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Review article

Poly-flex-antennas: Application of polymer substrates in flexible antennas

Praveen Kumar Sharma[1], *Jae-Young Chung*[2*]

[1]Research Center for Electrical and Information Technology, Seoul National University of Science and Technology, 01811 Seoul, Republic of Korea
[2]Department of Electrical and Information Engineering, Seoul National University of Science and Technology,01811 Seoul , Republic of Korea

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Abstract. The proliferation of flexible electronics has entirely transformed the field of antenna design and paved the door for cutting-edge uses in communication, sensing, and other areas. The present research lends a succinct overview of the intriguing advancements in flexible antenna technology, with specific emphasis on the implementation of polymer substrates. As we refer to poly-flex antennas in this article, they stand for the incorporation of polymer substrates in antenna design. Polymer substrates are the optimum candidate for flexible antenna applications as they have specific advantages, including being lightweight, conformable, and inexpensive. The main features of poly-flex antennas, such as their design concepts, fabrication processes, and performance characteristics, are being explored in this proposed article. We delve into the wide variety of polymer substrates that are appropriate for antennas, taking into account their dielectric characteristics, flexibility, and environmental resistance. Their dielectric characterization, bending effects, challenges, and future prospects of this burgeoning field are also addressed. We conclude by emphasizing the immense potential of poly-flex-antennas to shape the future of wireless communication and sensing systems, and how the adoption of polymer substrates is driving innovation in antenna engineering.

Keywords: *additive, biopolymer, biocompatible polymer, mechanical properties, orientation, substrate, toughness*

1. Introduction

The demand for flexible electronics devices (FEDs) has increased exponentially in the last few decades due to their wide range of applications in various sectors like medical, defense, sports, communication, membranes, industries, fashion, sensors, and displays (Figure 1). The FEDs offer an assortment of advantages over rigid electronic devices, including the ability to be bent, twisted, and even stretched without sustaining the compromise of losing functioning. By enabling the development of devices that can adapt to different forms and surfaces, this characteristic opens up new form factors and applications. Flexible electronic components tend to be thin and light, which makes them perfect for wearable and portable gadgets. They can enhance comfort and convenience by blending into clothing, accessories, or even the skin itself.

FEDs exhibit greater shock, vibration, and impact resistance. They are more reliable and durable since they can tolerate challenging operating situations and frequent bending. They often prove more energy-efficient than their rigid equivalents and use less power. The aforementioned advantage is particularly significant for portable and battery-operated gadgets because it can increase their battery life and lessen the frequency of charging. FEDs can easily be incorporated with different parts and materials. To build

*Corresponding author, e-mail: jychung@seoultech.ac.kr

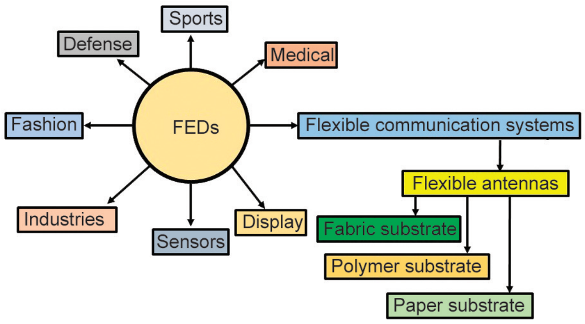


Figure 1. Applications of flexible electronic devices (FEDs).

multifunctional systems, they can be integrated with sensors, actuators, wireless communication components, and energy storage gadgets. This integration creates new opportunities for cutting-edge, networked technological devices. The global market for flexible electronics is estimated to surge by more than 19% from 2017 through 2024 [1].

Flexible materials – more precisely, flexible substrate materials – such as plastics, polymers, textiles, *etc.* – are used in the edifice of FEDs. Arguably, the most significant step involves selecting an appropriate substrate material, upon which the entire circuit evolves, and the sort of application for the FED significantly impacts this decision. In recent years, there has been an increase in demand for novel communication systems with adaptable properties and unconventional performance requirements. A vital component of every communication system is the antenna. The implementation of antennas for flexible communication systems requires antenna designers to overcome technical hurdles. It is preferable to have an affordable, flexible, compact, and effortlessly integrable antenna for such applications. Therefore, a flexible substrate should be deliberately selected and utilized for developing an antenna with flexible properties. In the literature, there are plenty of choices for substrates for flexible antennas. There are benefits and drawbacks to each category of substrate. The primary focus of the research that is being presented here is on the application and benefits of polymer substrates for flexible antenna design.

The main objectives and highlights of this paper, supported by the latest research, are summarized as follows:

- Section 1 provides an overview of FEDs, their benefits, and applications.
- Section 2 presents flexible antennas, their design and fabrication processes, and various materials for their development with the available literature.
- In Section 3, the benefits of employing polymer substrates in flexible antenna design over other flexible substrates are discussed, along with different kinds of polymer substrates employed by the researchers.
- Section 4 presents a brief overview of the dielectric characterization of the polymer substrates, particularly for antenna applications.
- In Section 5, the effect of bending of the polymer substrates on the antenna performance is highlighted.
- Section 6 addresses the challenges encountered in implementing polymer substrates in the flexible antenna design.
- The conclusions reached, and the potential implications of the polymer substrates used in flexible antennas are outlined in Sections 7 and 8.

2. Flexible antennas

Flexible antennas are currently grabbing the spotlight of academics, businesses, and scholars due to the meteoric rise of flexible electronics. An antenna that can bend or flex without damage or impairment of its operation is recognized as a flexible antenna. Compared to rigid antennas, these antennas have the following benefits:

- Flexible antennas are designed to endure bending, twisting, and flexing, which increases their vulnerability against damage from vibrations or physical impacts. In circumstances in which antennas may be susceptible to rigorous handling, such as in portable devices or wearable technologies, this resilience is especially helpful.
- In comparison to conventional rigid antennas, flexible antennas can be fabricated and rendered significantly thinner as well as lighter. They are suited for applications that need a compact footprint or where minimizing weight is essential, such as small electrical devices, drones, or positions with restricted space.
- The adaptability of these antennas offers a variety of installation possibilities. They are simple to incorporate into a variety of abrasive surfaces, including curved or non-planar items. This adaptability creates the potential for antenna deployment in unusual designs and complicated configurations.
- Flexible antennas can be produced using inexpensive materials and techniques, including flexible substrates or printing methods. Because of this, they are relatively cheap to manufacture in significant

amounts, which is advantageous for cost-sensitive purposes like mass-market consumer electronics.
- The electromagnetic attributes of flexible antennas have substantially enhanced, despite the fact that they might not always perform as well as bigger rigid antennas. Several flexible antennas exhibit excellent radiation efficiency, wide bandwidth, and good impedance matching, thereby rendering them perfect for a variety of wireless communications purposes.

Figure 2 illustrates the conventional procedure that is to be used when designing flexible antennas. The selection of materials and assessment of their dielectric properties, particularly their conductivity, dielectric loss tangent, and dielectric constant, are the first and most important steps in the design process. The radiating patch, ground, and feed lines, as well as the appropriate geometry of the antenna structure, are then chosen based on the applications. The antenna is then optimized and simulated using the proper 3D electromagnetic solvers, such as Ansys HFSS or CST, *etc.* A suitable vector network analyzer (VNA)-based setup is then used to perform measurements and performance evaluation of the fabricated antenna, validating the simulation results in the process.

In recent years, many flexible antenna designs using a range of substrates have been published in the literature for deployment in diverse applications. The authors [2] designed a flexible antenna that could adapt to wear in 2001 using fabric substrates. Then, in 2002, a flexible antenna was created employing fabric-based substrates this time for WLAN (2.04 GHz) and UMTS (2.1 GHz) applications [3]. Between 2003 and 2007 [4, 5], flexible antennas for wearable applications were created for the military and safety. A wearable antenna that operates in a variety of humid environments was described in [6]. The past few years have seen an increase in the employment of flexible antennas for biological applications [7]. The implementation of vital sign monitoring systems, organ function regulation systems, brain interfaces, intracranial sensors, drug administration systems, and a range of other activities connected to health monitoring systems primarily require flexible antennas in particular [8].

