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REVIEW ON DESIGN TECHNIQUES AND SUBSTRATE SELECTION FOR WEARABLE MICROSTRIP PATCH ANTENNA

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ABSTRACT:
As the new technologies address requirement of high data rate, multiple communication channel, affordable and simple design, compactness, low power consumption, and conformality. Microstrip patch antenna are the most preferred option over the conventional antenna specially when the antenna is designed for wearable applications. In this paper, a comparative analytical study is presented on a fixed and conformal substrate. The outcomes are discussed on the bases of challenges involved, design structures as well as substrate selection for wearable antennas.

Keywords:
Conformal substrate, wearable microstrip patch antenna, Design techniques, Loss Tangent, Permittivity

Introduction:

Microstrip patch antennas have been significantly popular choice due to their highly compact size, low footprint, low weight, ease and cost-effective fabrication, desirable radiation patterns, frequency versatility, considerable gain, reliable efficiency and adaptability. These antennas find widespread applications in countless fields of communication applications that includes Satellite communication[1], maritime navigation [2], radar applications [3], 4G/5G/Wimax as well as IoT applications[4], Mobile telephony[5] as well as biomedical applications[6]and applications ranging from frequencies of sub-6 GHz[7] to several THz [8]. In fact, as the demand for a compact and wearable communication devices increases, the microstrip antennas becomes more indispensable as only these variety of antenna can fulfil the demands laid by the compact devices.
There are several design technologies that is involved in designing of a patch antenna. Researchers are mainly concerned for appropriate selection of the design techniques and methodologies, some of these are broadly classified as

- **Selection of Substrate**: The choice of substrate is the most important selection parameter. The substrate are chosen for the desired characteristics of the antenna such as bandwidth, efficiency, gain and impedance matching. It also depends on substrate selection that the designed antenna is flexible or rigid. The substrate could be anything from a Fire retardant(FR-4)[9] to flexible substrates such as flexible rogers[10], Acrylonitrile Butadiene Styrene[11], Ecoflex [12], Flennel fabric [13] or even daily use materials such as jeans material[2], wash cotton[14] or polymer[15].
- **Dimensional structure of the patch**: The patch designed for a specific resonant frequency, bandwidth and radiation pattern. It is the dimension of the patch, which decides that how compact the antenna would be. Conventionally, the antenna could be a square, rectangular or circular patch, fractal geometry, meander line etc, metamaterial characteristics and miniaturization could effectively reduce the size of antenna to a desirable limit[16].

- **Feed Technique**: Microstrip antennas could be classified by the technique through which the RF signal is fed so as to maximize the transfer of power to the radiator, the prominent feeding techniques used are coaxial, SMA, line feed, aperture coupling and proximity feeding [17].
- **Multiple radiators with feed and arrays:** Multiple Input Multiple Output(MIMO) antennas are specifically used for higher channel capacity and lower latency[18]. MIMO antenna are constructed with more than one radiator in a single substrate, where each radiator have its own feed[19]. It is important to mention here that the electromagnetic radiations from the radiators does not interfere each other. The lesser the interference, the higher is the isolation. Researchers has come up with variety of structures such as meander line[20], defected ground structures[21], SRR and CSRR [22]Electromagnetic Band Gaps(EBG)[23], slotted ground etc for minimizing the isolation. Other type of structure is array, where there are multiple radiators are connected on a single feed. Arrays are utilized to achieve higher gain, directivity improvement, beam shaping as well as steering capabilities in definite directions[24].
- **Modifications of substrate:** The substrates are modified to enhance antenna performance by controlling the radiation characteristics and miniaturization of the antenna such as metamaterials or structures such as Frequency Selective Surface(FSS)[25], artificial magnetic conductor(AMC)[26], Electromagnetic Band gaps(EBG)[27], photonic band gaps[28] etc.
- **Design of the Ground Plane**: The ground plane is behind the patch, which is utilized for impedance matching and the resonance between the radiator and ground plane actually decides the resonating band. In general, the ground plane could be classified in three categories,
  - **Full Ground:** The band obtained through a full ground is generally small and sharp, the gain is also generally high.
  - **Partial Ground:** In this type of antennas, the band obtained is generally wide, a wideband is utilized for trans receiving more than one band, i.e these types of antennas generally cater more than one frequency through a single antenna, these types of antennas have lower gain in general and interference from other bands is inevitable[29].
  - **Defected Ground:** Defected ground antennas alter the impedance matching and results in the more complex and desired band output, notch bands are also generated through this type of ground structure that eliminates the interference from the adjacent band[30].

