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Evolution of Compact Flexible Antennas Using Exotic Nano, Metamaterials for Wearable and Bio Medical Applications

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Abstract

Recent innovations in engineered materials have been leveraged to augment the field of flexible electronics. Flexible electronic devices are often lightweight, portable, less expensive, environment friendly, and disposable. Flexible electronics systems require the integration of flexible and stretchable antennas operating in specific frequency bands to provide wireless connectivity, which is necessity in today's information-oriented society. The markets for flexible wireless devices are rapidly increasing partly due to the demands in wearable and implantable devices for health-monitoring systems and daily-life wireless devices. For this reason, the need for flexible printed antennas has increased in recent years, especially for biomedical applications. This paper focuses on the need for flexible antennas, materials, and processes used for fabricating the antennas, various material properties influencing antenna performance, and specific biomedical applications accompanied by the design considerations. After a comprehensive treatment of the above-mentioned topics, the paper will also focus on inherent challenges and future prospects of flexible antennas. Finally, an insight into the application of flexible antenna on future wireless solutions is discussed.

Keywords: Meta-materials • Flexible antenna • Wearable antenna • 3-D printing • Specific absorption rate • Internet of things • Implantable antennas • Ingestible antennas • Nano materials

Introduction

The field of stretchable or flexible antennas is witnessing an exponential growth due to the demand for wearable devices, Internet of Things (IOT) framework, and point of care devices, personalized medicine platform, 5G technology, wireless sensor networks, and communication devices. The choice of non-rigid antennas is application specific and depends on the type of substrate, materials used, processing techniques, antenna performance, and the surrounding environment. There are numerous design innovations, new materials and material properties, intriguing fabrication methods, and niche applications. The availability of high speed, massive capacity, and low latency 5G networks has enabled the 'Fourth Industrial Revolution. Every sector will benefit from 5G networks ranging from 3-D imaging , advanced health care, streaming services, and smart cities, to name a few . Further, a strong 5G network is essential to the proper functioning of the Internet of Things (IOT) devices. One of the critical barriers to technological advancements of next-generation IOT related devices is inflexibility stemming from form factor and weight considerations. The flexible electronics market is expected to reach 40.37 billion in revenue by 2023. Apart from biomedical applications, there is shared interest between defense agencies, industry, and academia in developing a flexible antenna for extreme conditions. Several recent investigations have reported that provide extensive review on materials, fabrication, and applications of different flexible and wearable antennas.

The main focus was the different fabrication technologies for flexible antennas along with a design and analysis of a printed monopole antenna. A complete survey of recently used materials and fabrication methods of wearable antennas, ranging from Very High Frequency (VHF) to millimeter-wave band was presented earlier. Different types of implantable antennas, their design requirements, and performance comparison was surveyed in a prior article. The uniqueness of this article stems from the fact that this paper is the fact that we cover the entire area of flexible antenna rather than focusing on any subset such as wearable. Further, the authors discuss antenna applications covering a wide frequency bands unlike other articles restricting the scope on the working frequency. In any wireless application, the choice and design of the antenna vary depending on the environment, transmission strength, and frequency range. Further, the performance of the antenna depends on the material used, the type of fabrication technique employed, and the

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substrate properties. In this context, the article reviews the research trend in conductive materials used, the substrates, the different fabrication techniques to realize the flexible antenna, and their diverse applications. Besides, the challenges in flexible antennas, research and future directions are also highlighted [1].

Materials for Flexible Antennas

Flexible antennas are fabricated using various conductive materials and substrates. The substrate is chosen based on their dielectric properties, tolerance to mechanical deformations (bending, twisting, and wrapping), susceptibility to miniaturization, and endurance in the external environment. In contrast, the selection of conductive material (based on electrical conductivity) dictates the antenna performance, such as radiation efficiency.