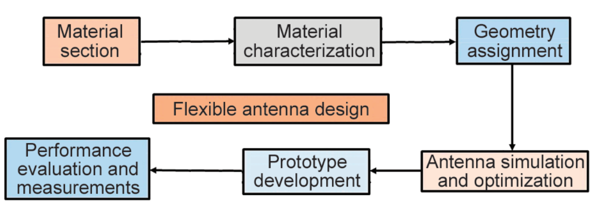


Figure 2. Design steps of flexible antennas.

This section provides a concise introduction to flexible antennas, which are supported by the literature, including a variety of materials and fabrication techniques.

2.1. Materials

As they are unable to endure the demands of flexibility and conformal conditions, conventional stiff substrates and conducting materials are not suitable for designing flexible antennas. As a result, scientists are continually exploring new materials with the characteristics required for a variety of applications. In the literature, a number of materials have been proposed for flexible antennas. The type of target applications, radiation properties for flexible antennas, dielectric properties, tolerance limits for the working environment, such as mechanical deformations-bending, twisting, and stretching conditions, and required compactness are taken into consideration when choosing these materials. Materials are picked to ensure they remain to be useful even under challenging working conditions, like harsh and rough surfaces. All of these demands have prompted researchers to constantly look for and create new materials using cutting-edge fabrication techniques that are more accurate in terms of dielectric properties, flexibility, stability, size, and effectiveness.

The electromagnetic performance of the flexible antennas is substantially affected by the dielectric properties of selected substrates. The required expectation of the antenna's behavior for a chosen application must be attained by accurately evaluating the dielectric constant, loss tangent, and height of the substrates. The literature describes a variety of characterization techniques, including the waveguide approach, the two-resonator method, the coplanar method, the ring-resonator method, the planar method, *etc.* [9–12], described in the later section of this paper. This section introduces various materials for the fabrication of flexible antennas. First, a brief description is offered of the conductive materials employed to form the conducting layers, such as patch, ground, and feed. The three primary categories of substrate materials – fabric, polymers, and paper-based substrates are then covered.

2.1.1. Conducting materials

The choice of conductive material for the patch, ground, feed, and other parts should have a high electrical conductivity, which is essential for attaining acceptable performance of the flexible antenna. Another desirable attribute of the conductive material is its ability to resist performance degradation due to the flexible antenna's different conformal geometries. Because of their excellent electrical conductivity, materials such as silver and copper, often known as nanoparticle (NP) inks, are frequently used to fabricate conductive parts of flexible antennas. These materials have their own advantages. For example, silver has a lower oxidation rate than copper, which is more cost-effective than silver [13]. Electro-textile materials, such as Flectron, copper-coated nylon fabric, Ni/Ag-plated threads, and nonwoven conductive fabrics (NWCFs) are commonly utilized in flexible textile-based antennas in addition to copper and silver. In [14], the authors have reviewed different conductive materials used for flexible antennas. The self-adhesive tapes of copper [15, 16] are also employed to create flexible antennas. Conducting polymers are also becoming increasingly popular for developing the conducting sections of flexible antennas. Different polymers, such as polyethylenedioxythiophene polystyrene sulfonate (PSS) [17], polyaniline [18], and polypyrrole [19], are examples of popular conducting polymer materials (Figure 3) that could be used in flexible antennas.

2.1.2. Substrate materials

Different substrate options are available for designing flexible antennas; they are essentially divided into three primary categories, which are as follows:

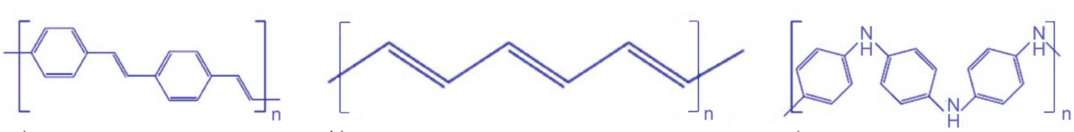
A. Fabric (textile) substrates

The fabric substrates are a promising candidate for flexible antennas, particularly for different wearable applications like body-centric wireless communications. The IEEE 802.15.6 standards group was formed in November 2007 [20] to support the growing interest in antennas and propagation research for body communication systems. The fabric-based antennas can be categorized according to the materials used in the antenna structure. In the first category, the antenna substrate is a non-conductive textile material. For other segments like patch, ground, and feed, different conductive nanoparticle inks like silver and copper, as described above, can be used. In the following category, both substrate and other conducting antenna segments are textile materials. Electro-textile (e-fabrics) materials are utilized to produce the conductive segments of the antenna in the second category of flexible wearable antenna. These e-fabrics are typically metal-plated fabrics in which various types of metals are implanted in standard textile fabric materials by weaving various metal wires in different directions (the orthogonal arrangement generally is chosen). Knitting is another method in which woven mesh is used to embed metal conductors into ordinary fabric materials. In terms of conductivity, durability, and mechanical strength, the percentage of metal conductors added to pure fabric materials defines the fiber's potential [21]. The typical examples of frequently used e-fabric materials for flexible antennas are Flectron®, Nora®, and Zelt®.

The fabric substrates can also be divided into natural or artificial (synthetic). The artificial textile substrates derive their properties from their molecular structure, unlike natural textile materials such as wool, silk, and cotton, which are sourced from nature. The textile substrates are preferred for specific wearable applications as they generally have a low dielectric constant value, which reduces losses due to the surface waves and enhances the performance characteristics of the antenna like efficiency and bandwidth. However, different conformal conditions of the flexible antennas might affect the overall radiation characteristics of the antenna.

B. Paper substrates

In recent years, the utilization of paper as a substrate for the design of flexible antennas has increased tremendously with the advancements in print technology. The word 'paper' is derived from the Latin



a) b) c)

Figure 3. Typical examples of conducting polymers used in flexible antennas. a) Polyaniline (PANI), b) polyacetylene $(CH)_x$, c) polyphenylene vinylene (PPV).

word 'papyrus', which is a Cyprus papyrus plant; it is an organic material that, because of its mass manufacture, is readily available at a low cost. Paper comes in various densities, coatings, thicknesses, and textures. Instead of standard metal etching procedures, paper can be used with quick printing processes. Because of the ongoing concern about environmental issues, using these paper-based antennas, which are environmentally benign, is a significant step toward the development of 'green' electronic products. Paper is a suitable candidate as a substrate for different latest RF devices, such as microwave filters, radio frequency identification (RFID) tags, and wearable/flexible antennas, due to their lightweight, low-profile structures and minimal thickness.

The paper can be used for quick printing processes with a suitable coating like calcium carbonate or kaolin, which can be applied either on one side or on both sides to make the surface water-resistant and increase its suitability for high-resolution halftone screens. Both uncoated and coated paper surfaces can be polished by the calendaring process. The coated papers are available in various finishes, including matte, semi-matte, and gloss.

Instead of using the classic metal etching procedures, direct-write methodologies can be applied to paper substrates. Electronic circuits can be printed on these paper substrates using different quick printing processes like inkjet printing using specific printers like material printer by Dimatic™, *n*Scrypt system by *n*Scrypt™, and the Maskless Mesoscale Material Deposition (M^3D) system by Optomec™. The flexible antennas, RFIDs, and sensors can all be easily incorporated in or on paper as a result of this [22]. Like any other substrate, the dielectric characterization of paper before using it as a substrate for different RF applications is important.

