently under the deformation because the inelasticity of the woven antenna merely causes a small elongation with the bending radius. The existing work on woven antennas has been further improved with the introduction of composite antennas (Kuang et al., 2018; Singh et al., 2018). Kuang et al. (2018) analyzed the electromagnetic properties of a composite woven antenna for ultra-wideband applications. The bending tests were implemented considering a bending radius from 5 cm to 25 cm along the \( x \)-axis and \( y \)-axis to assess the electromagnetic properties under deformation. The results demonstrated that \( x \)-axis bending has a significant effect on return loss than \( y \)-axis bending. However, both bending conditions showed a little influence on antenna bandwidth and radiation pattern, indicating the appropriateness of composite woven antennas for on-body communications. To sum up, geometry accuracy is essential for microstrip antennas and further research into this area is therefore useful. The paper will discuss how robust design variations improve and maintain stable performance under deformation in the below sections.

\[
Q_{r_{space}} \sim \frac{\varepsilon_r L_2}{W_2 h}
\]

(3)
\[ L_e = L + 2\Delta L, W_e = W \]  
\[ W = W_e = \frac{c}{f_r\sqrt{\varepsilon_r + 1}} \]  
\[ L_e = \frac{1}{2f_r\sqrt{\varepsilon_{\text{eff}}\mu_0\varepsilon_0}}, L = \frac{1}{2f_r\sqrt{\varepsilon_{\text{eff}}\mu_0\varepsilon_0}} - 2\Delta L \]

L and W are length and width of the radiating patch; \( L_e \) and \( W_e \) are effective length and width of the patch, which account for the fringing effect; \( \Delta L \) is the extended length due to the fringing field; \( f_r \) is the resonant frequency; \( c \) is the speed of light; \( \mu_0 \) is the permeability of free space \( (4\pi \times 10^{-7} \, \text{H/m}) \); \( \varepsilon_0 \) is the permittivity of free space \( (= 8.85 \times 10^{-12} \, \text{F/m}) \); \( \varepsilon_r \) is the relative permittivity of the dielectric substrate; \( \varepsilon_{\text{eff}} \) is the effective dielectric constant.

### 4.4. Lateral radiation loss \( (Q_{\text{lateral}}) \)

Microstrip antennas also excite lateral radiation, which propagates outwards from the antenna (Figure 7). The field generated by lateral radiation is more dominant at moderate and small distances from the antenna than that of the surface wave field (Jackson, 2016). Lateral radiation depends on the relative permittivity and thickness of the dielectric substrate; this lateral radiation bounces between the dielectric substrate and the ground plane and also diffracts from the edges of the ground plane (Jackson, 2016). This diffraction often creates distortions in the radiation pattern of the space waves and hence affects the radiation efficiency of the antenna. Textile materials are heterogeneous in structure, and the surface volume fraction are lower than their conventional metal counterparts. Due to heterogeneities and low surface volume fraction (mesh structure), lateral waves are diffracted from the edges of the surface boundary of the mesh. Due to these reasons, material variants and construction techniques of microstrip antennas should be selected to minimize the lateral radiation loss and thereby increase \( Q_{\text{lateral}} \).

### 4.5. Dielectric loss \( (Q_d) \)

The value of \( Q_d \) is calculated by loss tangent \( (\tan\delta) \), as described in Equation (7). The electric permittivity \( (\varepsilon) \) of a substrate depends on the complex magnitude that describes how the substrate behaves within an electric field (Equation (8)).

\[ \tan\delta = \frac{1}{Q_d} \]  
\[ \varepsilon = \varepsilon_r\varepsilon_0 = \varepsilon'_r + j\varepsilon''_r \]  
\[ \tan\delta = \frac{\varepsilon''_r}{\varepsilon'_r} \]  

\( \varepsilon_r \) is the dielectric constant (relative permittivity) and \( \varepsilon_0 \) is the permittivity of vacuum. The real part of the electric permittivity, \( \varepsilon_r \), defines the amount of energy stored in the electric field. The imaginary part, \( \varepsilon' \), defines the amount of energy dissipated from the material in the electric field. The loss tangent is the ratio between \( \varepsilon''_r \) and \( \varepsilon'_r \). Following Equation (9), it can be concluded that minimizing energy dissipation from the material reduces the loss tangent and thereby
increases $Q_0$. Therefore, a lower loss tangent should be considered when selecting a dielectric substrate because a higher loss tangent leads the antenna to lose more power. In Puttaswamy et al. (2014), the authors analyzed the effect of loss tangent on circular microstrip antennas at different operating frequencies and showed that a unit step increase in $\tan \delta$ resulted in an approximate 0.99% decrease in antenna gain. For textile substrates, studies have demonstrated a strong cross-link between porosity and dielectric properties for $\varepsilon_r$ and $\tan \delta$ (Ibanez-Labiano & Alomainy, 2020; Loss et al., 2019). Factors that influence dielectric properties and porosity evaluation of textile fabrics will be further discussed in Section 5.

5. Determinants of dielectric substrate
The space between the antenna patch and the ground plane is called the antenna substrate, in other words, the dielectric substrate. The characteristics of the dielectric substrate for microwave applications are determined by the dielectric constant ($\varepsilon_r$), loss tangent ($\tan \delta$) and thickness ($h$). It is generally agreed that dielectric substrates should possess a lower $\varepsilon_r$ and lower $\tan \delta$ for microwave applications. A lower dielectric constant reduces the surface wave losses (increase $Q_s$) and lateral radiation losses (increase $Q_{\text{lateral}}$, guide the space wave radiation pattern within the substrate (increase $P_{\text{space}}$; Jackson, 2016). In the previous section, we established that a lower loss tangent ($\tan \delta$) reduces the power loss of the antenna by means of dielectric loss and consequently increases $Q_0$. Therefore, both these parameters, $\varepsilon_r$ and $\tan \delta$, are equally important to improve the quality factor ($Q$) of the antenna. In microstrip antennas, impedance matching between the source and antenna is essential. The proper tuning of antenna input impedance, matching the source impedance, improves antenna performance for wideband applications. The antenna impedance is largely attributed to its dimensions that depends on $\varepsilon_r$ and $h$. Besides, the choice of $\varepsilon_r$ and $h$ can critically influence the lateral radiation and surface wave radiation, which forms an undesirable field in the radiation pattern (Jackson, 2016; Mukherjee, 2019). Due to these reasons, the dielectric properties of the textile substrate should be carefully considered to improve the performance of the microstrip patch antennas (Ibanez-Labiano & Alomainy, 2020; Prasad et al., 2020).

Textile materials are anisotropic, and their dielectric properties depend on the electric field orientation. The effect of dielectric constant is very crucial since the increase in dielectric constant degrades the performance of the antenna (Chandra Paul, 2015). Several properties of the textiles determine the dielectric properties, such as properties of the component fibers, properties of the structure of the yarn, and properties and structure of the fabric (Bal & Kothari, 2009; Salvado et al., 2012; Sankaralingam & Gupta, 2010). As explained in (Bal & Kothari, 2009), the fiber packing density and the properties of fiber constituents affect the dielectric properties. Textile materials have a very low dielectric constant as they are very porous, and the porosity of the fabric determines $\varepsilon_r$ and $\tan \delta$ (Bal & Kothari, 2009; Ibanez-Labiano & Alomainy, 2020; Loss et al., 2019). Dielectric properties also depend on surface roughness, moisture content, purity, and homogeneity of the fabric (Mukai & Suh, 2019). Moisture content is one of the unavoidable factors that affect the performance of textile antennas under normal atmospheric conditions. Water has a higher and stable dielectric constant than textile fibers ($\varepsilon_r = 78$ at 2.45 GHz and 25°C; Hertleer et al., 2009). When textile fibers absorb moisture, it changes the fabric’s electromagnetic properties and increases its dielectric constant, loss tangent (Hertleer et al., 2009; Monne et al., 2018), and shift resonant frequency (Wahab Memon et al., 2020)—yarns swell transversely and axially due to absorbed moisture and affect the tightness, dimension stability, and air permeability, affecting the dielectric properties. Hertleer et al. (2009) concluded that antennas fabricated from textile materials with small moisture absorption values (moisture regain less than 3%) are more stable. Therefore, the dielectric substrate should possess a low dielectric constant, a low loss tangent, and a low moisture regain value for microwave applications that allow the development of textile antennas with acceptable efficiency and high gain.
Table 1. Dielectric constants for textile materials and textile substrates used in the previous researches