Conductive materials

In wireless applications, the realization of conductive patterns with superior electrical conductivity is essential for ensuring high gain, efficiency, and bandwidth. Additionally, resistance to degradation due to mechanical deformation is another desired feature for the conductive material. Nano Particle (NP) inks are often preferred for fabricating flexible antennas due to their high electrical conductivity. Silver-nano particle ink edges over copper nano particles due to their low rate of oxide formation. Various types of textile and non-textile conductive materials for developing flexible antennas have been reviewed in an earlier article. Adhesive copper, copper tapes, and copper cladding have been reported in the development of flexible antennas. Conductive polymers like polyaniline (PANI) ,polypyrrole (PPy) , and poly(3,4-polystyrene sulfonate seem to be promising materials for flexible and wearable antennas. The low conductivity of conductive polymers was improved by adding carbon nanotubes, graphene, and carbon nanoparticles. Very few investigations have been observed for flexible antennas based on copper-based [2]. Flexible antennas using graphene are promising due to their decent electrical conductivity and excellent mechanical properties. Graphene paper, graphene nanoflake ink, graphene oxide ink, and graphene nanoparticle ink have been used in prior studies for fabricating flexible antennas. The performance of flexible antennas relies heavily on the fabricated conducting traces with high deformation sustainability while maintaining electrical conductivity. For accommodating mechanical strain and deformation without deteriorating the performance of the antennas, different stretchable conductive materials exploit doping to improve their conductivity. Some of the examples include silver nanowire embedded silicone, silver loaded fluorine rubber, Carbon Nanotubes (CNT) based conductive polymers, liquid metals in the stretchable substrate, and use of stretchable fabric itself.

Substrates

The substrate material used in flexible antenna needs to possess minimal dielectric loss, low relative permittivity, low coefficient of thermal expansion, and high thermal conductivity. Such a constraint is driven by the need for increased efficiency at the cost of larger antenna size. An exception to the above-mentioned fact is the need for large dielectric constant for miniaturized antennas. Three types of substrates have often surfaced in the fabrication of flexible antennas:

thin glass, metal foils, and plastics or polymer substrates. Though thin glass is bendable, the intrinsic brittle property restricts its utility. Metal foils can sustain high temperatures and provide inorganic materials to be deposited on it, but the surface roughness and high cost of the materials limit its applications. Plastic or polymer materials are the best candidates for flexible antenna applications which include. Flexible antennas made for wearable purposes need unique attributes such as limited visibility for the user, robust antenna performance in different conditions, mechanical stability, and withstanding rigor, such as washing and ironing.

Different types of substrates used in wearable antennas have been reported in a prior article. Felt, fleece, silk, and Cardura, off-the-shelf (electro) textile materials, and standard apparel are a few examples of substrates that have been used for wearable/flexible antennas. The use of Polydimethylsiloxane (PDMS) polymer as a substrate has been emerging because of its low Young's modulus suggesting high flexibility/conformality. However, the development of a flexible antenna is limited on the PDMS substrate due to the weak metal–polymer adhesion. Nevertheless, some solutions to this issue have been found in literature such as implanting carbon nanotube sheets or different microspheres like glass, phenol or silicate or nanowires (AgNWs), injecting liquid metal, and oxygen plasma treatment on the PDMS surface. It can be concluded without a doubt the choice of substrate material is of paramount importance in the realization of flexible antennas. Due to their conformal behavior and operational suitability, flexible materials have gained immense interest. These flexible materials need to be chosen carefully to withstand the physical deformation conditions such as bending, stretching, and even twisting while maintaining its functionality. Flexible antennas require low-loss dielectric materials as their substrate and highly conductive materials as conductors for efficient EM radiation reception/transmission [3].

Fabrication Techniques for Flexible Antennas

The performance of a flexible antenna is determined by the fabrication method. The common fabrication techniques include wet-etching, inkjet printing, screen printing, and other special methods for fabricating flexible wearable antennas.

Inkjet printing

Inkjet-printing technology has emerged as an alternative to conventional fabrication techniques such as etching and milling. It is an additive process so that the design is directly transferred on to the substrate without any masks and ensures less material wastage. It is the preferred fabrication technique for polymeric substrates like polyimide, PET, paper due to its accurate and speedy prototyping fabrication method. An example of inkjet printing is the use of silver nanoparticle ink to fabricate a wideband right-hand circularly polarized high-gain 4 × 4 microstrip patch array antenna on a PET substrate using Epson stylus c88 series printer. Another example of an inkjet-printed antenna is epidermal antennas suitable for Radio-Frequency Identification (RFID), and sensing on transparent PET film has been presented in an earlier study. The unique feature of this antenna fabrication method is that no heat sintering is needed. A miniaturized fully inkjet-printed flexible Multiple-Input-Multiple-Output

(MIMO) antenna for Ultra Wideband (UWB) application was proposed on Kapton polyimide substrate using a Di matix DMP 2800 printer. Using Dimatix DMP 2831 printer, a flexible, wearable, and reversibly deformable CPW fed antenna was designed on PET substrate using silver nanoparticles. A high-gain, multi director Yagi-Uda antennas for use within the 2.45-GHz ISM band were realized using silver and dielectric ink on LCP substrate using the same printer.