The flexible antennas designed using paper substrates exhibit good efficiency (>80–85%) due to their low profile structure and thin width. The initial research using paper as a substrate for the design of flexible antennas was related to RFIDs like in [23]; the authors have proposed a U-shaped dipole passive RFID antenna. The same design is extended to design a paper-based wireless module [24]. In [25], the authors have proposed a bowtie-shaped planar antenna using a paper substrate with its dielectric characterization. The first antenna using a paper substrate radiating above 1 GHz was proposed in [26] for Wi-Fi applications having a PIFA (planar inverted F antenna) structure. The antenna was fabricated using M^3D technology for 2.4 GHz, and it was observed that the antenna was more than 82% efficient with good synthetic aperture radar (SAR) characteristics. Since then, continuous progress in the fabrication of paper substrate-based antennas has been going on with the advancements in printing technology.

C. Polymer substrates

Polymers have become increasingly popular as a substrate for the design of flexible/wearable antennas in recent years due to their numerous advantages over the fabric and rigid substrates like rigid substrates cannot be used for flexible antennas. They fail to operate correctly under bending, stretching, and twisting processes, which are the significant requirements of flexible antennas. However, fabric substrates can be used for flexible antenna designs [27]. Still, these substrates also have some limitations, like such substrates are more prone to environmental effects like moisture absorption, temperature variations, *etc.*, which affect the antenna's radiation characteristics. On the other hand, the polymer substrates provide flexibility, stretchability, and bending characteristics in addition to robustness, less dielectric loss, high thermal conductivity, and high transition temperature to the antenna designs.

A variety of polymer substrate materials for the design of flexible antennas have been documented in the literature, including liquid crystal polymer (LCP) [28], polypyrrole (PPY) [29], thermoplastic semi-crystalline polymers like polyethylene terephthalate (PET) [30] and polyethylene naphthalate (PEN) [31] which provides very good conformal, mechanical, electrical and resistant to moisture absorption properties, thermoplastic non-crystalline polymers like polycarbonate (PC) [32] and polyethersulfone (PES) [33], high transition temperature polymers like polyimide (PI) [34] which became very popular in recent years. When the flexible antenna is designed for wearable applications like health monitoring systems, *etc.*, it should possess some essential characteristics such as stable and high performance under different conformal and environmental conditions, robustness and high mechanical strength, and transparent and it should not affect the health of the users (low SAR). Wearable antennas built on fabric substrates may meet some of the requirements, but limiting their visibility and shielding against changing external conditions is practically difficult. That is

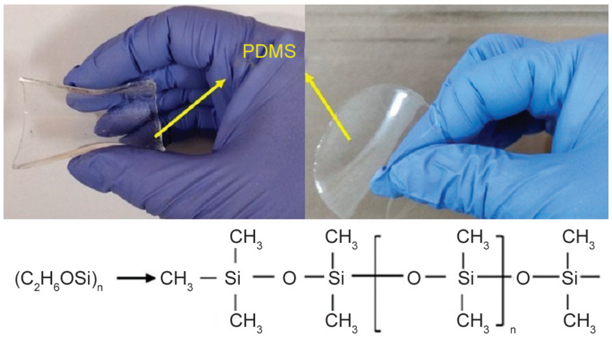


Figure 4. Polydimethylsiloxane (PDMS) substrate.

why polymer-based antennas are becoming increasingly popular. Polydimethylsiloxane (PDMS), as shown in Figure 4, is also an emerging silicone polymer substrate with all of the desirable properties such as transparency, flexibility (with Young's modulus <3 MPa), water resistance, thermal stability, isotropy, and homogeneity that confirm its suitability as a potential substrate for flexible wearable antennas [35]. These polymers, with their applications in flexible antenna design, are also detailed in the later sections of this presented paper.

2.2. Fabrication methods of flexible antennas

The fabrication methods utilized to develop the flexible antennas also govern its performance, which varies depending on the substrate. This section presents the commonly used fabrication techniques available for flexible antennas.

2.2.1. Chemical etching

The method of corrosively etching away the undesirable area to obtain the desired metallic patterns is the chemical etching process, which is often accompanied by photolithography, as shown in Figure 5. This technology first arose in the 1960s with the rise of the printed circuit board (PCB) sector. It has since grown in popularity because of its ability to make high-resolution patterns with fine details. The etching process is carried out by applying certain chemicals known as photoresists. Photoresists are organic polymers that change their chemical properties when exposed to ultraviolet light. Positive photoresists are preferred in this procedure over negative photoresists due to the better resolution of the patterns. Although chemical etching is a standard process for producing flexible/wearable antennas, it has a limited throughput and requires dangerous chemicals, which have significant environmental consequences [36, 37].

2.2.2. Inkjet printing

Inkjet printing technology has emerged as an alternative to the conventional printing method to develop flexible antennas [38]. This is a direct write method in which the pattern is directly transferred on the substrate using conductive inks like silver nanoparticle ink, graphene nanoflake inks, other organic metal inks, *etc.* The viscosity, surface tension, and particle size of the ink significantly impact printing quality.

In contrast to the chemical etching approach described above, which involves removing the undesirable conductive component from the substrate surface, inkjet printing involves depositing a controlled quantity of ink droplets from the nozzle to a specific location. As a result, no waste is produced, and chemical compounds are removed, resulting in a cost-effective, quick, and environmentally friendly solution. The inkjet printing setup and method are shown in Figure 6.

2.2.3. Screen printing

The screen printing process (Figure 7) is another potential option for fabricating flexible antennas [39, 40]. This is a quick and straightforward process for

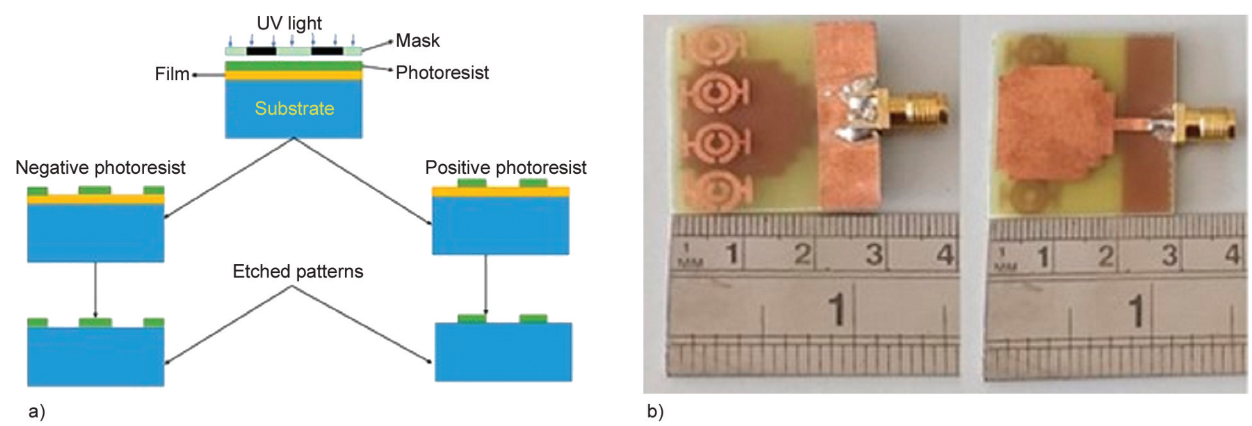


Figure 5. Chemical etching process: a) block diagram, and b) chemically etched antenna [37].

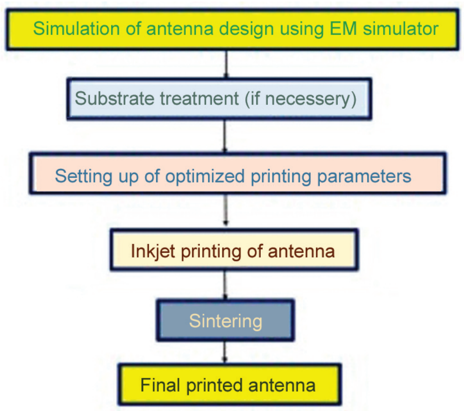


Figure 6. Inkjet printing process.

manufacturing a low-cost antenna. The screen used in this method is woven with a mesh of fabric threads having different thicknesses and densities. The non-printable regions of the screen are blocked using a stencil or emulsion, but the print areas are left open. A squeeze blade is driven down to create a printed pattern, forcing the screen to contact the substrate. Ink ejects through the exposed screen portions on the substrate, forming the desired pattern. Like inkjet printing, this process of fabricating flexible antennas is an additive process rather than a subtractive one like chemical etching, so it is less expensive and better for the environment. Despite its many advantages, it has significant drawbacks, such as resolution being dependent on substrate surface quality, limited layer control, and no thickness control for the conductive layer. Due to these considerations, the implementation of such a technique has been limited, as the printing technology for flexible antennas needs greater precision for better performance under different operating conditions.