Microstrip patch antennas are becoming more and more common in a variety of communication domains because of their small size, low weight, economical production, and adaptable performance attributes. Their extensive applications include frequencies from sub-6 GHz to several THz and include satellite communication, radar systems, 4G/5G/Wimax, IoT, mobile telephony, and medicinal equipment. Researchers concentrate on important design elements like as substrate selection, feed methodologies, dimensional structure of the patch, use of numerous radiators and arrays, substrate modifications, and ground plane design in order to maximize the performance of these antennas. With the use of these design tools, engineers may customize patch antennas to meet the demands of a given application, guaranteeing effective transmission, increased gain, and reduced interference. Fig-1 depicts the design technologies for wearable microstrip patch antennas that are being used. Researchers are investigating more design methods that can be seen n near future.

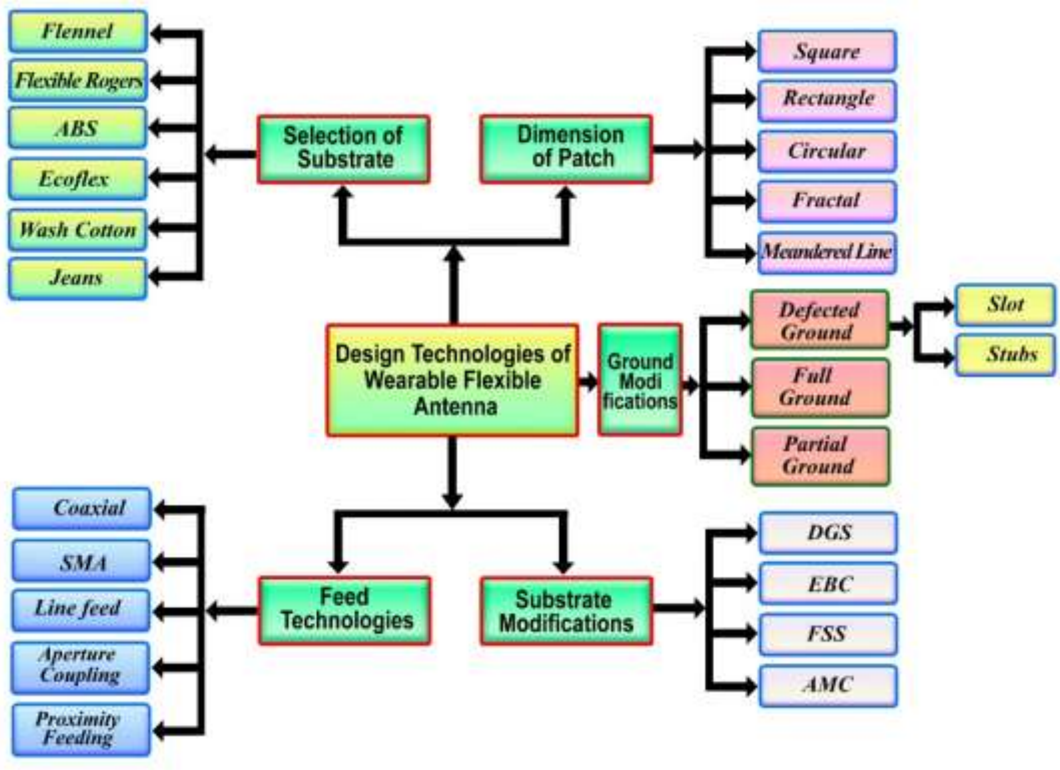

Fig 1. Design Technologies for wearable antennas

Substrate Selection:

One of the important criteria for designing a patch antenna, the selection of substrate depends on factors such as

Dielectric Constant:

1. **Resonant Frequency:** The influence of dielectric constant (ε_r) is at resonant frequency of the patch antenna. The physical dimension of the antenna is directly affected by dielectric constant of the substrate of patch antenna for a particular frequency of resonance. With the increase in dielectric constant, there is a decrease in resonant frequency, therefore higher dielectric constant results in a more compact antenna[31].
2. **Bandwidth:** Bandwidth is directly influenced by dielectric constant of the patch antenna. Wider bandwidth is generally generated by lower dielectric constants, this enables the antenna to operate in a broader range of frequencies. Contrarily, higher dielectric constants lead to narrower the bandwidth[32].
3. **Radiation Pattern:**. Surface wave propagation and the radiation efficiency is directly effected by the dielectric constant of the patch antenna. Changes in the dielectric constant can alter the distribution of the electromagnetic fields around the antenna, affecting the radiation pattern.
4. **Impedance Matching:** The dielectric constant actually effects the capacitance in the characteristic impedance of the transmission line that is formed by the patch and substrate, thereby effecting the impedance matching of the antenna and the feedline.
5. **Efficiency:** As the losses(dielectric and surface wave) are effected by the substrate material Overall efficiency of the patch is effected by dielectric constant.