Screen printing

Screen printing is a simple, fast, cost-effective, and viable solution for fabricating flexible electronics, which has been widely adopted to implement RFID antennas by printing conductive inks or pastes onto low-cost, flexible substrates such as PET, paper, and textile substrates. It is a woven screen-based technique having different thicknesses and thread densities. A squeegee blade is driven down, forcing the screen into contact with the substrate to produce a printed pattern. Thus, the desired pattern is formed by the ink ejecting through the exposed areas of the screen on the affixed substrate. It is also an additive process like inkjet printing as opposed to the subtractive process of chemical etching, which makes it more cost-effective and environmentally friendly. A screen-printed dual-polarization 2.45 GHz antenna and rectenna on polycotton for RF power transfer and harvesting were demonstrated in a prior article. The rectenna was tested and compared with a similar FR4 rectenna, and the performance was found a third of standard FR4. The fabrication process has been given in figure below. A DEK Horizon 03i semiautomatic screen printer was used to fabricate a graphene-flakes-based wideband elliptical dipole antenna on a polyimide substrate operating from 2 to 5 GHz for low-cost wireless communications applications. Screen printing is cost-effective compared to other fabrication technologies of flexible antennas. However, it has some limitations like resolution dependence on the surface quality of the substrates, the limited layer control, and lack of thickness control for the

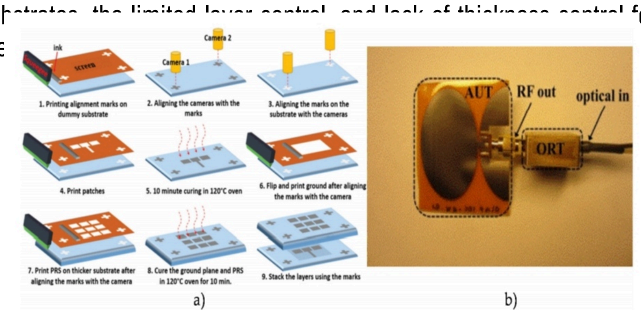


Figure 1. Schematic of the screen-printed antenna.

3-D printing

Recently, additive 3-D printing techniques for flexible antennas are gaining popularity with a myriad of commercially available printing materials and processes. It exhibits several advantages like in-house-made, fast fabrication of complex 3-D structures with various materials, and the capability to change the density of the printed object. The flexibility to realize complex 3-D shapes from bulk materials and 3-D printing of flexible materials like polymers, metals, ceramics, and even biological tissues make it attractive for antenna design. Polymers, such as thermosets and thermoplastics, are used as 3-D printing materials for flexible antenna applications. The common printing techniques of the polymers are Fused Deposition Modeling (FDM), Stereo Lithography (SLA), Direct Light Processing (DLP), and Material Jetting (MJ). The most common 3-D printing technology is FDM. In FDM, the filament is fed through to the extrusion head of the printer, and the motor of the heated-nozzle drives the filament melting it. The printer then lays down the melted material at a precise location, where it cools down and solidifies.

The process repeats by stacking up the part layer-by-layer. One of the first examples of the exploitation of 3-D-printing in microwave components and antennas fabrication was presented in an earlier article .Ninja Flex, a new 3-D printable, flexible filament, has been adopted for manufacturing a 3-D printed patch antenna. FDM technique has been used to realize 3-D printing substrate. A linearly polarized patch antenna was designed and implemented on the Ninja Flex substrate 100% infill at 2.4 GHz operating frequency. Experimental verification under nominal and bending conditions showed good agreement with the simulation. A 'button-shaped' compact RFID tag fabricated by the combination of 3-D printing and inkjet printing technologies was also reported for wearable applications. The antenna showed a good performance with a measured maximum reading range of 2.1 m in the RFID Federal Communications Commission band. A proof-of-concept of the fabrication and performance analysis of a flexible and stretchable wearable antenna on a 3-D printed Ninja Flex substrate is shown in Figure 2.