2.2.4. Embroidery and sewing

This is one of the conventional methods employed to fabricate flexible antennas. In this method, no adhesive material like copper tape or any type of conductive ink is used on the substrate for making conductive parts. A conductive textile yarn is woven or stitched on the non-conductive textile substrate to make the flexible antenna's conducting sections [41], as illustrated in Figure 8. Additionally, using a computer-aided embroidery machine, these antennas can be directly embroidered onto the non-conductive textile fabric [42]. Traditional digital embroidery machines, for example, have been utilized to weave the radiating parts of the antenna on textile materials using conductive threads. The flexibility and strength of the conductive threads, the high accuracy of the embroidery machine, as well as the direction and density of stitching on the fabric substrate are some of the critical factors to be considered while creating an efficient antenna design using this method.

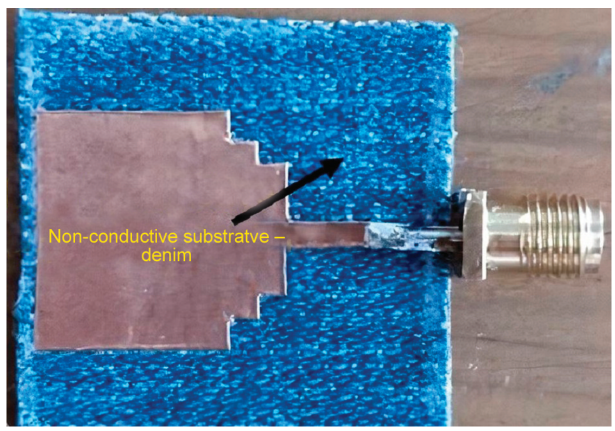


Figure 8. Embroidered antenna.

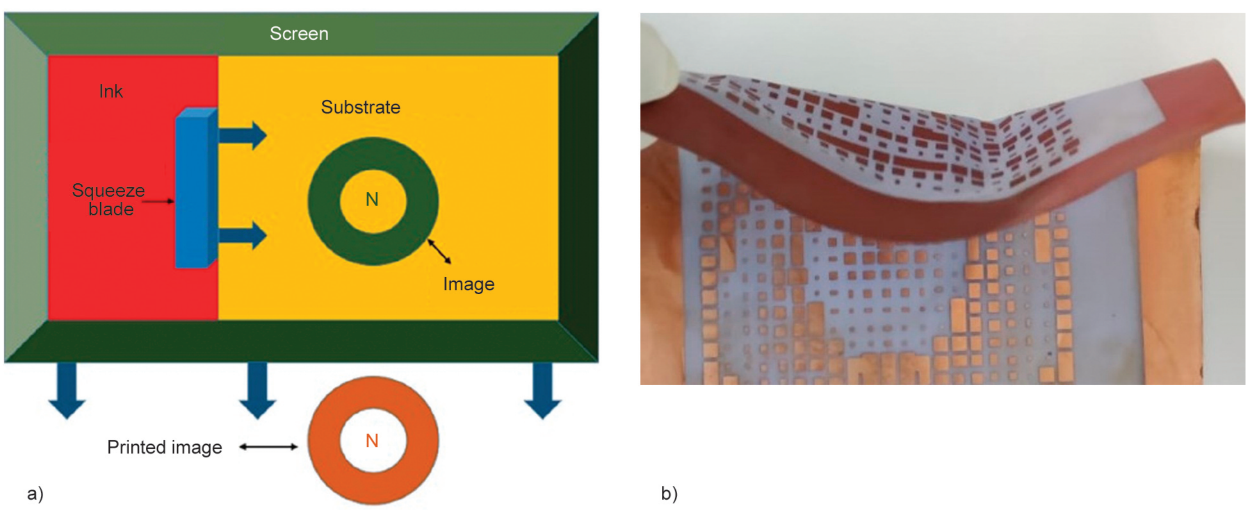


Figure 7. Screen printing process: a) block diagram, and b) screen printed antenna.

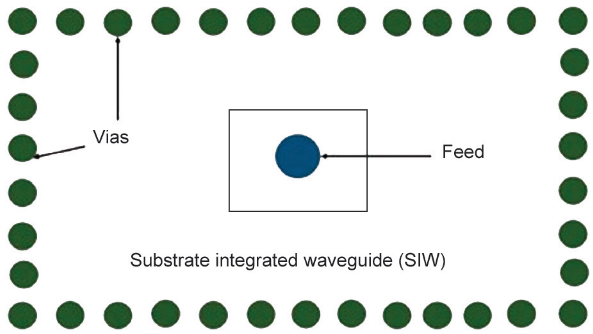


Figure 9. SIW antenna.

2.2.5. Substrate integrated waveguide (SIW)

Substrate integrated waveguide (SIW) is a recent technology for fabricating a wearable system on a single platform. This technology allows future 'System on Substrate' (SoS) systems to be realized, which are essential to building cost-effective and easy-to-fabricate high-performance mm-wave systems [43]. These structures (Figure 9), by employing shorting vias on the cavity's sidewalls, backed by the entire ground plane, ensure the containment of electric fields inside the cavity. This improves the structure's quality factor while also boosting the isolation between the antenna and the human body for wearable applications [44].

3. Polymer substrates for flexible antennas

The electrical behavior of polymers was first reported in 1977. Since then, the applications of polymers in the electronics sector have gained much popularity by progressive refinement in their characteristics like flexibility, conductivity, *etc.* [45]. Polymer substrates offer several advantages over other types of substrates in the flexible antenna design. Polymer substrates are generally lightweight compared to traditional substrates like ceramic or metal. This characteristic is particularly beneficial for applications where weight is a critical factor, such as aerospace and mobile devices. The reduced weight helps improve portability and reduces structural constraints. Polymer substrates are highly flexible, which allows for the design and fabrication of conformal and flexible antennas. They can be bent, curved, or conform to irregular shapes, making them suitable for applications where antennas need to be integrated into curved surfaces or wearable devices. This flexibility also enables antenna integration in unconventional spaces, leading to enhanced design possibilities.

Polymer substrates possess desirable dielectric properties, such as low dielectric loss and high dielectric constant, which are essential for efficient antenna performance. The low-loss tangent of polymers helps minimize signal attenuation, leading to improved antenna efficiency and performance. Additionally, high dielectric constants allow for the miniaturization of antennas by reducing the required physical dimensions. Polymer substrates are generally more cost-effective to manufacture compared to other substrates. They can be produced using various low-cost manufacturing techniques like roll-to-roll processes, screen-printing, or injection molding, enabling large-scale production at reduced costs. This aspect makes polymer substrates a suitable choice for applications that require mass production, such as consumer electronics.

These types of substrates are compatible with a wide range of manufacturing processes, including inkjet printing, photolithography, and deposition techniques. This compatibility facilitates the integration of other components, such as passive elements or active devices, directly onto the substrate, enabling multifunctional antenna systems. The ability to integrate multiple functionalities onto a single substrate simplifies the overall system design and reduces the footprint of the antenna module. Some polymer substrates exhibit excellent environmental resistance, including resistance to moisture, chemicals, and temperature variations. This characteristic makes them suitable for outdoor or harsh environment applications, where antennas may be exposed to extreme weather conditions, chemicals, or contaminants.