| Textile substrate                     | Fabrication method | Thickness (mm) | $fr$ GHz | $tan\delta$ | $\varepsilon_r$ | Ref                          |
|---------------------------------------|--------------------|----------------|----------|-------------|-----------------|------------------------------|
| Single layer denim                    | Weaving            | 0.53           | 2.45     | 0.0737      | 1.97            | (Zhang, 2014)                |
| Two-layer denims with no adhesives    | Weaving            | 1.10           | 2.45     | 0.0751      | 1.92            | (Zhang, 2014)                |
| Four-layer denims with copolyimide web| Weaving+Non-woven  | 2.24           | 2.45     | 0.0661      | 1.90            | (Zhang, 2014)                |
| Woolen felt                           | Non-woven          | 3.5            | 2.4      | 0.02        | 1.45            | (Ibanez-Labiano et al., 2006) |
| Viscose                               | Weaving            | 3              | 2.45     | 0.016       | 1.64            | (Ibanez-Labiano & Alomainy, 2020) |
| Polyamide spacer fabric               | 3D warp Knitting   | 6              | 2.4      | -           | 1.14            | (Lacher et al., 2006)        |
| Polyester spacer fabric               | 3D weft knitting   | 2              | 5.8      | 0.006       | 1.1             | (Loss et al., 2021)          |
| Fleece fabric                         | Weaving            | 2.56           | 2.45     | -           | 1.25            | (Xu et al., 2020)            |
| Cotton                                | Weaving            | 3              | 2.45     | 0.02        | 1.58            | (Ibanez-Labiano & Alomainy, 2020) |
| 3D composite                          | 3D orthogonal weaving | 5          | 1.3      | 0.008       | 1.68            | (Xu et al., 2020)            |
| Bedsheet cotton                       | Weaving            | 1.26           | 1.48     | 0.0057      | 3.13            | (Roy et al., 2017)           |
| Corduroy                              | Weaving            | 1.04           | 1.44     | 0.0059      | 3.32            | (Roy et al., 2017)           |
| Wool                                  |                    | 1.19           | 1.32     | 0.008       | 3.98            | (Roy et al., 2017)           |
| Terry Wool                            | Weaving            | 1.14           | 1.52     | 0.0022      | 2.96            | (Roy et al., 2017)           |
| Polypropylene +soybean                | Knitting           | 0.62           | 2.45     | 0.2120      | 1.76            | (De Holanda et al., 2017)    |
| Polypropylene +corn                   | Knitting           | 0.70           | 2.45     | 0.0954      | 1.40            | (De Holanda et al., 2017)    |
| Polypropylene +bamboo                 | Knitting           | 0.70           | 2.45     | 0.2265      | 1.94            | (De Holanda et al., 2017)    |

5.1. Fabrication Methods of Dielectric Materials

Apart from the relative humidity and constituents of fibers in the material composition, the material fabrication method plays a significant role in the electric permittivity. In recent studies, the authors have proved that the relative permittivity of textile materials depends on fabric construction, thread count, yarn geometry, manufacturing method, and solid volume fraction (De Holanda et al., 2017; Ibanez-Labiano & Alomainy, 2020; Locher et al., 2006; Mukai & Suh, 2019; Mukherjee, 2019). In Mukai and Suh (2019), the authors analyzed the effect of thread count, construction, and surface volume fraction on the dielectric constant of cotton samples and proved that the increase in thread count increases the dielectric constant. This increase in relative permittivity was attributed to the increase in surface volume fraction and better yarn orientation. To validate this concept, the authors experimentally showed that woven samples of the same surface volume fraction have a higher dielectric constant than knitted samples (Mukai & Suh, 2019). However, studies have shown that improvements in woven substrates can be achieved through material and fabrication variants-Three-dimensional woven antenna composites have a lower dielectric constant than two-dimensional woven antennas (Xu et al., 2020). Table 1 summarizes dielectric constants and loss tangent values experimented with some woven, knitted, and non-woven substrates. De Holanda et al. (2017) examined the dielectric properties of knitted substrates based on biodegradable synthetic fibers for microwave devices. The
knit structure of interest in developing dielectric substrate was studied in De Holanda et al. (2017) as a single jersey structure. The open structure presented in the single jersey fabric showed a relatively low dielectric and loss tangent value. Knitted fabrics are more breathable than woven fabrics due to their porous structure. The moisture content of knitted materials is, therefore, lower than woven materials, resulting in a lower dielectric constant at atmospheric conditions. The effect of fabric porosity on dielectric properties was also analyzed by Ibanez-Labiano and Alomainy (2020) and Loss et al. (2019). Figure 8 represents how different porosities of commercially available textile fabric affect $\varepsilon_r$ and $\tan\delta$, illustrating applicability for on-body worn communications. All analyzed materials in Ibanez-Labiano and Alomainy (2020) exhibited preferable performance as dielectric substrates for wearable antennas, with the 3D knitted fabrics presenting the best results (Loss et al., 2019). Figure 8 elucidates that increase in porosity of the substrate decreases the dielectric constant exponentially; furthermore, warp-knitted spacer fabrics have a significantly low surface volume fraction than sandwiched-knitted dielectric substrates. The honeycomb structure is the most porous warp-knitted structure with the lowest surface volume fraction and superior moisture management properties. This is an area that requires further investigation and can be further explored by incorporating these structures in 3D composite antennas for wideband applications.

Common practical problems associated with knitted substrates are related to mechanical stabilization, bending deformation and assembling of multiple layers. Spacer-knitted fabrics, however, mitigate these issues since the dielectric substrate can be modified and fabricated in a single process, considering $\varepsilon_r$, $\tan\delta$, and $h$. Locher et al. (2006) experimented with commercially available polyamide spacer fabric to develop purely textile patch antennas for WPAN (Wireless Personal Area Network) applications. The findings substantiated that the effect of moisture on EM (Electromagnetic) properties can be mitigated using knitted-based spacer fabrics as no significant permittivity variation was presented under extensive humidity conditions, covering a range from 20%RH to 80%RH at 25°C.
With the continual advances in 3D composites, previous studies can be further extended for exploring various warp-knitted pattern variants like fillet hexagonal structures based on the antenna application.

5.2. Effect of the thickness of the dielectric substrate for antenna performance

As mentioned in Section 4, height of the dielectric substrate is a crucial parameter in determining the dimensions of microstrip antennas. The effect of this parameter—based on gain, bandwidth, and radiation efficiency—will be further discussed in this section, referencing textile-based microstrip antennas. In microstrip patch antennas, according to the transmission-line model, the radiating patch and ground plane’s dimensions depend on three key parameters: the resonant frequency, the dielectric constant of the substrate, and the height of the dielectric substrate. Dimensions of the radiating patch determine the input impedance of the radiating patch, hence governing the performance of the antenna (Afridi, 2015; Mathur et al., 2015; Paraskevopoulos et al., 2016; Zhang, 2014). Therefore, the thickness of the dielectric substrate is a crucial parameter for designing microstrip antennas.

Several authors have studied the effect of substrate thickness on antenna performance. Generally, when we increase the thickness of the dielectric substrate, more fringing effects occur, which leads to better performance in terms of bandwidth and radiation efficiency; however, beyond the optimum thickness, higher modes of surface waves are excited and we observe a reduction in bandwidth and radiation efficiency. Chandra Paul (2015) showed that an increase in substrate height increased the bandwidth of the inset-fed microstrip antenna. However, Chandra Paul (2015) observed a shift in operating frequency away from the desired resonant frequency. This study also showed that thicker material enables larger surface waves, which ultimately reduces the radiation efficiency. Vallozzi et al. (2016) proposed that the height of the dielectric substrate should typically be between 0.003λ and 0.05λ, and a further decrease in substrate height increases the conduction loss. Similarly, substrates exceeding the optimum height lead to excite higher modes of surface waves and hence degrade radiation efficiency and antenna gain (Vallozzi et al., 2016). Surface wave loss, however, is
negligible for very thin substrates (substrate height \( h \ll \) wavelength, Zhang, 2014). Mishra et al. (2015) achieved similar results and proposed that substrate height and width of the radiating patch are equally important for maximizing radiation efficiency and bandwidth of microstrip antennas. Mohammed et al. (2020) also showed that there is an optimum thickness to maximize the return loss and gain of the microstrip antenna. The authors in (Mishra et al., 2015) substantiated that an increase in thickness of the dielectric substrate increases the fringing effect and hence improves bandwidth. A more detailed analysis of space radiation efficiency and surface wave losses was proposed by Gupta and Srivastava (2012). This paper analyzes the effect of the dielectric substrate height on the radiation efficiency of rectangular microstrip antennas, based on low permittivity (2.04 \( \leq \varepsilon_r \leq 2.17 \)) and high permittivity (6.702 \( \leq \varepsilon_r \leq 7.44 \)) multilayer dielectric substrates. For low permittivity substrates, radiation efficiency increased from 71.33% to 85.48%; surface wave losses increased from 3.91% to 13.48%, and bandwidth percentage increased from 1.87 to 5.82 with the change in height from 1.27 mm to 1.5 mm. However, with the change in height from 1.5 mm to 3 mm, radiation efficiency decreased from 85.48% to 80%, surface wave losses increased from 13.48% to 17.79%, and bandwidth percentage decreased from 5.82 to 4.07. The experienced variation in radiation efficiency and bandwidth on low permittivity substrates was attributed to surface waves that start dominating for heights greater than 1.5 mm. In the case of a high permittivity multilayer microstrip antenna, the radiation efficiency increased from 56.78% to 72.37%; surface wave losses increased from 7.76% to 26.86%, and bandwidth percentage increased from 2.14 to 4.45 with the change in height from 1.27 mm to 1.5 mm. Moreover, with the change in height from 1.5 mm to 3 mm, the radiation efficiency decreased from 72.37% to 63.21%, surface wave losses increased from 26.86% to 28.6%, and bandwidth percentage further increased from 4.45 to 4.85. This analysis can be merged with textile microstrip antennas to improve bandwidth and radiation efficiency by minimization of surface losses by changing the compositions of \( \varepsilon_r \) of different layers. Besides the one-step antenna fabrication method, the dielectric substrate is a composition of multilayers in most common sandwiched dielectric substrates; therefore, analysis of the effect of \( \varepsilon_r \) and thickness of each multilayer is essential to improve antenna bandwidth, radiation efficiency, and gain.