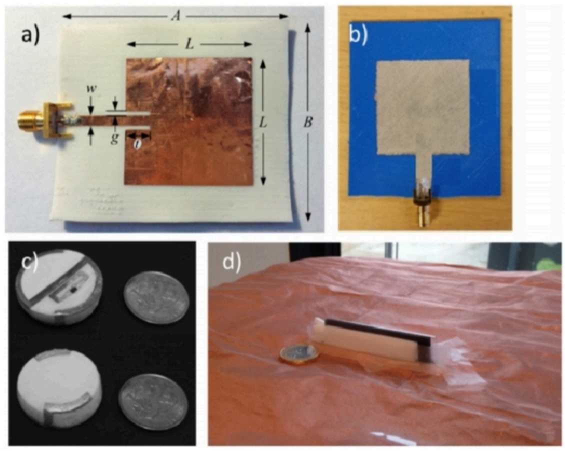


Figure 2. Examples of 3D printed antennas.

The radiator of the antenna was brush-painted from the stretchable silver conductive paste shown in figure above. The antenna's wireless performance under flat and bending conditions was satisfactory. Specific Absorption Rate (SAR) simulations validate its use for wearable applications. The antenna showed impedance bandwidth of 990 MHz (1.94-2.93 GHz) with a peak gain of -7.2 dB at 2.45 GHz. Recently, a 3-D flexible, miniaturized inverted-F antenna for wearable applications was designed, manufactured using the Galinstan liquid metal to realize the radiating element, the NinjaFlex flexible plastic to realize dielectric substrate through a 3-D FDM printing process shown in figure above and the electro-textile copper constituting the antenna ground plane. The performance of the antenna in several bent configurations and in the presence of the human body was found satisfactory [4].

Chemical etching, often accompanied by photolithography, emerged in the 1960s as a branch-out of the Printed Circuit Board (PCB) industry is the process of fabricating metallic patterns using photoresist and etchants to mill out a selected area corrosively. For fabricating complex designs with high resolution accurately, it is the best choice among all other fabrication techniques. Organic polymers are suitable for photoresists as their chemical characteristics change when they are exposed to ultraviolet light. Current practice in the photolithography based antenna and RF circuits industry relies mainly on positive resists since they present higher resolution than negative resists. A multilayer type of flexible monopole antenna was designed and fabricated on a transparent polyimide substrate for application in wearable glasses in an earlier article. A 100-nm-thick Indium-Zinc-Tin Oxide (IZTO)/Ag/IZTO (IAI) is a transparent (81.1%) conducting oxide electrode, which was used as the conductors of antennas and ground planes of the wearable glasses. Physical Vapor Deposition (PVD) process is employed to fabricate this multilayer type of stretchable and flexible antennas. These smart materials provide the feasibility of wearable, flexible antennas for optical and electrical applications using the photolithography process.

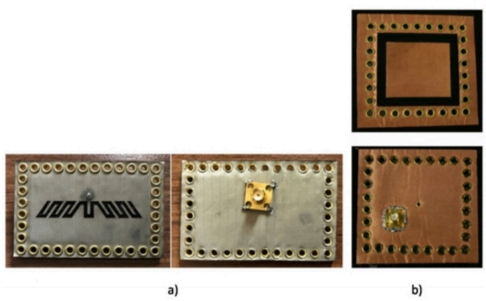
Special Fabrication Techniques for Flexible Wearable Antennas

The special fabrication techniques for fabricating flexible antenna can be divided into the following categories:

- SIW based technology.
- Stitching and embroidery.
- The use of conductive textile yarns to embroider the conductive patterns of the antenna on a non-conductive textile substrate
- Inkjet and screen printed printing on non-conductive textile materials.

Substrate integrated waveguide based technology

A relatively new method referred to as Substrate Integrated Waveguide (SIW) is highly desirable to realize future System On Substrate (SOS) platforms for developing high-performance mm-wave systems. This structure ensures the confinement of electric fields inside the cavity by the use of shorting wires on its sidewalls, backed by the full ground plane. The main advantages of the SIW based technology are the improvement of the Q-factor of the antenna and improving isolation between the antenna and wearers body. A compact Substrate Integrated Waveguide (SIW) based wearable tri-band leather antenna, designed for optimal on-body performance was proposed in.



Figiure 3. Antennas fabricated using the substrate integrated waveguide (SIW) method.