3.1. Polymer substrates for flexible antennas

The commonly used polymer substrate materials for the design of flexible antennas are as follows:

A. Polydimethylsiloxane (PDMS)

Due to desirable characteristics, including flexibility, transparency, biocompatibility, and ease of production, polydimethylsiloxane (PDMS) is a versatile polymer material that is extensively utilized in a number of applications [46–48]. PDMS substrates have attracted attention in the field of antennas due to their ability to provide flexible, lightweight, and conformal antenna designs, as shown in Figure 10 [49]. PDMS can easily molded into a variety of shapes and may conform to non-planar surfaces. This characteristic enables the development of conformal antennas that can be smoothly integrated into irregularly shaped things like wearables, medical

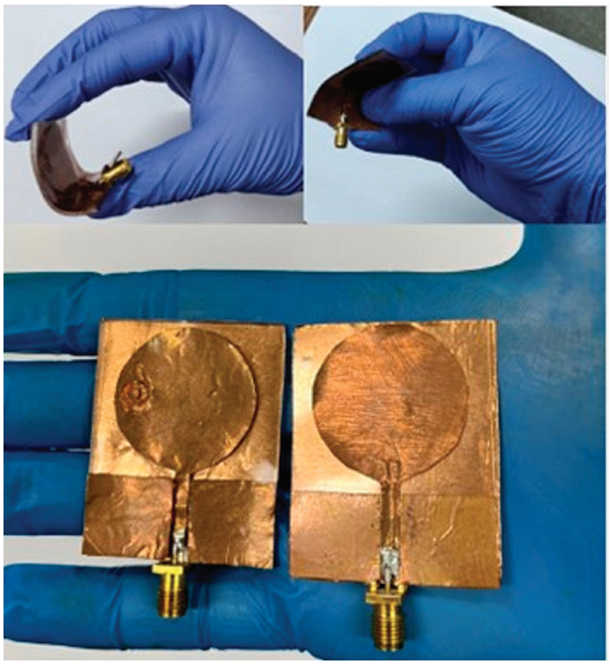


Figure 10. PDMS substrate-based flexible antennas [49].

equipment, and curved surfaces. It is also a lightweight material, which makes it ideal for situations where weight is a concern. This feature is critical in aerospace, automotive, and unmanned aerial vehicle (UAV) applications where antenna weight is critical. PDMS is biocompatible and can be used in medical applications such as implantable antennas or wearable health monitoring systems without risk of contamination. Its non-toxicity and biocompatibility make it appropriate for applications involving human-body contact. Because of its low dielectric loss, PDMS is well-suited for high-frequency antenna designs. Materials with low dielectric loss aid in maintaining antenna efficiency and radiation performance. Our prior research encompassed PDMS characterization [9–12]. Quick prototyping and customization are feasible by employing PDMS. Using PDMS, antenna designers may swiftly develop and evaluate various antenna configurations, allowing for faster development cycles.

While PDMS has a low dielectric loss, its relative permittivity (ε_r) is usually greater than that of air or certain other materials. This attribute can alter the antenna's radiation properties and must be considered during design. PDMS has a low melting point and can distort when heated to high temperatures. This drawback limits its employment in high-temperature situations, such as aerospace applications where antennas may be subjected to tremendous heat; nonetheless, PDMS temperature analysis is well conducted in [9]. When exposed to specific substances, UV light, or continuous exposure to outside ambient conditions, PDMS can degrade. In such instances, protective coatings or encapsulation may be required. PDMS is an excellent substrate for a variety of antenna applications; PDMS-based antennas are ideal for incorporation into wearable devices such as smartwatches, fitness trackers, and apparel. PDMS is a good material for medically implanted antennas used in applications such as remote monitoring and therapeutic devices. PDMS antennas can be utilized in communication systems for airplanes, satellites, and unmanned aerial vehicles (UAVs) in the aerospace industry. Because of their flexibility and customizability, PDMS substrates are useful for IoT applications. They are compatible with a wide range of IoT devices and sensors [50–53]. To build creative and high-performance antenna designs, PDMS can be integrated with other sophisticated materials, such as conductive inks and metamaterials. To verify the advantages of polymer-based substrates, especially PDMS, authors in [27] have compared the same antenna designs on PDMS and denim substrates and the obtained results show that the PDMS is a quite promising substrate for the antenna design.

B. Polyethylene terephthalate (PET)

PET has a dielectric constant that is normally about 3.0. This feature is appropriate for antennas operating at moderate to high frequencies and contributes to high radiation efficiency. PET is a lightweight material, making it perfect for applications requiring a low antenna weight, such as consumer electronics and lightweight communication devices. PET substrates are mechanically durable, which makes them resistant to mechanical stress, bending, and vibrations. PET is resistant to a wide range of common chemicals and solvents, making it ideal for use in a variety of situations. PET has a low melting point and may not be appropriate for high-temperature applications. Extreme temperatures may necessitate the use of different substrate materials for antennas. While PET is appropriate for moderate to high frequencies, it may not be the ideal choice for very high frequency or millimeter-wave antennas, which require lower-loss substrates such as PTFE. PET substrates have a widespread application in antennas for consumer electronics such as cell phones, tablets, and laptop computers. Because of their low cost, lightweight nature, and moderate dielectric constant, they are a popular choice in various applications. PET-based antennas can be found in a variety of wireless communication devices, including Wi-Fi routers, Bluetooth devices, and Internet of Things sensors. PET substrates are utilized for antennas in keyless entry systems, remote start systems, and GPS devices in-vehicle applications. PET-based antennas are used in smart packaging and RFID tags, allowing products to be tracked and monitored during delivery and storage [54–57].

C. Polyimide (PI)

Polyimide substrates are prominent for their substantial thermal stability. They are capable of withstanding high temperatures without incurring dimensional changes or deterioration. This characteristic is critical for antennas used in harsh environments, such as aircraft and automotive applications. Because PI materials have low dielectric constants and loss tangents, they are well-suited for high-frequency antennas. These factors influence antenna efficiency and signal loss minimization. These substrates have exceptional mechanical qualities, such as high tensile strength and wear resistance. This longevity is beneficial for antennas that are subjected to mechanical stress, vibration, or handling during installation. PI is chemically resistant to a wide range of substances, including solvents and oils. Because of this feature, it is appropriate for antennas that may be exposed to corrosive conditions. Polyimide substrates are relatively flexible and lightweight, although not as flexible as some other polymers, such as PDMS. They are suitable for applications requiring conformal or flexible antennas, such as curved surfaces or wearable devices. Antenna fabrication on polyimide substrates may necessitate specialized procedures such as photolithography and plasma etching. These procedures can be more difficult and costly than typical PCB manufacture. While PI materials have low dielectric constants in general, the specific dielectric qualities depend on the type and formulation of the polyimide employed. To obtain the desired antenna performance, the polyimide material must be carefully selected. PI substrates are well-suited for high-frequency antennas used in applications such as wireless communication systems, radar, and millimeter-wave technology due to their good dielectric characteristics. RFID antennas use PI substrates because of their ability to deliver stable performance under a variety of environmental situations, including exposure to moisture, chemicals, and temperature fluctuations. Ongoing research could lead in the creation of new polyimide formulations with improved dielectric characteristics, allowing for higher-performance antennas, particularly in the mmWave and terahertz frequency ranges. In order to create unique and extremely efficient antenna configurations, PI substrates can be used with emerging technologies such as additive manufacturing (3D printing) and metamaterials [60–66].