All these findings reported in the literature relate back to the concept of space radiation that was previously discussed. The Q-factor of space radiation (\( Q_r \)) is inversely proportional to the thickness of the dielectric substrate. Following this relationship, we can establish that the increase in substrate height, keeping the same \( L \) and \( W \), will decrease \( Q_r \). The cross-references of prior studies underpin the fact that there is a trade-off between antenna bandwidth and space radiation efficiency. It is therefore important that a balance is found between antenna bandwidth and radiation efficiency while setting the substrate height.

5.3. A novel approach for textile dielectric substrates

In recent studies, the authors have used the purest form of the knitted structures, planar structures for the dielectric substrate. The planar fabric is then sandwiched either using glue or stitching to get the required height(\( h \)). However, warp and weft spacer knitted fabrics which are characterized by the presence of successive yarn layers within the fabric structure, can be effectively used to serve this problem. These fabrics are made of two independent materials connected through either yarns or knitted layers (Figure 9c). The general method of fabricating spacer fabric is warp knitting technology (Figure 9b: Rachel spacer warp knitting). The issues related to knitted dielectric substrates are associated with mechanical stabilization, bending recovery, and assembling of multiple layers. However, spacer warp knitted fabrics mitigate these issues since the whole dielectric substrate can be customized and interlaced in a single process according to the determinant factors of the dielectric substrate: \( \varepsilon_r \), \( \tan \delta \), and \( h \). Moreover, the thickness of the dielectric substrate can be adjusted using the trick plate distance. Monofilament yarns such as polyester and polyamide can connect the top and bottom layers to impart an excellent bending recovery needed for
wearable antennas. As mentioned in Mukai and Suh (2019), the surface volume fraction of dielectric substrates is a determinant factor that affects the relative permittivity. However, warp-knitted spacer fabrics have a significantly lower surface volume fraction than those of sandwich knitted dielectric substrates. The honeycomb structure in Figure 9a is the most porous warp-knitted structure. Combining the top and bottom honeycomb open structures using a monofilament yarn creates a dielectric substrate with the lowest surface volume fraction for wearable antennas (Figure 9d). Moreover, these structures have superior moisture management and hence are more breathable. As the moisture content of the dielectric substrate increases $\varepsilon_r$, these structures are more suitable for wearable antennas. Although there is a dearth of literature review on composite spacer dielectric substrates, Locher et al. (2006) used a commercially available polyamide spacer fabric for microstrip antennas. However, there is great potential in the sector of wearable antennas to use more effective open structured spacer fabrics such as fillet hexagonal structures and research on various warp-knitted patterns based on their application.

6. Textile based antenna components

6.1. Compare fabrication methods antenna and ground plane

The choice of the conductive material for antenna components requires careful material characterization together with appropriate fabrication techniques to optimize antenna performance. The conductive material should possess a very low electrical resistivity to minimize the electric losses. As discussed above, the anisotropic nature of the textiles creates some discontinuities in the electric current. Suppose the discontinuities are parallel to the flow of current. In this case, they will not interfere with the electromagnetic field and wave propagation. Still, if the discontinuities impede the current flow, the increase in resistivity will interfere with electromagnetic fields and wave propagation. Moreover, textile antennas require optimization by considering application requirements and antenna fabrication techniques, including additional margins to accommodate adverse effects of body proximity, bending deformation and unpredictable environmental conditions.

There are two ways of producing a conductive fabric, i.e., (i) depositing a conductive layer on top of the non-conductive substrate via plating, coating, transfer printing and lamination, or (ii) conductive yarns can be intergraded onto a non-conductive substrate by using fabrication techniques, such as knitting, weaving, and embroidery (Locher et al., 2006; Möhring et al., 2006; Ouyang & Chappell, 2008). Locher et al. (2006) investigated the suitability of conductive fabrics for wearable antennas by differentiating plating, weaving, and knitting procedures. Ouyang and Chappell (2008) examined the same fabrication techniques for wearable antennas. Both researchers proposed that woven structures are more effective than knitted structures for conductive fabrics. Electro-textiles, which are commercially available, have been studied in the literature for radiating patch and ground plane. These fabrics are metal-plated fabrics—plated with conductive metals such as Copper, Nickel, and Silver. Agbor et al. (2018) used Copper Polyester Taffeta, Cobaitex, and ShieldIT electro textiles for the antenna and ground plane and experimentally showed that these fabrics have good impedance and radiation characteristics, with Copper Polyester Taffeta presenting the best results. Wahab Memon et al. (2020) used Electron fabric for antenna patch and ground plane—Electron is a thin copper-plated fabric. However, the main drawback of the conductive layer deposition method is associated with surface discontinuities that affect the continuous electric conduction. Locher et al. (2006) concluded that fabrics manufactured using electro-conductive textile yarns exhibit a higher antenna performance than metal-plated fabrics. This is attributed to the surface discontinuities found in the plated fabrics that increase the effective electric length. The Nickel-plated woven fabric in this study experienced non-plated sections, especially at crosses where warp and weft yarn interface. Consequently, yarns on the surface do not create a continuous path for the electric current, leading to higher resistance and higher conduction loss. Therefore, authors in Locher et al. (2006) concluded
that electro-conductive yarns are preferred over conductive layer deposition techniques for developing homogeneous conductive materials for textile antennas.

The process parameters, and merits and demerits of each fabrication technique are discussed in detail in the following sub-sections.

6.2. Knitted antenna

Although there have been several studies on woven and embroidered antennas, the research in knitted antennas remains limited. Zhang et al. (2013) fabricated a fully knitted antenna with a knitted ground plane, knitted dielectric substrate, and knitted patch. The results showed that return loss (S11) of the knitted antenna improves when the design of the knitted radiator becomes denser. Patron et al., 2016 showed the same conclusions that loops should be tightly knitted to ensure good conductivity in the overall design and improve antenna performance. In this study, Patron et al. (2016) experienced a 10 dB bandwidth in return loss, covering the desired frequency range of 100 MHz. This yield in bandwidth is attributed to the lossy structure of the knitted radiator.

Compared to all fabrication procedures, the knitting technique produces sufficient elasticity for stretchable antenna systems. For instance, knitted antennas outperform woven and embroidered antennas for wearable sportswear applications, which demand high mobility and comfort for users. Knitted fabrics, however, stretch on both axis: y-axis and x-axis. Subsequently, conductive materials developed via knitting technique may undergo significant fluctuations in sheet resistance due to the stretching effect. In support of this argument, Locher et al. (2006) showed that elongation along the y-axis has a minor effect on the sheet resistance, whereas elongation along the x-axis has a significant impact on the sheet resistance. Furthermore, the sheet resistance curve against elongation follows a linear pattern at small elongations below 4%. Collectively, Locher et al. (2006) suggested that the stretching effect on both axis should be taken into account while designing knitted antennas since stretching affect the sheet resistance and hence the conduction; Jia (2020), however, proved that 3D flatbed-knitted textile waveguide provides a stable performance in terms of gain, radiation efficiency, and bandwidth under H and E planes bending unless a severe shape distortion occurred. Subsequently, the author further examined how slotted waveguide 3D antennas perform under bending conditions. The comparison of findings between the two antenna designs highlights an important aspect that needs further research. In this study, the author proposed that optimization techniques for antenna design may create adverse effects as slotted waveguide 3D knitted antenna underperformed compared to the antenna without slots, under H and E bending.