Stitching and embroidery

Weaving or knitting the conductive textile on the substrate is another method for fabricating flexible wearable antennas. Knitting copper on a fleece substrate, the first compact fabric antenna design for commercial smart clothing was presented in an earlier article. Embroidery with conductive yarn is a simple fabrication method with great potential in flexible wearable antenna fabrication due to its compatibility with non electronic textile processing capabilities. An embroidered antenna-IC in–reconnections in passive UHF RFID electro textile tags and the possibility of creating a planar dipole tag by only embroidering the borderlines of the full antenna shape was studied earlier. A 160-mm-diameter Archimedean spiral antenna was weaved using seven-filament silver-plated copper Elektrisola E-threads on a Kevlar fabric substrate. The application area of this antenna covered several wideband, conformal, and load-bearing applications, such as airborne and wearables. Recently, a mix of these two methods was presented in a study as shown in the Figure 4. This work demonstrated the possibility of implementing an all-textile antenna, reducing the backward radiation via the use of a SIW topology.

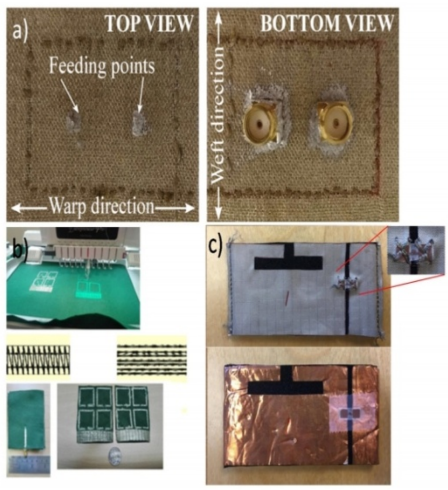


Figure 4. Embroidery and stitching based flexible antennas.

Applications of Flexible Antennas under Different Frequency Bands

Even the most conservative projection for the growth of the Internet of Things (IoT) shows that the global IoT industry set to reach over USD 363.3 billion by the year 2025. A significant portion of this market includes health monitoring and clinic therapeutic devices, medical microwave radiometry, wearables, vehicular navigation systems, etc. Because of the nature of these applications, the antenna used should be flexible, conformal, and stretchable to comply with the curvilinear surfaces and dynamic motions. Besides civilian applications, it also plays a vital role in the military domain. Most of the military devices are connected to a large ad-hoc network. Military personnel are required to carry a large amount of equipment with different sensors and health monitoring devices. Therefore, flexible, and lightweight antennas are desirable in the military sector to reduce the burden of the soldier. In this article, flexible antenna applications are delineated into two categories: below 12 GHz and above 12 GHz. The development of flexible materials has paved the way for innovation in antenna designs and new applications that were not possible with rigid substrates.

For flexible antenna applications below 12 GHz, RFID tag or smart card systems are typically designed using the flexible antennas at Ultra-High Frequency (UHF) band. The ultra-wideband applications of the flexible antenna cover WiMAX, WiFi, lower band of 5G, and one of the ISM radio bands. For flexible display devices working in the UHF band, a dipole antenna was reported on the Kapton polyimide substrate. Kapton substrate ensures mechanical robustness and low dielectric loss for this antenna. In the UHF spectrum, antennas for smart cards and RFID tags dominate. Flexible RFID tags for non-invasive sensor applications like patient tracking in the medical system, Internet of Things (IoT) devices, childcare centers, humidity, and temperature sensing have been reported. According to Radio Society of Great Britain (RSGB), above 12 GHz, the Ku band starts, and these high-frequency bands are primarily used for radar, satellite communications, astronomical observations, radio astronomy, and microwave remote sensing. For remote sensing, radar, and future communication systems, dual-polarization microstrip antenna arrays were reported on LCP substrate operating at 14 and 35 GHz. Dual-polarization and dual-frequency ensures higher capacity data transfer. A flexible, washable, and reusable UWB fully textile-based wearable antenna was designed and analyzed in earlier reports. It maintained excellent efficiency from 3 to 20 GHz conductive for medical monitoring applications and smart garments. For example, flexible graphene antennas in single and array on polyimide substrate shown in figure below operating at 15 GHz produced large bandwidth to support higher-speed for 5G applications [5].

Miniaturization of Flexible Antennas

The desire to connect all electronic devices into the IoT, has accelerated the need for integrated smaller flexible antennas. As a result, research investigations for small antennas have been increasing. The major challenge for researchers in this field is reducing the size of the antenna in order to integrate with miniaturized devices without compromising the antenna performance parameters such as impedance matching, gain, bandwidth, radiation pattern, and efficiency. Although, it is a difficult and daunting task, researchers have found a number of creative approaches for shrinking antenna size. In the literature, there are various techniques proposed to reduce the antenna dimensions. Here, the focus is on the methods used for lowering the form factor of the flexible antennas. The applied methods can be mainly classified into three groups: material based miniaturization, topology-based miniaturization, and use of Electromagnetic Band Gap (EBG) structures. Artificial Magnetic Conductors (AMC) and High Impedance Surfaces (HIS) were applied to design low profile antennas. PBG periodic structure was used in the conformal antenna and array to suppress the surface wave propagation. It is shown to help to reduce the effect of radiation on the cylindrical curvature that is supposed to affect the resonance frequency. The gain and directivity of the antenna were improved by using PBG.