D. Polytetrafluoroethylene (PTFE)

PTFE is well-known for having a very low dielectric constant (usually approximately 2.1) and a low loss tangent. Because of these characteristics, PTFE substrates are ideal for high-frequency and microwave antennas, as they minimize signal losses while maintaining high antenna efficiency. PTFE has exceptional thermal stability and can survive a wide variety of temperatures without affecting its electrical or mechanical properties significantly. This property is useful for antennas used in high-temperature situations, such as space applications. It has a strong chemical inertness and is resistant to a wide range of chemicals, solvents, and acids. As a result, it is appropriate for antennas used in severe or corrosive environments, such as chemical processing plants. Since PTFE absorbs extremely little water, the dielectric characteristics of the substrate remain steady even under high-humidity settings. This attribute is required for dependable antenna performance. Even when subjected to mechanical stress or vibration, PTFE substrates retain their dimensional stability. This characteristic is beneficial for antennas that are prone to physical disturbances. Specialized manufacturing methods, like as chemical etching or specialist machining, may be required for fabricating antennas on PTFE substrates. While PTFE substrates have high dimensional stability, they are somewhat inflexible when compared to flexible substrates such as polyimide or PDMS. This rigidity may limit their utility in applications requiring conformal antennas. PTFE substrates are ideal for high-frequency and microwave antennas used in wireless communication systems, radar, satellite communication, and millimeter-wave technologies. They are used in satellite communication antennas, space probes, and spacecraft. Because of its low loss tangent, PTFE is a good choice for radar antennas that require little signal attenuation and high precision. Antennas in military and defense applications frequently need to function well in difficult environments. Antennas for military communication, surveillance, and radar systems em-ploy PTFE substrates [69–72].

3.2. Selection of the polymer substrates for flexible antennas

In order to ensure the optimum performance of the poly-flex antenna, adopting the appropriate polymer substrate is very vital. The different key considerations for that are as follows:

A. Dielectric properties

In the antenna design the dielectric properties – dielectric constant and loss tangent of the substrate play a very crucial role. The velocity at which electromagnetic waves propagate through a material is influenced by the substrate's dielectric constant. A substrate with a low dielectric constant is typically selected for flexible antennas. Higher dielectric constants may cause a rise in capacitance and may disturb the antenna's impedance matching. Similarly, the lower loss tangents are preferred to minimize the signal losses.

B. Thermal stability

Depending upon the type of application where the antenna is to be employed, it could be exposed to a range of temperatures so proper care must be taken in selecting the polymer substrate. It should not lose its functionality for a wide temperature range and maintain its performance.

C. Mechanical durability

One of the main reasons for employing polymers in antenna applications is that they can be easily bent and suitable for conformal applications. So, such a polymer substrate is selected depending on its applicability that can retain its functionality even in stress and conformal conditions.

D. Operating Frequency

The frequency of operation plays an important in the selection of the type of polymer substrate, as different polymer substrates have varied performance under different frequency spectrums.

The specific requirements associated with antenna application and the trade-offs between different material characteristics will ultimately determine which polymer substrate is suitable. Ensuring that the chosen substrate satisfies the required performance standards can be achieved by comprehensive testing, simulations, and prototyping. Table 1 summarizes the commonly used polymer substrates with their applications.

4. Dielectric characterization of polymer substrates

The decision regarding the selection of substrate is an essential step in antenna design. The dielectric attributes of the substrates have a tangible difference in antenna performance. As a consequence, it is essential to carefully conduct the dielectric characterization of the substrates so that precise values of the dielectric constant and loss tangent can be included in the antenna design for optimal performance. Characterization of polymer substrates is also vital for inclusion in flexible antennas. However, since there are no uniform methods for binding to all polymer substrates, various investigations use different dielectric values for the same substrates.

For example, using PDMS substrates, we can infer through the literature that various investigators have used different values of the dielectric properties for various applications [73–75]. This difference in dielectric parameter values is mostly due to the characterization methods utilized, including traditional approaches such as Kent, free-space, Courtney, and so on, that assess the dielectric parameters in a parallel direction [76–78]. Approaches such as transverse magnetic (TM) mode, re-entrant cavity, substrate integrated waveguide (SIW), and others examine dielectric parameters perpendicularly [79–81]. Most of the aforementioned techniques are inappropriate for the characterization of polymers and can yield inconsistent outcomes for anisotropic substrates since contemporary substrates are reinforced to be a combination of one or more materials, leading to dielectric parameter values that differ in parallel and perpendicular directions.

Our prior research has focused on the characterization of PDMS and other polymer substrates [9–12]. For the characterization of dielectric properties, we employed the resonance and planar approaches on the samples having thicknesses from 0.5 to 1.5 mm. To analyze the dielectric properties in parallel and perpendicular directions, two distinct resonators R_a and R_b are applied in resonance measurements as shown in Figure 11a. The dielectric constants were 2.7 and 2.5, respectively, and the loss tangents were

Table 1. Different polymer substrates for flexible antennas

Substrate	Dielectric properties $(\varepsilon_r/\tan\delta_{\varepsilon r})$	Antenna type	Frequency band	Applications	References
DMS	2.8/0.002	Circular patch antenna	2.45/5.8 GHz	ISM band	[50]
	2.8/0.001	Microstrip patch antenna	2.4 GHz	Body centric wireless communication	[51]
	3/0.001	Monopole slotted antenna	3.43-11.1 GHz		[52]
	2.7/0.001	Microstrip patch antenna	3–4 GHz	Conformal applications	[53]
PET	3.0/0.008	Microstrip patch antenna	2.35 GHz	BAN and IoT applications	[54]
	2.8/0.003	Monopole antenna	1.8 GHz	Wearable applications	[55]
	3.2/0.022	Bowtie-shaped slot antenna	2.1–4.5 GHz	WLAN and WiMAX applications	[56]
	3.2/0.022	Slotted disc monopole antenna	2.45 GHz	ISM band	[57]
PEN	2.9/0.005	Microstrip patch antenna	Sub-6 GHz	5G applications	[58]
	2.9/0.005	Meander antenna	800 MHz	UHF applications	[59]
	2.9/0.005	PIFA antenna	3.81/6.22 GHz	5G applications	[31]
PI	2.8/0.002	PIFA antenna	5.18–5.32 GHz	WLAN applications	[60]
	3.5/0.003	MIMO antenna	2.39–5.86 GHz	WLAN and applications	[61]
	3.5/0.002	Planar monopole	1.2–3.4 GHz	Wearable applications	[62]
	3.5/0.003	Monopole antenna	2.5/5.2 GHz	WLAN applications	[63]
	3.5/0.002	Fractal antenna – elliptical shaped	9.07 GHz	X-Band applications	[64]
	4.3/0.004	Monopole antenna		UWB and Body centric Wireless Communication	[65]
	4.3/0.004	Flower shaped antenna	3.5 GHz	WiMAX applications	[66]
Liquid crystal polymer (LCP)	2.9/0.003	Tapered patch antenna	Ka-band (26.5–40 GHz)	5G applications	[67]
	2.9/0.003	Circularly polarized antenna	3.5/5.8/5.9 GHz	WiMAX/WLAN/vehicular comm. band applications	[68]
	2.9/0.003	Tuning fork shaped patch antenna	20.7–36 GHz	5G applications	[23]
PTFE	4.0/0.18 (Compositesubstrate)	Microstrip patch antenna	2.45, 5.25, and 5.75 GHz		[69]
	2.2/0.001	Fractal antenna	2.45 GHz	WBAN and wearable applications	[70]
	2.2/0.002	Mosaic antenna	2.4 GHz	Wearable antenna for Cross-body communications	[71]
	3.0/0.001	Crossed dipole antenna	2.4, 4.6 GHz	MIMO, UAV Applications	[72]

0.03 and 0.02 in parallel and perpendicular directions, according to the measurements. As a result, the perpendicular dielectric constant is approximately 5.1% less than the parallel one, illustrating the material's low anisotropy.