Similarly, agreeing with the recent literature on the effective conductive path, several studies experimentally proved that the electric current path of knitted antennas is highly dependent on the direction of the current flow, which determines the length of the conduction path and hence the resistance of the radiator (Tess; Tess Acti et al., 2015; Zhang, 2014). Due to the interlacing loop structure, the knitting process creates the longest electric path than weaving and embroidery procedures (Jia, 2020). In knitted conductive materials, conductive paths run in all directions. When adjacent loops are loosely interlaced, the conductivity through these current paths is not uniform, and therefore conduction through point connections dissipates more conduction losses than conduction via conductive threads (Ouyang & Chappell, 2008). To mitigate this issue, previous studies proposed that higher loop density reduces the conduction loss (Patron et al., 2016; Zhang et al., 2013). On the contrary, a recent research suggested that the increase in loop density increases the biaxial anisotropic resistance (Tokarska, 2019). The increase in anisotropic resistance can be argued due to the fact that the author in Tokarska (2019) used plated-knitted fabrics for this experiment. This reason alone may lead to increased conduction loss; however, further research is required to establish a strong relationship between loop density and electrical resistance. Loop length, which is influenced by the gauge of the machine, is a prime factor that
determines the loop geometry and loop density of knitted substrates. Referring Section 4, controlling variables that are related to the loop geometry is of the utmost importance for knitted antennas. Apart from loop length, the knitting technique equally plays an essential role on the antenna’s performance. There are several knitted structures that can be used to fabricate antennas: yarn plating, wrap knitting, single jersey, double jersey, etc. Complex planar knitting topologies increase the heterogeneities and create a lossy surface, reducing the Q factor of the antenna. A single jersey is the simplest knit structure, and hence less variables to control during the knitting process. Despite being the simplest planar structure, the single jersey structure enables to fabricate planar complex topologies with minimal bulkiness and fewer heterogeneities. These advantages have attracted researchers to use single jersey structures to fabricate radiating patches and ground planes of the knitted antennas (Jia, 2020; Möhring et al., 2006; Tess Acti et al., 2015). However, single jersey fabrics have an unbalanced residual torque after knitting, which leads to edge curling. Mechanical stabilization is an essential characteristic to retain stable antenna performance, and therefore problems associated with edge curling should be addressed. Locher et al. (2006) proposed to use a non-knitted ground

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**Figure 10.** A schematic explaining the possibility of one-step seamless integration of wearable antennas by using flatbed knitting technology: (a) The concept illustration of fabricating a wearable pressure sensor by using MXene coated cellulose yarns which can be further extended to integrate planar antenna structures on to the garment; (b) Single Jersey, Half gauge and Interlock knit structures to fabricate conductive components of the wearable sensor. Figures (a–b) reprinted with permission from Uzun et al. (2019), Copyright 2019 John Wiley & Sons: Hoboken, NJ, USA.

**Figure 11.** A novel approach to produce a 3D composite warp knitted antenna using spatial fabrication technique, a concept developed through spacer fabric fabrication technique; radiator patch and ground plane are fabricated using a tricot structure; the rest of the dielectric substrate is fabricated using a hexagonal structure.
plane or dielectric substrate in the presence of a knitted radiator to retain mechanical stabilization.

Although there are few limitations, the knitting process allows single-step fabrication of both base fabric and antenna design, thus enabling seamless integration onto the textile. Patron et al. (2016) developed a fully knitted dipole antenna in one step for wearable applications. The authors designed a small pocket by knitting between the two arms of the dipole and used it to integrate an RFID microchip without soldering or using conductive epoxy resin. This kind of seamless integration avoids the impedance variation due to deformation and coupling reduction between microchip and antenna.

6.2.1. The new approach for textile knitted microstrip antennas (one-step knitted antenna)

Even though there are few limitations in knitted antennas, conductive and non-conductive yarns can be knitted in a single process enabling seamless integration onto the garments. This kind of one-step integration process eliminates the degradation in antenna performance due to bulkiness and electrical losses. However, the existing literature has only studied single jersey knitted antennas to fabricate in a one-step knitting process that can only be used for planar antennas such as dipole, which does not require a specified ground plane (Patron et al., 2016). The authors in (Patron et al., 2016) developed a fully knitted dipole antenna using single jersey structures in a single process for wearable applications. T. However, the jersey knitting method cannot produce a sandwich structure for microstrip antennas. Therefore, it requires a 3D spatial fabrication technique to produce a radiator, a dielectric substrate, and a ground plane in a one-step process. Figure 11 represents a possible one-step knitted antenna based on the warp knitted spacer fabrication method. The radiator on the top layer of the dielectric substrate is knitted using a tricot structure that is the simplest warp knitted structure to create the shortest electric path. The rest of the dielectric substrate in the top layer is knitted using a fillet hexagon structure. The ground plane is knitted using the same tricot structure as the radiator. However, further research is required to develop lockknit and other dense structures for conductive material due to the lower cover factor in tricot structures. The electronic flat-knitting technique can also be used to design 3D composite materials in a single process. Electronic flatbed knitting machines offer patterning options for 3D and 2D shapes. Furthermore, the computerized patterning option allows to develop intricate microstrip antenna designs for wearable applications. The entire antenna design—the radiating patch, ground plane, and dielectric substrate (spacer layers)—can be knitted in a single process. Such continuous processes for E-textiles have obvious advantages because of their low cost and high efficiency in terms of manufacturing time. However, several questions regarding structural variants remain to be addressed. The effect of pattern variants on textile sensors or antennas has been assessed only to a very limited extent.

Uzun et al. (2019) analyzed the suitability of weft-knitted structures such as single jersey, half gauge, and interlock structures to fabricate a knitted capacitive pressure sensor device using MXene-coated conductive yarns. Figure 10 dictates how the conductive yarn is incorporated to create different knit structures. However, during the experiment, breakages were observed in the single jersey structure due to lower flexibility with the conductive yarn. The yarn breakage can be attributed to yarn-to-yarn abrasion with small bending radius when loops of single jersey structures are formed using every needle adjacent to each other on the needle bed. The half gauge structure of (Uzun et al., 2019) forms a porous structure where every other needle in the bed forms loops. These structures impart a higher stretchability than single jersey structures and can be used to fabricate sensors in stretchable areas. However, these structures are not suitable for wearable microstrip antennas since high stretchability changes antenna input impedance and radiation efficiency. Despite the fact that planar knit structures suffer from mechanical stabilization, it can be argued that the most suitable knit structures through flatbed knitting technology for wearable antennas are interlock structures. The interlock structures are produced by two feeder systems, each with a separate needle bed.
producing a half gauge structure whose sinker loops cross over each other. The interlock structure provides a mechanically more stable and dense fabric than other weft knitted structures. However, antenna characteristics with other structural variants like interlock are insufficiently explored in the literature.

6.3. Woven antenna
For woven conductive materials, a compact design with a high density of conductive threads leads to a higher effective conductivity (Ouyang & Chappell, 2008). Conductive yarns, however, alone cannot create a compact structure due to process constraints. Thread density—ends per inch and picks per inch—is the main parameter that should be considered for creating a compact design. Furthermore, thread density determines the resistance and conduction loss of the conductive woven materials (Tess Acti et al., 2015; E. Moradi et al., 2012; Ukkonen et al., 2012). In line with the weaving specifications, the increase in the number of warp yarns increases the end density (ends per inch). Similarly, increasing warp yarn tension and weft picking speed increase the pick density (picks per inch). It is, therefore, challenging to fabricate compact woven antenna designs because conductive yarns may undergo high strain and mechanical abrasion due to yarn-to-yarn abrasion and yarn-to-machine abrasion, with the increase in thread density. A higher level of abrasion applied to conductive yarns will create fuzziness and yarn filamenting, creating a lossy surface to increase current discontinuities. Furthermore, the conductive layer on the yarn surface has a tendency to peel off during the motions—shedding, picking, and beating—due to the abrasion between yarn and machine parts. Similarly, high-speed and high-tension lead to a higher percentage of yarn breakages by creating defects like start-up marks, which is undesirable for fabricating a homogeneous conductive material. In such situations, to overcome these issues, the conductive yarn must be drafted and twisted with a non-conductive yarn to make it suitable for weaving. This may in return increase the contact resistance of the conductive yarns, resulting in a higher conduction loss.
Several studies have developed woven radiators in the antenna design with mono yarns—the mono yarn is a non-conductive yarn plated with a conductive material that serves both yarn strength and conductivity. Although it was not mentioned in these studies, to minimize fuzziness and yarn filamenting, conductive yarn should be used in the weft direction. Alonso-Gonzalez et al. (2018) developed a woven microstrip-fed slot antenna for short-range communications (5.9 GHz and 9.3% bandwidth). The three layers of the microstrip antenna were connected by only one conductive thread, and the slot was created using a stenter machine. Locher et al. (2006) used a silver-copper-nickel plated polyamide yarn to fabricate a woven microstrip antenna patch. This study shows that woven fabric possesses better electric properties than its knitted counterpart due to low sheet resistance and geometrical accuracy. Ouyang and Chappell (2008) examined the electrical conduction of 100% knit fabric by using X-static® conductive yarn and satin woven fabric by using X-static® conductive yarn/Codura-Lycra non-conductive yarn. The results of this study established that woven patterns are much more efficient than knit patterns since woven structures show a better alignment with the current direction. Ouyang and Chappell (2008) also examined the effect of pattern variants on the electrical properties of woven antennas by comparing four different asymmetric satin weave patterns: 4/1(satin 5), 9/1(satin 10), 15/1(satin 16), and double face satin 4. The ratio between metallic surface and fabric surface is 4:1 for satin 5. In (Ouyang & Chappell, 2008), the author pointed out an interesting aspect regarding the pattern variations, based on the effective conductivity. Even though it was presumed that the increase in conductive surface ratio (conductive thread density) increases the effective conductivity, the assumptions were not substantiated experimentally. On the contrary, stain 5 showed the highest effective conductivity, and satin 16 showed the lowest conductivity. These results are attributed to the loosely bound connections of the conductive yarn as the weaving ratio increases, which creates a longer path for the current. Hence, to improve the optimum interconnections between conductive threads, as already described under Section 4, the pick spacing (d) should be reduced with the increase in the weaving ratio. Consequently, Ouyang and Chappell