When designing a patch antenna, the choice of substrate material with a specific dielectric constant is critical as it directly influences the antenna's electrical characteristics and performance parameters. Engineers carefully select substrate materials based on their dielectric properties to achieve the desired antenna performance in terms of frequency, bandwidth, radiation pattern, and efficiency.

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Loss Tangent:

Loss tangent or tangent loss(tan δ), is another vital parameter for substrate material of antennas. It is the measurement of electromagnetic energy dissipation within the material. This dissipation is because of its integral imperfections and conductivity[11]. Performance parameters are effected as :

1. **Radiation Efficiency:** Higher loss tangent leads to increased dissipation of energy in the substrate and reduces the radiation efficiency. As a result, a greater portion of the RF energy gets absorbed within the substrate which is not radiated, thereby reducing the efficiency.
2. **Signal Attenuation:** Higher tangent loss results in more attenuation of signal within the substrate. Thus, signal strength and integrity is effected as the signal propagates through the substrate, therefore the antenna performance is deteriorated or more attenuated. Thus more tangent loss results in increased signal attenuation.
3. **Bandwidth:** The bandwidth is narrowed with increase in tangent loss, therefore with increase in loss tangent, the covered operating frequency is reduced. On the contrary, lower tangent loss permits wider bandwidth capabilities to antenna.
4. **Resonant Frequency Shift:** Resonant frequency shift is caused by increase in loss tangent. Therefore higher the loss tangent, higher the frequency shift.
5. **Temperature Sensitivity:** The parameters of every microstrip antenna is effected by the change in temperature. The substrate becomes more sensitive by the increase in the tangent loss.

Loss tangent plays a prominent role in deciding the performance parameter of microstrip antenna, therefore loss-tangent is an important consideration of engineers where radiation efficiency, mechanical stability and performance is critical.

Permittivity:

A patch antenna's electrical and radiation properties are greatly influenced by the substrate material's permittivity. The following are the ways that permittivity affects a patch antenna's behaviour and performance:

1. **Resonant Frequency:** The substrate's permittivity has an impact on the patch antenna's resonance frequency. The resonance frequency is increased by substrate with lower permittivity and decreased by those with higher permittivity. This relationship results from the substrate's permittivity altering the patch's effective electrical length.
2. **Dimensions:** For a given resonant frequency, permittivity affects the patch antenna's physical dimensions. Higher permittivity materials can produce resonance at a given frequency with smaller physical dimensions of the patch, but lower permittivity materials need larger dimensions.
3. **Bandwidth:** The antenna's bandwidth is influenced by the substrate's permittivity. Wider bandwidth is produced by materials with lower permittivity. Higher permittivity materials, on the other hand, typically narrow the bandwidth.
4. **Radiation Pattern:** Distribution of electric field and surface wave propagation is directly affected by the permittivity of the substrate and influence the radiation pattern of the antenna.
5. **Impedance Matching:** As the antenna is an extension of transmission line. The characteristic impedance of the transmission line produced by the patch and substrate is influenced by the permittivity of the substrate. This has an effect on the feedline and antenna's impedance matching, which in turn impacts the efficiency and performance of the antenna.
6. **Substrate Thickness:** The impedance and radiation properties of the antenna are determined by the interaction between the substrate's permittivity and thickness. Permittivity and thickness work together to give the antenna the performance qualities that are needed.

In order to achieve the appropriate electrical characteristics and performance parameters of the patch antenna, engineers choose substrate materials based on their permittivity. The resonance, bandwidth, radiation pattern, and overall efficiency of the antenna are all dependent on the substrate material selection, which has a certain permittivity.

Thickness:

One crucial design factor that has a big impact on a patch antenna's performance is the substrate material's thickness. The following are the ways that substrate thickness affects a patch antenna's performance:

1. **Resonant Frequency:** The resonant frequency of the patch antenna's is highly influenced by the substrate thickness. The resonance frequency is increased by thinner substrates and decreased by thicker substrates. This relationship results from the substrate's thickness altering the patch's effective electrical length.
2. **Size and Dimensions:** For a particular resonant frequency, the patch antenna's physical dimensions are affected by the thickness of the substrate. In order to obtain resonance at a given frequency, thicker substrates demand higher physical dimensions of the patch, whereas thinner substrates permit smaller dimensions.
3. **Bandwidth:** The thickness of the substrate affects the antenna's bandwidth. Wider bandwidths are typically produced by thinner substrates, which allows the antenna to function across a wider frequency range. In contrast, the bandwidth is generally smaller on thicker substrates.
4. **Radiation Pattern:** The antenna's radiation pattern is influenced by the thickness of the substrate. It affects how electromagnetic fields are distributed around the antenna construction, which affects the properties of the radiation pattern.
5. **Impedance Matching:** The impedance properties of the antenna are determined by the interaction between the thickness and permittivity of the substrate. The dielectric constant of the substrate and its optimal thickness work together to provide the necessary impedance matching between the feedline and the antenna.
6. **Mechanical Stability:** The mechanical stability and rigidity of the antenna structure can be affected by the thickness of the substrate. In comparison to thinner substrates, thicker substrates may provide superior mechanical stress resistance and structural support.
7. **Manufacturing Considerations:** The thickness of the substrate has an impact on the patch antenna's manufacturing process and manufacturability. Working with thicker substrates during manufacturing procedures like drilling, cutting, or etching could be more difficult. Also the thick and rigid substrate could cause hindrance to the desired structure of the device and the device is designed in consideration to the antenna dimensions.
8. **Stacked or Multilayer Configurations:** Patch antennas with stacked or multilayer substrates are frequently used by researchers to accomplish particular design objectives, such as increased gain, bandwidth, or lower cross-polarization[33]. To achieve desirable antenna characteristics, these layers thickness and arrangement are critical.

Researchers carefully evaluate bandwidth requirements, impedance matching, ideal resonant frequency, and mechanical constraints while building patch antennas. This includes choosing the substrate thickness. Achieving the necessary electrical performance and antenna properties for a given application depends critically on the substrate thickness.

Flexibility:

Patch antennas with flexible substrates have several benefits that improve the antenna's functionality in a number of ways.

1. **Conformal Design:** Antennas that have flexible substrates can adapt to curved or uneven surfaces. With this conformal design flexibility, antennas can be integrated without sacrificing performance into a variety of irregularly shaped objects, including wearables, curved surfaces, and conformal structures.
2. **Mechanical Flexibility:** Mechanical flexibility and durability are provided via flexible substrates, such as polyimide or flexible PCB materials. Because of this characteristic, the antennas can be bent, twisted, or deformed without experiencing a major reduction in performance[18], which makes them appropriate for use in flexible or bendable electronic systems.
3. **Low Profile and Lightweight:** Generally speaking, flexible substrates are lighter and have a smaller profile than rigid substrates[34]. Applications including wearable technology, Internet of

Things devices, and aerospace applications—where weight and space limits are crucial, benefit from this feature of the substrate.

4. **Durability and Robustness:** Flexible substrates can improve an antenna's longevity and dependability in challenging surroundings or dynamic conditions since they frequently show strong resistance to mechanical stress, vibration, and shock.
5. **Versatility in Design:** Innovative antenna designs and form factors are possible with flexible substrates that are not possible with rigid substrates[35]. To maximize antenna performance for a given application, engineers can experiment with non-traditional forms, folding, or conformal configurations. Flexible substrates can improve an antenna's longevity and dependability in challenging surroundings or dynamic conditions since they frequently show strong resistance to mechanical stress, vibration, and shock.
6. **Ease of Integration:** The antenna can be easily integrated with other flexible electronic components on the same substrate with flexible substrates[36]. This integration encourages the creation of compact, integrated systems and streamlines the assembly process.
7. **Portable and Wearable Applications:** Flexible patch antennas are used in portable and wearable electronics, medical equipment, smart clothes, and Internet of Things wearables all applications where comfort and conformability are crucial[18].
8. **Customization and Prototyping:** Flexible substrates make prototyping and fast customization more possible, enabling quick iterations and adjustments in antenna designs for test or particular application[5].
9. **RF Performance:** Although flexible substrates and rigid substrates may have slightly differing material qualities, developments in material technology have produced flexible substrates with respectable RF performance and good dielectric properties.
10. **Reduced Manufacturing Complexity:** When producing antennas on a big scale, using flexible substrates can streamline manufacturing procedures like roll-to-roll printing and possibly lower manufacturing costs.

Because of these benefits, flexible substrates are favored in many applications, particularly those requiring conformal, lightweight, and mechanically sturdy antenna designs. Innovative and adaptable patch antenna designs that are appropriate for a wide range of new and upcoming applications are made possible by the use of flexible substrates.