This procedure is also used to validate the acquired values on other similar materials, and when the outcomes are compared to the values provided by the manufacturer, a reasonable correlation is observed. The covered ring resonator is depicted in Figure 11b

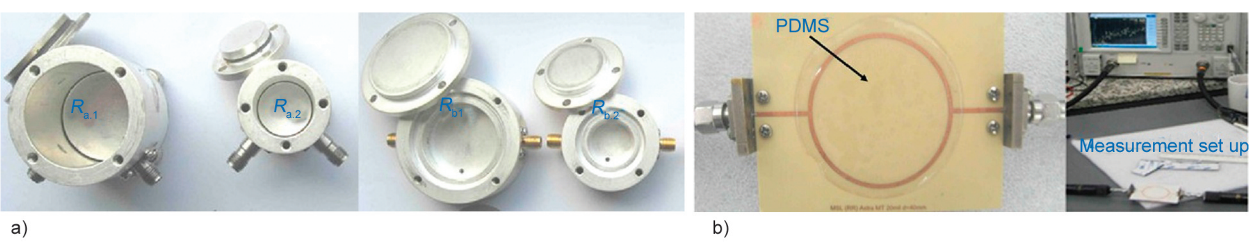


Figure 11. Resonance (a), and planar structure measurements (b). a) R_a and R_b resonators of 30.0 mm ($R_{a.1}$, $R_{b.1}$) and 18.10 mm ($R_{a.2}$, $R_{b.2}$) diameters to measure the dielectric parameters in parallel and perpendicular directions, respectively. b) Covered ring resonator of 18.10 mm diameter for the investigation of the equivalent dielectric parameters.

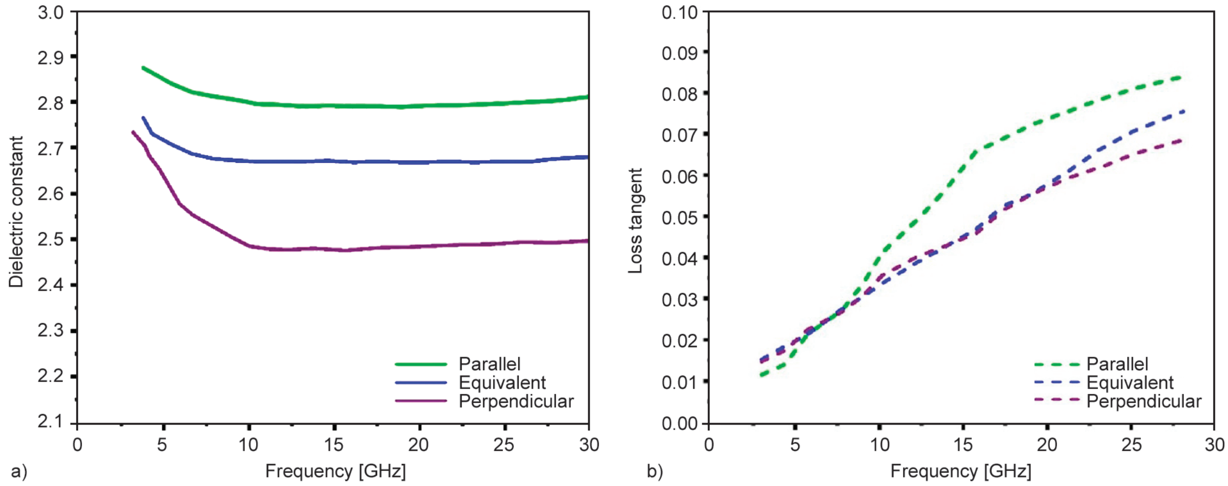


Figure 12. Measured dielectric parameter values by a) resonance measurements, and b) planar structure measurements.

has been employed in planar structure measurements to examine the isotropic equivalents to PDMS's anisotropic dielectric properties and to aid in the reduction of modeling issues with anisotropic substrates in antenna applications. The dielectric constant is 2.65, and the loss tangent is calculated to be 0.02. As shown in Figure 12, the isotropic equivalent values of the PDMS lay between the parallel-perpendicular values.

The methods employed are highly appropriate for characterizing the dielectric properties of various polymer substrates that can be applied to the design of flexible antennas. Through the application of these techniques, it is possible to acquire values for the dielectric coefficients of polymer substrates in both parallel and perpendicular orientations with their equivalent values, which improves the flexible antennas' design in terms of accuracy.

5. Effect of bending of polymer substrates on flexible antennas

t is crucial to assess the flexible antenna's performance in bent circumstances as one of its most significant advantages is that it may be employed and should function effectively in conformal environments. The conformal analysis of the flexible antennas is generally performed using bending radius (B_R) as a parameter to access the bending effect. However, the authors in [12, 82] have implemented another parameter, which is the bending angle (B_α), to analyze the effect of bending on the performance of the flexible antennas. Depending upon the B_α two different cases for the bending are formulated as positive ($B_\alpha > 0$) and negative bending ($B_\alpha < 0$), as shown in Figure 13.

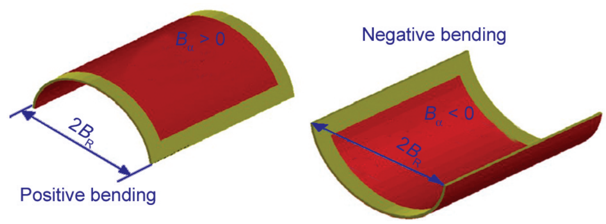


Figure 13. Bending orientation with respect to the bending angle [12].

After performing the conformal analysis, the authors have observed that for the polymer substrate-based flexible antennas, the resonant frequency of *L* (length) – bend structures increase as the bending increases in comparison to the flat case for positive bending case and *W* (width) – bend case this effect of bending is less. For negative bending, this effect is just the opposite and a decrement in resonant frequency is observed for *L*-bent structures, and an increment in resonant frequency is observed for *W*-bent structures, as shown in Figure 14.

Table 2 summarizes the effect of bending on the performance of the flexible antennas using the polymer substrates, and it can be observed as the bending increases (B_R and B_α), the shift in the resonant frequency increases.

In order to observe the effect of bending on other performance parameters of the flexible antenna designed using a polymer substrate like PDMS, authors in [49] have employed two different cylinders of 4 and 3 cm radius, as shown in Figure 15, and put the antenna over it to analyze its effect. It has been observed that there is a change in its resonant frequencies as per the previous discussion, its gain slightly increased by 2 dBi, and a decrement in the efficiency

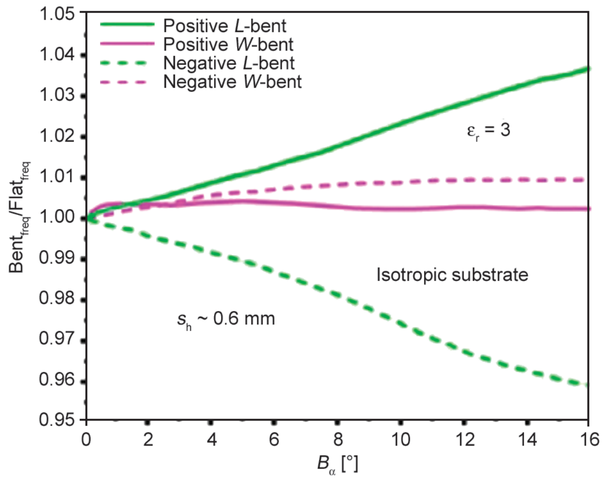


Figure 14. Bending analysis (ε_r: dielectric constant; s_h: substrate height; frequency unit: GHz).

Table 2. Bending effect of polymer substrates on the resonant frequency of flexible antennas.