Figure 13. Parallel and Perpendicular embroidery in antennas: (a) Illustration of the return loss(S11) for different stitch spacings in perpendicular direction; (b) Physical appearance of embroidered line with stitch spacing 0.4 mm and 0.8 mm and stitch direction in the perpendicular direction. (c) Physical appearance of embroidered line with stitch spacing 0.4 mm and 0.8 mm and stitch direction in the parallel direction. (d) Illustration of the return loss (S11) for different stitch spacings in parallel direction. Figure (a-d) reprinted with permission from Zhang (2014), 2014 CC BY-NC 4.0 license, Loughborough University, UK.
(2008) elucidated an optimum level of interconnection of conductive threads, determined by the weave pattern, for minimum conduction loss.

6.3.1. The new trend for woven microstrip antennas (one-step woven antennas)
As discussed in Section 3.1, 3D orthogonal weaving can be used to develop woven antennas in a one-step process, avoiding additional-assembling process to sandwich multiple layers. There are three types of yarns used in orthogonal weaving: warp, weft, and Z yarn (Figure 12a). These sets of threads are interlaced to form a composite structure wherein warp yarns are longitudinal, and weft and Z yarns are orthogonal. The Z yarn in the woven composite binds the preform through the thickness direction. Xu et al. (2013) developed a three-dimensional integrated microstrip antenna (3DIMA) via orthogonal weaving technique. The performance of the antenna between parallel and perpendicular stitch directions was also examined (Figure 12c,d). In parallel-3DIMA, the current flows in parallel to the feeding direction, whereas the current flows in the perpendicular to the feeding direction in perpendicular-3DIMA (Figure 12b). The experimental results show that perpendicular-3DIMA has a larger back lobe, side lobes, and lower gain value than parallel-3DIMA. The VSWR (Voltage Standing Wave Ratio) and radiation pattern of parallel-3DIMA showed similar characteristics as conventional copper microstrip antenna (Figure 12c,d). These findings can be linked to the higher conduction loss in the perpendicular stitch direction—the effective electrical length in the perpendicular direction is significantly higher than that of parallel direction (Figure 9b). Gimpel et al. (2004) developed a woven RFID tag antenna using multi-layer Jacquard weaving technology to eliminate the cut and assembly process to produce multi-layers. In Gimpel et al. (2004), on the top layer (radiating patch), conductive yarns were used in the weft direction, and conductive yarns were incorporated in the warp direction on the bottom layer. Both conductive layers were separated from an insulation layer. Xu et al. (2020) developed a 3D woven spacer microstrip antenna (3DWS-MA) using the same technique—orthogonal weaving—for GPS applications. The 3DWS-MA had a spacer dielectric structure with a high air volume fraction, leading to very low density (0.5 g/cm³), dielectric constant (1.75) and dielectric loss (0.0085). The 3DWS-MAs with single and double elements showed gain values of 7.1 dB and 9.3 dB, respectively, much higher than traditional microstrip antenna (2.5 dB). Moreover, Alonso et al. (2015) developed a millimetre wave TIW slotted beamforming antenna for radar application using a flat weaving machine, avoiding the use of Jacquard or 3D weaving machines. The TIW antenna performed with the frequency band of 70–77 GHz, similar to the simulated SIW band of 70–79 GHz band. Further, the simulated SIW antenna pointed an angle from 7 to 22 degrees. The beam tilt angle of TIW showed a good agreement with the simulated SIW antenna, covering 11 to 23 degrees. On this basis, composite antennas have broad applications for wearable interactive systems. All these research findings direct towards an interesting research field for future work to explore more on composite woven antennas and experiment on their adaptability for microwave applications.

6.4. Embroidered antenna
Embroidery is the most attractive technique among researchers to fabricate textile antennas. For instance, RFID applications-patch antennas (Chen et al., 2017; El Gharbi et al., 2020; Swarnakar & Sarkar, 2018; L. Xu et al., 2018), dipole antennas (Gil et al., 2019; B. Moradi et al., 2020), array antennas (Mao et al., 2020) and antennas with meander lines (Y. Liu et al., 2019). The embroidery geometry is much more stretchable than metallic antennas and inlays; therefore, the stretching effect combined with the low resolution of the yarn stitches creates a fine geometry for textile-based antennas (Y. Liu et al., 2019). The main advantage of the embroidery technique over weaving and knitting is that sheet resistance can be easily adjusted by controlling the stitch spacing (distance between two stitches) and stitch direction (horizontal, diagonal, vertical, zig zag, etc.). Furthermore, without controlling complex parameters, a homogeneous sheet resistance for complex topologies can be achieved by designing through CAD (Computer-aided design) software. Embroidering is also
a promising technique to fabricate conformal antenna designs and integrate them into textiles in an aesthetically pleasing manner. Therefore, embroidering electronic components into textiles for various wearable applications has been explored by many researchers (Anbalagan et al., 2020; El Gharbi et al., 2020; Koski et al., 2013, 2014; Y. Liu et al., 2019; Song et al., 2019).

Koski et al. (2014) developed an embroidered 866 MHz RFID radiating patch and compared its performance, with an equivalent copper-plated radiating patch. The experiment was conducted by positioning the antenna on the arm while taking measurements. The read range of the embroidered antenna was on the lower side than that of the equivalent copper fabric antenna. However, the embroidered antenna provides better performance in terms of flexibility, robustness, and isolation between antenna and body. The paper (Koski et al., 2014) further indicates that the embroidery technique provides similar link loss and shadowing effects similar to that of copper fabric antennas. Y. Liu et al. (2019) investigated how parasitic capacitance affects the performance of embroidered dipole antennas by comparing antennas with different meander lines. The author experimentally proved the fact that simple rectilinear geometry with fewer bends avoids the parasitic capacitance of embroidered designs.

The effective electric length of an embroidered antenna depends on the stitch direction and stitch spacing. The lower stitch spacing increases the point interconnection between adjacent stitches via loose fibers, hence reduces the effective electrical length (De Holanda et al., 2017). A higher stitch spacing increases the gap between adjacent stitches, hence increasing the contact resistance, which in turn increases the effective electrical length (Figure 13b,c). As discussed in Section 4, stitches in parallel stitch direction create a lower resistance and hence low conduction loss than stitches in the perpendicular direction, resulting in lower insertion loss (Figure 13a). A higher conduction loss results in a higher insertion loss, and therefore perpendicular embroidery technique is not suitable for fabricating antenna’s conductive components (Figure 13d).
Koski et al. (2013) used embroidered ground planes with different stitch densities and different directions to analyze the effect of ground plane structure on UHF RFID tag performance (Figure 11di). The author (Koski et al., 2013) pointed out that embroidery patterns with longer current paths showed a shift towards a higher frequency level. Moreover, the increase in thread density beyond the optimum density decreases the tag electrical length but reduces the read range due to interactions of threads in the dense pattern (Figure 11di). Anbalagan et al. (2020) analyzed the performance of a rectangular patch antenna with and without a slot. The performance of the antenna with the slot had a higher S11 (~16.97 dB) and gain (4.34 dBi) than the antenna without the slot (S11: ~1.159 dB and gain: 1.14 dBi). The increase of the slot width and length, each from 8 mm to 12 mm, increased the return loss and, however, obtained the highest return loss for 10 mm length. The effective electrical length of an embroidered antenna depends on the stitch direction and stitch spacing. Similar to weaving and knitting techniques, a higher stitch spacing increases the gap between adjacent stitches, increasing the contact resistance. This increase in contact resistance eventually increases the effective electrical length. Similarly, the lower stitch spacing increases the point interconnections between adjacent stitches via loose fibers and reduces the effective electrical length (Zhang, 2014). However, the increase in thread density beyond the optimum density decreases the tag electrical length but reduces the performance due to the interaction of threads in the dense pattern (Koski et al., 2013; Song et al., 2019).