Cost

The total cost of manufacturing patch antennas is significantly influenced by the cost of the substrate used in them. The following are some ways that substrate costs are included in the creation and manufacturing of patch antennas:

1. **Material Selection:** The choice of substrate material has a big impact on price. The cost of various substrate materials varies, including FR-4[37], Rogers[38], ceramic[39], and specialized high-performance materials. Superior electrical qualities and high performance substrates are frequently more expensive than conventional materials.
2. **Manufacturing Processes:** Certain substrate materials may need particular manufacturing procedures, including surface treatment, lamination, or specialist etching methods, which raises the overall cost of production.
3. **Substrate Quality and Performance:** superior dimensional stability, reduced loss tangents, and superior dielectric qualities are frequently seen on more expensive substrates. These characteristics raise the cost of the substrate even while they improve antenna performance.
4. **Customization and Complexity:** Higher costs may be associated with customized substrates with particular qualities or distinctive features intended for specialized applications because of the customisation processes, R&D costs, and limited production scales.

5. **Integration with Other Components:** Due to extra production stages and complexity, substrates with integration capabilities such as integrating other electrical components or functionalities may be more expensive.
6. **Reliability and Quality Control:** More expensive substrates frequently go through stricter quality control procedures to guarantee performance uniformity and dependability. Manufacturing costs may increase as a result of quality assurance
7. **Market Dynamics and Availability:** Substrate pricing can be impacted by several market factors, including as variations in the supply chain, the availability of materials, and demand-supply situations. Substrate prices can be impacted by changes in the price of raw materials or the state of the market.
8. **Research and Development:** Due to R&D expenses, new substrate materials created through research and development initiatives may initially be more expensive; but, when these materials gain traction and are utilised more frequently, costs may fall down.

In order to minimize overall production costs, engineers and manufacturers select substrates that satisfy the necessary mechanical and electrical qualities while striking a compromise between cost and performance. The choice of substrates for patch antennas is heavily influenced by cost, particularly in sectors where cost-effectiveness is one of the top priority.

The substrate has a significant impact on a number of performance metrics, including mechanical stability, bandwidth, resonant frequency, radiation pattern, impedance matching, and efficiency. Considerations including permittivity, dielectric constant, loss tangent, thickness, flexibility, and cost are important in assessing whether a substrate material is appropriate for a certain use. To guarantee the best possible antenna performance, engineers carefully assess these characteristics, taking into account the unique needs of the intended use case. Engineers can attain the required mechanical and electrical qualities by carefully choosing the substrate material, which will ultimately result in the creation of dependable and effective patch antennas for a variety of applications. Fig. 2 Depicts the selection criteria of the substrate for microstrip patch antenna.

Fig 2. Characteristics for the selection of substrate in Wearable Antennas

Conclusion

In conclusion, a crucial component of the design and functionality of microstrip patch antennas is the substrate material choice. When selecting the substrate for a certain application, designers take into account a number of variables, including the dielectric constant, loss tangent, permittivity, thickness, flexibility, and cost. The electrical characteristics, radiation qualities, mechanical stability, and overall performance of the antenna are all directly impacted by each of these factors.

The dielectric constant has an impact on the antenna's efficiency, radiation pattern, bandwidth, impedance matching, and resonant frequency. While higher dielectric constants result in narrower bandwidth but more compact antennas, lower dielectric constants lead to greater bandwidth and higher resonant frequencies, making them appropriate for compact designs.

Radiation efficiency, signal attenuation, bandwidth, resonant frequency shift, and temperature sensitivity are all impacted by loss tangent. The performance of the antenna is impacted by higher loss tangents because they cause greater signal attenuation and a narrower bandwidth.

Resonance frequency, size, bandwidth, radiation pattern, impedance matching, and substrate thickness are all significantly influenced by permittivity. Higher permittivity materials allow resonance with smaller dimensions but narrower bandwidth, whereas lower permittivity materials require bigger dimensions for resonance at a given frequency but offer wider bandwidth.

Resonant frequency, dimensions, bandwidth, radiation pattern, impedance matching, mechanical stability, manufacturability, and integration with other components are all impacted by the thickness of the substrate. While thicker substrates offer mechanical stability but may be difficult to fabricate, thinner substrates increase resonance frequency and bandwidth.

Conformal design, mechanical flexibility, low profile, light weight, durability, adaptability, simplicity of integration, mobility, and customization are all made possible by flexibility. Applications demanding conformal, lightweight, and mechanically robust antenna designs are better served by flexible substrates.

The choice of materials, production techniques, substrate quality, customization, integration, dependability, market dynamics as well as research and development, all have a big impact on cost. In order to decrease overall production costs while meeting application requirements, engineers and manufacturers work hard to strike a balance between cost and performance.

To summarize, the selection of substrate material for microstrip patch antennas necessitates a meticulous evaluation of several aspects in order to get the intended mechanical attributes, electrical performance, and affordability for certain uses.

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