Substrate	Bending radius/ Angle	Shift in resonant frequency	Reference
Kapton polyimide	13 mm	80 MHz	[83]
PDMS	30 mm	50 MHz	[27]
Kapton polyimide	9 mm	1.1 GHz	[84]
PDMS	13°	104 MHz	[12]
PTFE	200 mm	84 MHz	[85]
PDMS	10°	101.3 MHz	[49]

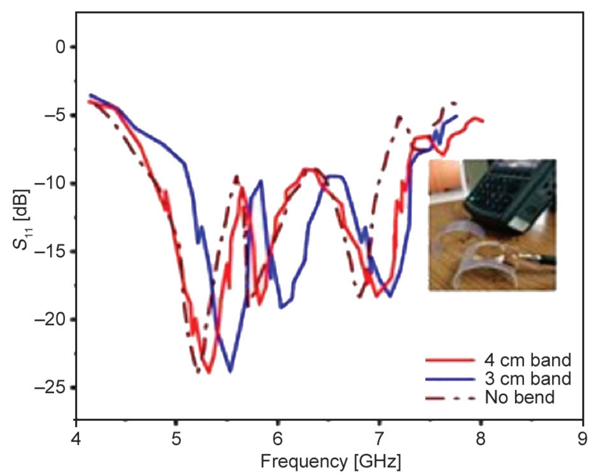


Figure 15. Bending analysis of PDMS substrate-based antenna [49].

was observed as the bending radius increased, these cases were of *L*-bent structures.

6. Challenges for polymer substrate based flexible antenna design

Due to their distinctive characteristics such as flexibility, lightweight design, and conformal capabilities, flexible antennas have attracted more interest in a variety of applications such as wearables, IoT devices, military equipment, and more. However, developing and deploying flexible antennas on polymer substrates such as polyimide (PI), polyethylene terephthalate (PET), and polydimethylsiloxane (PDMS) pose a number of substantial obstacles that must be properly addressed in order for antenna performance to be effective and efficient. The major challenges in employing polymer substrates in the design of flexible antennas are as follows:

A. Substrate material selection

The substrate selection is an essential step in the design of antennas since its features have a direct impact on antenna performance. While dielectric characteristics of polymer substrates are generally acceptable, they might vary across the material, influencing antenna performance. Dielectric constant changes can cause alterations in the antenna's resonant frequency and impedance matching. When contrasted to rigid substrates, these substrates may have larger loss tangents. Signal losses, poor antenna efficiency, and limited communication range are all caused by high-loss tangents. A design problem is balancing flexibility with low-loss tangent features. At high temperatures, polymer substrates may distort, affecting antenna performance in high-temperature situations such as those seen in aircraft or automotive applications.

B. Conformal design and fabrication

Flexible antennas with polymer substrates typically require specific fabrication processes such as screen printing or inkjet printing. These procedures can be complicated, necessitating precision control to ensure constant performance. When bent, stretched, or twisted, polymer substrates deform, changing the physical dimensions and resonance frequency of the antenna. It is critical to design antennas that can accommodate substrate deformation. It is difficult to integrate flexible antennas into devices while preserving performance under varied bending and stretching situations.

C. Durability and environmental factors

It is crucial to ensure that flexible polymer substrate-based antennas are capable of withstanding bending, twisting, and other mechanical loads without impairing electrical performance. Flexible antennas may be subjected to extreme conditions such as dampness, UV radiation, and chemicals. Protective coatings or durable materials are required to ensure that they maintain performance under such conditions. It is critical to ensure the long-term dependability of flexible antennas, particularly those subjected to repetitive flexing or harsh climatic conditions.

D. Bandwidth and frequency range
Poly-flex antennas often have a lower bandwidth than rigid alternatives, causing challenges for wideband applications. It might be difficult to design flexible antennas that cover a wide frequency range, from low to high frequencies, while maintaining acceptable performance.

E. Radiation efficiency and gain
With regard to substrate qualities and fabrication procedures, poly-flex antennas may have poorer radiation efficiency. It is difficult to achieve great radiation efficiency while remaining flexible. It can be challenging to design flexible antennas with appropriate gain for directional transmission.

F. Integration with electronics
Due to limited space, integrating poly-flex antennas with electronic components while maintaining electrical isolation is difficult. Impedance matching for flexible antennas with various characteristics might be difficult.

G. Testing and characterization
To reliably quantify poly-flex antenna performance under varied bending situations, specialized measurement sets and procedures tend to be essential. Due to differences in manufacturing procedures and material qualities, ensuring consistent performance across several antenna units can be difficult.

H. Regulatory compliance
Due to the flexible nature of such antennas and their impact on electromagnetic behavior, meeting regulatory criteria for radiated emissions, EMC, and SAR can be difficult.

7. Future aspects

The future of flexible antenna design with polymer substrates offers exciting advancements and breakthroughs that will likely influence the field of wireless communications and antenna technology. Several significant future elements can be anticipated as researchers and engineers continue to investigate the possibilities of polymer substrates:

A. Advanced material formulations
Researchers will certainly concentrate on creating polymer substrates with even more precisely controlled dielectric characteristics. Antennas with improved performance and wider frequency ranges will be possible through adjustable dielectric constants and low-loss tangents. Polymer formulation advancements may result in substrates with enhanced thermal stability, enabling the deployment of flexible antennas in higher-temperature situations.

B. High-frequency and millimeter-wave applications
Polymer substrates will be investigated further for application in high-frequency and millimeter-wave applications. Flexible antennas that operate in these frequency ranges are critical for developing technologies such as 5G, IoT, and others. Miniaturizing flexible antennas for even higher-frequency bands could serve as the primary objective of future research, enabling minuscule and high-performance antennas for mm-wave communication.

C. Innovative fabrication techniques
3D printing and other methods of additive manufacturing will almost certainly play a substantial part in the development of flexible antennas. These methods permit fine control over antenna geometries and material placement. To improve the electrical and mechanical properties of polymer substrates, nanomaterials, and nanofabrication processes can be combined. This has the potential to result in extremely effective and efficient flexible antennas.

D. Multi-band and wideband antennas
New polymer-based flexible antennas that span several frequency bands are likely to be designed, providing a greater range for modern communication systems that operate in a variety of frequency ranges. Researchers seek to create wideband antennas on polymer substrates that would allow for uninterrupted communication across an extensive spectrum of frequencies.

E. Environmental resilience and durability
Improved coatings and encapsulation processes are being explored to improve the environmental durability of flexible antennas, allowing them to be deployed

in harsh environments, including outdoors. Stretchable polymer substrates may allow antennas to conform to dynamic and uneven surfaces, thereby expanding their utility in applications such as smart apparel and health monitoring devices.

F. Conformal and wearable antennas

Polymer substrates will be employed as biocompatible and implantable antennas for medical devices, allowing for seamless integration with the human body and healthcare systems. Antennas will become an integral part of conformal and flexible electronic devices, offering unobtrusive and effective communication solutions.

G. Testing and characterization techniques

Advanced non-destructive testing methods will be devised to evaluate the performance of flexible antennas without jeopardizing their integrity. This serves to assist with quality assurance as well as assessing the dependability of flexible antennas.

8. Conclusions

In this paper, a comprehensive review of the implementation of polymer substrates in the design of flexible antennas is presented. The polymer substrates are quite advantageous over other types, like paper or fabric substrates, for the design of flexible antennas. The fabric substrates are prone to environmental effects; for example, the performance of the flexible antennas made up of fabric substrates degrades in the presence of moisture, but polymer substrates have very little or no effect in the presence of moisture and other factors. Different polymer substrates implemented for the design of flexible antennas for different applications are presented in this paper. The application of polymer substrates in flexible antennas represents a groundbreaking development in the field of wireless communication and technology. These substrates offer a versatile and cost-effective solution for designing antennas that can conform to various shapes and surfaces, making them ideal for a wide range of applications. Whether it is in wearable devices, IoT sensors, or aerospace technology, polymer substrates provide the flexibility and durability required to meet the ever-evolving demands of modern wireless communication. Furthermore, the integration of polymer substrates in flexible antennas has the potential to revolutionize industries by enabling innovative design possibilities. As technology continues to advance, the demand for compact, lightweight, and conformable antennas will only grow, and polymer substrates are at the forefront of meeting these demands. With ongoing research and development in this field, we can expect even more exciting breakthroughs in flexible antenna technology, further expanding the horizons of wireless communication in the coming years.

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