Despite many advantages of embroidered antennas over knitted and woven antennas, embroidery techniques are only limited to antenna designs that do not require a separate ground plane or separate assembling process. Therefore, embroidery technique cannot be used as a one-step integration technique for designing microstrip antennas; instead, it is commonly used for dipole type antenna designs.
6.4.1. Embroidered textile antennas for communications

El Gharbi et al. (2020) designed an embroidered circular patch antenna over a felt material with a T-shaped slot, microstrip feed line, and partially embroidered ground plane for ultra-wideband microwave applications. The proposed antenna is operated within the Ultra-Wideband range of 3.1–10.6 GHz with over 60% efficiency. The effect of bending was also studied for on-body communications, considering a typical bending human-shape radius of 30 mm and 45 mm. The researchers showed that the increase in bending radius increases the detuning of the resonant frequency. A similar experiment was conducted by Swarnakar and Sarkar (2018) to fabricate an antenna design over a denim jean material. The design consists of an optimized embroidered circular patch with a central square slot surrounded by four symmetrically placed thin rectangular slots, a microstrip feeding line, and a partially embroidered ground plane. The wearable antenna of Swarnakar and Sarkar (2018) showed its adaptability for body-centric wireless and satellite communication, covering five frequency bands between 2 GHz and 18 GHz with impedance bandwidth percentages of 27.44%, 20.88%, 17.35%, 23.13%, and 36.80%. Wang et al. (2012) developed an embroidered patch antenna array on a PDMS polymer substrate with a resonant frequency of 2.31 GHz and a realized gain of 7.0 dB. This gain was only 0.6 dB lower than the measured gain of the equivalent copper array counterpart, and the resonant frequency was almost the same as that of the copper patch array. In Wang et al. (2012), the authors also measured the RF performance of embroidered and equivalent copper patch antennas on a metallic cylinder surface of 80 mm diameter. Even though the realized gain of the embroidered array antenna was 4.6 dB on the curvilinear cylindrical surface, there was a good agreement with the RF (Radio Frequency) performance of copper array antenna. The resonant frequency of both copper and the embroidered antenna was 2.33 GHz, and the gain of the embroidered antenna was only 0.8 dB lower than the copper counterpart on the curvilinear surface. Wang et al. (2014) proposed a novel embroidered body-worn multiband patch antenna covering GSM/PCS/WLAN communications, Mobile Communications (GSM 850/900 MHz), Personal Communications Service (PCS 1800/1900 MHz), and Wireless Local Area Network (WLAN 2450 MHz) bands. The proposed antenna consists of two asymmetric antenna arms with slots and a feeding port between the arms. This antenna (Wang et al., 2014) also includes a loaded loop for impedance matching (S11 < −10 dB) at all three frequency bands. The impedance tuning was done with the help of a shorted transmission-line stub. Furthermore, the detuning of resonant frequencies for all three bands and radiation pattern shadowing at different body positions were also examined. This research showed that antennas need to be placed at least 10 mm away from the body tissue to mitigate unfavourable body effects and retain sufficient bandwidths in all three bands. While analyzing the interaction of the antenna with the human body, the author in Wang et al. (2014) proposed shoulder area as the best position to mount the antenna for minimizing shadowing of the radiation pattern. The shoulder-mounted antenna provided the strongest cross-polarization with an improved radiation pattern in the upper hemisphere, compared to locations of front and back torso and arm. Figure 14.

7. Selection of conductive yarns

Conventional conductive yarns are either thin-steel yarns made by twisting Nickel, Copper, Aluminum, and other conductive metal monofilament fibers or composite yarns wrapped in a non-conductive yarn. There are two primary methods of developing conductive composite yarns: 1) a metal monofilament is wrapped and twisted with a non-conductive yarn and then plied to form a composite yarn; and 2) a metal monofilament is wrapped and twisted with a non-conductive yarn, then plied and wrapped with a reinforcing polymer yarn and finally twisted to form reinforced composite yarn (Figure 15a). The main drawback of conductive composite yarn is associated with the contact resistance that edges adjacent unit cells. The increased contact resistance of composite conductive yarns can be attributed to point interactions between conductive and non-conductive areas in adjacent unit cells. This may ultimately lead to a comparatively high electric length for textile antennas due to discontinuities via non-conductive gaps. Technically, the contact resistance can be reduced by increasing the twist factor.
of the composite yarn; however, the increase in twist factor increases the number of turns per unit length, hence the DC resistance per unit length and conduction loss (Figure 15ii). In the case of conventional metal yarns, yarn dynamics do not provide the desirable characteristics of a standard textile yarn during manufacturing. The difficulty of going through metal contact points due to high surface friction at high speeds, thread breakages, fraying at high thread tension, permanent deformation, and poor recovery are some of the undesirable issues associated with metal yarns. To overcome these issues with metal and composite yarns, researchers have explored techniques for metallocizing textile yarns via a thin conductive layer that covers the fiber or yarn surface. Such techniques include dip-coating with Intrinsically Conducting Polymers (ICPs; Allison et al., 2017; Onggar et al., 2020) and electrically conductive filler materials, such as Carbon Black (CB; Onggar et al., 2020), Graphene (Onggar et al., 2020) and Carbon Nanotubes (CNT; Allison et al., 2017); Vapor deposition (Allison et al., 2017), electroplating (Onggar et al., 2020), electroless plating (Jiang & Guo, 2009; X. Liu et al., 2010), plasma sputtering (Hegemann et al., 2009), Atomic Transfer Radical Polymerization (ATRP; X. Liu et al., 2010), and Atomic Layer Deposition (ALD; Lee et al., 2016). Figure 15d represents a SEM image of copper-coated PET (Polyester) yarn by electroless plating technique: the technique provides a uniform and highly covered conductive layer around fibers. Figure 15e compares the electrical resistivity of silver electroless plated and plasma coated silver fibers with the number of washing cycles. It was also observed that conductive coating by plasma sputtering exhibited a resistive coating rather than electroless plating.

There are several conductive yarns in the market with similar characteristics of a textile yarn. They are either made of Carbon, Nylon, or Zylon® cores coated with Silver, Nickel, Aluminum, or Copper metals. Most of the commercially available conductive yarns are multifilament yarns with fibers in μm diameter twisted together (Figure 15c). The single fiber has a polymer core that provides flexibility and tensile strength and is coated with a thin layer of a conductive metal to provide the
### Table 2. Conductive yarns used in the previous researches for fabricating wearable antennas

| Ref | Name | Technology | DC resistance (Ω/m) | Diameter (mm) | Supplier | Merit | Demerits |
|-----|------|------------|---------------------|---------------|----------|-------|----------|
| (Garnier et al., 2020; Ismar et al., 2020) | TibTech Datatrans | Twisted polyester, polyamide and four copper micro filaments | 4.2 | 0.28 | TIBTECH INOVATIONS.INC | Higher electric conductivity, Smooth surface, mechanical performance is close to ordinary yarns | High stiffness |
| (Kourtí et al., 2016) | 7-filament silver-plated copper Elektrisola | Silver plated copper multifilament | 1.9 | 0.12 | ELEKTRISOLA | Lower tension and higher flexibility, and can lead to geometrical precision for intricate designs. Silver coating provides high corrosion resistance. Good solderability for electrical contacts | High stiffness. Less flexibility compared to metal-coated textile yarns |
| (Y. Liu et al., 2019) | SILVERPAM25 | Silver grafted | 50 | 0.08 | TIBTECH INOVATIONS.INC | Light weight, smooth surface and good elasticity. Can be used for demanding E.M. Shielding applications | Break under high speed and tension. Avoid whitening and oxidizing washing agents |
| (L. Xu et al., 2018) | Shieldex® 235/36 dtex 4-ply HC +B | Silver plated polyamide yarns | 33 | 0.6 | Statex Inc | Anti-static and Antibacterial Properties, | Large diameter than standard sewing thread |
| (L. Xu et al., 2018) | Liberator™ 40 | Nickel-copper braids | 3.3 | 0.4 | Syscom Advanced Materials Inc | Higher electric conductivity, Higher strength and higher thermal stability | Fuzziness after embroidery, Light twisted |
| (Tess Acti et al., 2015; Seager et al., 2013; Swarnakar & Sarkar, 2018) | Amberstand 66 | Silver coated | 0.1 | 0.065 | Syscom Advanced Materials Inc | Higher conductivity, Higher breaking force, Light weight | Fuzziness and filamenting due to higher number of monofilaments, lesser stretch ability |
| (Zhang, 2014) | Amberstand 166 | Silver coated | 0.25 | 0.103 | Syscom Advanced Materials Inc | Higher conductivity, Higher breaking force, Light weight | Fuzziness and filamenting due to higher number of monofilaments, lesser stretch ability |
| (Ouyang & Chappell, 2008) | Copper monofilament | Silver coated | 0.093 | 0.159 | - | Higher conductivity, Light weight | Break under high speed and tension |
Figure 17. Developing textile antennas with a higher resolution: (a) Comparison of geometry precision and accuracy of antennas embroidered with commercial conductive yarns and future ultra-fine thin yarn; (b) A schematic of low-voltage NFES setup; (c) Deposition pattern of nanofibers formed by high-voltage NFES(first two images the on left) and deposition pattern of nanofibers formed by low-voltage NFES(last two images on the right); (d) Comparison of current and future technology of embroidered antennas; (e) A schematic illustration of the fabrication process for the conductive SWNT/MWNT yarn; (f) Traditional cloth knitted with SMTY yarn. Figures (a & d) reprinted with permission from Z. Z. Wang et al. (2015), Copyright 2015 Elsevier: Amsterdam, Netherlands. Figures (b & c) reprinted with permission from Bisht et al. (2011), Copyright 2011 ACS Publishing: Washington, D.C. Figures (e & f) reprinted with permission from Y. Y. Li et al. (2018), Copyright 2018 Royal Society of Chemistry: Burlington House London.

electric conductivity (Figure 15b). Ouyang and Chappell (2008) experimentally showed that monofilament conductive yarns are better in conductivity than multifilament yarns because multiple conductive fibers increase the surface area and lead to a higher conduction loss. Moreover, multifilament fibers force the current to follow the filaments’ path, not preferably straight, increasing the resistance. The electromagnetic properties of fiber-based conductive yarns are different from their metal counterparts used in conventional microwave applications. Previous researches have examined the electric properties of various conductive yarns in terms of yarn resistance and their applicability for high-frequency applications (Tessa Acti et al., n.d.; Ouyang & Chappell, 2008; Seager et al., 2013; Zhang, 2014). The skin effect of conductive yarns reduces the effective conductive cross-section in which the current density is distributed(Koski et al., 2014). Therefore, when selecting a conductive yarn for high-frequency applications, especially for antennas, the thickness of the conductive layer should be taken into account, referring to the skin depth (G. Alonso-gonzález et al., 2017). Skin depth is one of the important parameters in determining the conductor thickness, yarn metalizing technique—conductive layer deposition method, and conductor material. For microwave applications, following Equality 10, a higher frequency results in a smaller skin depth. However, a smaller skin depth reduces the effective cross section and hence increases the effective electrical resistance. Though the increase in resistance with frequency seems undesirable, the RF losses per wavelength actually decreases. If the skin depth is larger than the conductor thickness, the current density is forced to distribute across the conductor thickness. This will result in resonating or interfering with the signal transmission and reception (Swarnakar & Sarkar, 2018). Similarly, a higher conductor thickness, exceeding the skin depth will add up unnecessary material cost and weight in terms of material consumption. Similar to the effective cross section, the length of the conductor also plays a vital role. Following Equation 11, the effective length of the conductive yarn
should be comparatively small to minimize the effective resistance. Therefore, the filament packing density and the diameter of the monofilament should be optimized to reduce resistance and improve conductivity (Swarnakar & Sarkar, 2018). Table 2 represents an analysis of conductive yarns used in previous studies for wearable antennas.

\[ \delta \propto \frac{1}{\sqrt{f}} \]  

(10)

\[ R = \frac{\rho l}{A} \]  

(11)

8. Future work: electrospun conductive mats and yarns for antennas

The future goal in the field of textile-based antennas is to fabricate conformal antenna designs with clean and sharp edges/corners and develop antennas with a conductive surface volume similar to their metal counterparts (Figure 17a). Figure 17d represents a typical illustration of a symmetrical embroidered mesh with a higher conductive surface volume (Z. Wang et al., 2015). However, developing such conductive components without degrading the conductivity is still a challenge. Until now, research focused on developing textile conductive meshes has only been limited to weaving, knitting, and embroidery fabrication techniques, and the emphasis on non-woven textile antennas has not yet been substantiated. To fill the gap, electrospinning has shown great promise to produce oriented conductive nonwovens via ultrafine conductive fibers (Xue et al., 2019; Figure 16a). Electrospun nonwoven meshes possess a higher surface volume fraction than meshes made by knitting, weaving, and embroidery methods. This method creates a layer with conductive phases connected to a continuous conductive path on the fabric surface. Moreover, it renders a multistrand structure with a high surface area, resulting in a high conductivity that is comparable to copper. The oriented electrospun composites can drive future work on textile antennas because continuous networks of conductive fillers can eliminate the electric discontinuities found in conventional textile fabrication methods. The methodology for developing a conductive electrospun composite is based on the integration of conductive nanoparticles or nanosheets. Figure 16b represents a methodology proposed in Guo et al. (2019) in which a stratified conductive electrospun mat was developed using a composition of Graphite nanoplatelets (GNPs) fillers and Polystyrene (PS). For oriented GNPs/PS composites, the authors in Guo et al. (2019) pointed out that GNPs fillers can interconnect with each other to form effectively conductive networks when GNPs fillers loading was more than 15 wt%. Figure 16f represents how the increase in GNPs filler percentage increases the surface volume of the composite and network matrix. The conductivity of random GNPs/PS composites is lower than that of oriented GNPs/PS composites because there are many interfaces between GNPs fillers and PS matrix, but not between GNPs/GNPs filler cells (Figure 16e). EMI performance of oriented GNPs/PS composites is higher than random GNPs/PS composite due to stratified network of conductive fillers (Figure 16d), thus enabling electrospun GNPs/PS composites to be used as a conductive material for antennas, especially in RFID systems.

A similar observation was made in Z. Li et al. (2020), where oriented conductive polymers were used to screenprint patch antenna conductive components to measure the RF (Radio Frequency) performance of patch antenna. Z. Li et al. (2020) used PEDOT: PSS (poly (3,4-ethylenedioxythiophene): polystyrene sulfonate) conductive polymer stems to fabricate the first ever all-organic screen-printed patch antenna on PET (Polyester) fabric—PEDOT is one of the sought-after conductive polymers due to higher conductivity and solution processability. As mentioned in Section 7, most of the conductive yarns experience a higher RF loss due to skin effect. However,
PEDOT: PSS oriented conductive layer utilizes the multistrand bundle structure, twisted and wound together, to form a unique 3D structure, which is similar to the high-frequency Litz wires on the fabric with a high RF conductivity (S11: ~50 dB and radiation efficiency: 28% at 2.35 GHz). Ultra-low sheet resistance was achieved on PEDOT: PSS surfaces (ground plane and patch radiator) with the help of enhancement in conductivity through nanoparticle assisted-chain orientation and phase-separation. A fumed silica nanoparticle network assisted this orientation and aggregation of PEDOT conductive on PET fabric surface. The silica nanoparticles induce sulphonate ester bonds, which remove PSS acid from PEDOT; upon drying under extremely low pH, there is a reaction between the -OH group on the silica surface and excess sulfonic acid groups of the PSS(Z. Li et al., 2020). These reactions lead to the formation of covalent bonds between the nanoparticles and the conducting PEDOT polymers, thus resulting in an oriented conductive layer. This method in Z. Li et al. (2020) creates a layer with conductive phases connected to a continuous conductive path on the surface. Hence, it renders into a multistrand structure, with a high surface area resulting in a higher conductivity comparable to copper. The experiments set up in Guo et al. (2019) and Z. Li et al. (2020) open the path for a new research field in wearable electronic and communication fields: chain-oriented conductive polymers that can be effectively used to compete with metal counterparts.

Next, developing scalable electrospun structures with conductive polymers has the potential to resemble conventional copper antennas. Recent advancements in Low Voltage Near-Field Electrospinning (LV NFES) technique allows to fabricate fine antenna geometries with perfect edges and corners. Recent developments in Near-Field electrospinning have produced encouraging results by opening up the possibility of achieving scalable precision patterning with polymeric nanofibers. Bisht et al. (2011) developed a continuous method for 2D and 3D nano substrates using low voltage near-field electrospinning (LV NFES; Figure 17b). This new methodology can be extended to fabricate conductive antenna components with geometric accuracy and resolution using conductive filler polymeric solutions. In this way, nanofibers can be directly written on the collector or dielectric substrate to produce a functional 3D microstructure by programming x, y, and z coordinates of the movable collector (Figure 17c, patterning effect). The embroidery technique produces the most precise geometry with defined corners and edges than patterns made by knitting or weaving. However, as shown in Figure 17a, the embroidery technique also suffers from achieving fine design details around edges and corners. The LV NFSS concept will serve this issue since nanofibers will be written on the pattern precisely. The technology of developing electrospun antennas by writing nanofibers on textile substrates via a programmed pattern opens a new direction for developing high precision wearable antennas that can have obsolete metal counterparts in smart textiles.

8.1. Conductive filler nanoplatelets based yarn
A general issue related to conductive yarns is that conductive coating is subjected to peeling off due to higher abrasive forces during production, leading to discontinuities in the electrical length. Another issue related to conductive yarns is attaining precise resolution and geometric accuracy without degrading the characteristics of standard textile yarn such as tensile strength and flexibility. As mentioned in Table 2, there are commercially available conductive yarns in μm diameter. However, the development of fine conductive yarns with superior textile characteristics and resistive conductive coating for peeling is still a challenge. Electrospinning with a conductive polymeric solution can mitigate these issues where nonconductive polymer composition in the polymeric solution serves characteristics of textile yarn, and conductive composition in the polymeric solution imparts the conductivity of the yarn. Common materials used in developing conductive polymers include electrically conductive filler materials such as Carbon Black (CB), Carbon Nanotubes (CNT), and Graphene. However, developing a continuous conductive matrix on the yarn is crucial; therefore, different composition ratios (non-conductive polymer/conductive polymer) should be tested to ascertain the optimum composition without degrading both conductivity and physical properties of a textile yarn.
(Guo et al., 2019; Y. Li et al., 2018; Z. Li et al., 2020). Y. Li et al. (2018) developed a mechanically strong, highly stretchable, and conductive SWNT/MWNT (Single-Wall Carbon Nanotube and Multi Wall Carbon Nanotube) yarn, which can be used in wearable electronics via a combined process of electrospinning, ultrasonication adsorbing, and bobbin winding process (Figure 17e). This process elucidates how yarns can be made from an electrospun non-woven fiber matrix by incorporating conductive polymer matrix modifications mentioned in (Y. Li et al., 2018; Z. Li et al., 2020). In the first step in Y. Li et al. (2018), TPU (Thermoplastic Polyurethane) fibers, which impart elasticity and flexibility, are electrospun onto a water bath to form a non-woven web. The conductive yarn’s physical properties can be modified by adjusting the polymeric solution, which is used to create the nonwoven fiber web. Next, the water is drained, and the fibers are bundled into a yarn with the aid of a godet roller (Figure 17e). It is further drawn to a U-shaped fiber in containers, which consists of SWNT and MWNT dispersions, and then subjected to ultrasonic adsorption of MWNTs and SWNTs. Finally, the yarn is air-dried with the aid of a hot winder and collected by a winding machine. It was also observed that the ultrasonication process provides a physical agitation to rearrange the stacking state of the fibers where absorbed MWNTs and SWNTs act as bridges between adjacent fibers by densely covering the spaces with carbon nanotube films and fiber surfaces. This process also elucidates the concept of chain-oriented conductive nanoplatelets connected to a continuous conductive path on the yarn surface for effective conductivity.

Further, the nonwoven fiber matrices discussed in Z. Li et al. (2020) and Guo et al. (2019) can also be converted into a yarn in two stages; first, taking off aligned bundle-like nanofibers by a proper mechanism such as a knife-edged disk or collecting on a rotating disk, and then drawing, twisting to archive required mechanical and yarn properties. This two-stage process can be done simultaneously or done as two separate processes. A typical two-stage manufacturing process is illustrated in Figure 17e.

Moreover, these kinds of ultrafine electrospun yarns provide a better alternative to conventional metal or metal-coated yarns for producing double-layer embroidered antennas. The double-layer antenna has a higher gain and radiation efficiency than the single-layer embroidered antenna and is comparable to copper etched versions (Simorangkir et al., 2016; Wang et al., 2012). Simorangkir et al. (2016) proposed a double-layer embroidered antenna where 5-filament copper thread from Elektroisol conductive yarns was used for both upper and bobbin threads. The researchers experienced difficulty with yarn breakage and fraying during production due to high friction metal surfaces; therefore, some adjustments such as reducing the upper thread tension, reducing the embroidery speed, and increasing the step pitch were made during the process. However, by developing a conductive nanoplatelet-based conductive yarn, the problems associated with lower speed and lower production time for fabricating complex double-layer embroidery geometries can be mitigated due to the smooth surface and ultrafine diameter of the yarn.

9. Conclusion
The choice of the fabrication method and material variants for the conductive and non-conductive components of the microstrip patch antenna depends on the application. For applications with a higher level of stretching and bending, such as sportswear, knitted antennas attract potential benefits since knitting geometry imparts the required elasticity for mobility and comfort. However, the antenna’s performance should be measured under deformation since performance tends to degrade with the increase in elongation and bending. Further research is required in this field in terms of stable knit structures because the majority of previous studies have focused on single jersey knit patterns, with less attention given to rib structures and 3D knit structures. Knitting parameters such as loop length and loop density should be adjusted to withstand deformation and maintain a stable performance with minimal fluctuations. Furthermore, the loop length and loop density are the two main parameters that determine the surface volume fraction of the conductive yarn on the fabric surface and hence the
effective electric length. Mechanical stabilization of antennas is essential to retain geometric accuracy. Therefore, a non-knitted ground plane or dielectric substrate should be used in the presence of a knitted radiator. One-step integration and spacer warp knitted 3D composites are new research fields for wearable knitted patch antennas. This technique can be extended to produce porous dielectric substrates, single process patch antennas (radiator, ground plane, and dielectric substrate fabrication in a single process) and high Q factor antennas such as cavity RSW antennas.

Woven antennas have a homogeneous sheet resistance and a shorter effective electrical length than knitted antennas. The thread density determines the surface volume fraction of the conductive area in the weave pattern and hence the effective electrical length. However, the increase in thread density does not necessarily increase the electric conduction without the support of the weave pattern. The number of point interactions along the electrical length between adjacent conductive yarns is equally important. The weaving ratio determines these point interactions. However, the increase in weaving ratio adversely affects the effective conductivity at a certain point as it increases loosely bound connections. Therefore, the weaving pattern of the conductive surface should support an optimum level of interconnections between adjacent conductive yarns to minimize the conduction loss. With the ongoing developments in composite fabrics, 3D orthogonal weaving can be used to produce patch antennas in a single process. In 3D Orthogonal weaving, antennas Q factor can be improved by altering the dielectric substrate's configuration, such as via loaded RSW antennas in which shortening pins are configured by using Z yarns.

Recently, embroidery techniques have attracted much attention for fabricating microstrip antenna designs. Embroidering techniques enable producing complex antenna designs with a homogeneous sheet resistance by controlling two primary parameters: stitch spacing and stitch direction. Therefore, the embroidery technique is the most suitable fabrication method for producing complex antenna geometries such as array antennas, circular patch antennas, slotted antennas, multiband antennas, and loaded loop antennas. The lower stitch spacing increases the number of point interconnections between adjacent stitches via loose fibers and reduces the effective electrical length. Previous studies experimentally proved that the parallel stitch direction possesses a lower resistance than the perpendicular stitch direction. However, embroidery techniques cannot produce patch antennas in a single process and require a separate assembling process to fabricate patch antennas. Embroidered antennas are suitable for planar antennas, which do not necessarily require a ground plane, such as dipole antennas. As a precise technique for fabricating textile antennas, embroidered antennas also suffer in terms of geometry accuracy and geometry resolution, especially around edges and corners compared to equivalent metal counterparts.

The non-conductive material of the microstrip patch antenna (dielectric substrate) should have these four characteristics to enhance the antenna performance: (1) a thick substrate below the optimum thickness, (2) a low dielectric constant, (3) a low moisture regain value, and (4) a low loss tangent value. Researchers have focused on commercial products such as jeans, cotton fabrics, felt, etc. as dielectric substrates in previous studies. However, the thickness of the substrate is achieved by assembling multiple layers, using either glue or stitching around edges. To overcome the associated difficulties by assembling multiple layers, the 3D spacer warp knitting technique can be used to produce porous composite structures according to their geometrical specifications. Moreover, the porosity of the surface, which is considered as a primary determinant factor for reduced dielectric constant and loss tangent, can be controlled by the warp knitting pattern changing from the simplest tricot structure to porous fillet hexagonal structure.

Metalized textile yarns with a thin conductive layer are preferred over pure metal yarns or composite conductive yarns. For high-frequency microwave applications, the skin depth of the metalized textile yarn is restricted to several nanometers. Due to this fact, there is a strong cross-
link between the conductor thickness and the skin depth for antenna's RF performance. The conductive material can peel off under high abrasive forces during the manufacturing process. Therefore, selecting a conductive yarn and controlling manufacturing variables are crucial in developing conductive materials for textile antennas. This article introduces the applicability of conductive filler nanoplatelets based electrospun yarns for mitigating the issues associated with the conductive coating of the yarns. These yarns have a continuous conductive path that is comparable to metal-coated yarn and have a high potential to replace conventional conductive yarns. Moreover, the conductive nanoplatelets based electrospun yarns can be effectively used to fabricate double-layer embroidered antennas with complex antenna geometries with similar antenna performance as metallic antennas due to improved yarn characteristics, such as flexibility and searchability compared to metal-coated yarns.

Nonwoven electro textiles are an untapped research field as fabrication methods for wearable antennas. Electrospin nonwoven fiber matrices produce a continuous conductive material with a similar cover factor as metallic antennas since conductive chain-oriented nanofibers create a continuous conductive path on the surface. With the latest developments in fiber patterning, such as patterning based on Near-Field Electrosprinning (NFES), nanofibers can be written directly on the collector surface based on programmed x, y, and z coordinates. This technology can be extended to develop intricate antenna designs with high resolution and precise geometry.

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