Applications of Flexible Antennas

Flexible antennas for implantable applications

In recent years, the continuous advancing and revolutionizing of health care systems towards the advancement of an efficient system to increase the quality of life as well as implementing future IoT in medical sector. An implantable antenna system transmits and stores the recorded physiological parameters, conditions for real-time communication. So, flexible antennas play a huge role in implantable antenna applications and they are receiving significant attention to the researchers and thus have become a current research focus. Flexible antennas are quite necessary as most of them are from polymeric substrate which can be biocompatible in nature. For designing an implantable antenna, the basic requirements are the small size along with proper placement inside the human body, larger bandwidth, flexibility, and low Specific Absorption Rate (SAR). It is also challenging due to the different dielectric constant of various tissues and organs of the human body. The SAR values for the flexible antennas are relatively higher than typical implantable antennas. So designing flexible implantable antennas is quite challenging.

Flexible antennas for ingestible application

Telecommunications and microelectronics have contributed a number of benefits in the field of medical applications. Ingestible Medical Devices (IMDs) are significant components for IoT applications in medical sectors. As a result, for monitoring devices and drug delivery system and monitoring internal condition of the patient, special types of flexible antennas are needed. Wireless IMDs have been widely used for diagnostic purposes, in particular for visualization of Gastrointestinal (GI). Because the digestive organs in the GI tract have different electrical properties, the antennas for these applications need to have broadband characteristics. In recent years, there are various antennas for wireless systems have been reported. However, heavy metals are mainly used to fabricate these antennas, which are potentially hazardous for human's health when the capsules fracture. Wireless Capsule Endoscopy (WCE) is a technique for medical applications that records images of the digestive tract. This method has various advantages, comparing to traditional methods, such as esophagogastroduodenoscopy or colonoscopy. WCE is painless and non-invasive. WCE system contains an antenna that offers wide bandwidth to scan different areas of the small intestine.

Challenges and Future Prospects of Flexible Antennas

Recently, the research on flexible wireless devices has attracted much attention because of its nature to comply with the requirements of biomedical applications, vehicular navigation systems, wearable, and so on. An antenna is one of the key components in this whole system, and for ensuring the device conformity, it should be flexible and stretchable. The first step towards this goal is to replace the conventional rigid substrates with flexible materials like textiles, paper, or elastomeric such as Polydimethylsiloxane (PDMS), PEN, PET, and PI. Thus, it can be said that the very first challenge of designing a flexible antenna is finding a suitable substrate. In comparison to the traditional substrates like FR4 or Rogers that have a dielectric constant around 3-10 and a loss tangent of 0.001-0.02, typical flexible substrates have low dielectric constants. Even though this low value of dielectric constant helps to achieve larger bandwidth and radiation efficiency, it creates a problem when miniaturization is needed. For flexible textile antennas, the uneven thickness is another problem to deal with. The electro textile substrate is prone to crumble and susceptible to fluid absorption. Paper-based flexible antenna faces similar problems with relatively high loss factor, which causes low antenna efficiency and impedance mismatch. In an earlier work, an organic paper-based UWB antenna was presented. Although it is a low-profile antenna, it is not the right choice for applications that require high levels of bending and twisting because of discontinuities and lack of robustness.

A polymer-based substrate is an excellent option to solve these problems. For example, an earlier report studied a compact polyimide-based antenna where Kapton polyimide film was used because of its low loss tangent (tan δ=0.002) for broadband frequency operation with physical and chemical flexibility. This substrate had a temperature rating up to 400°C and tensile strength of 165 MPa at 73°F that confirms the robustness of the Kapton polyimide film. Furthermore, polyimide and Kapton are not very expensive because of roll-to-roll mass production while being transparent and bendable. One problem that can arise from the polymer-based antenna is excessive bending or twisting that might result in micro-cracks in the substrate. This will affect the electrical conductivity of the antenna and raise the risk of breakdown. Further, low glass transition temperatures of polymer make them unusable in high-temperature applications. Ceramic substrates can be an alternative which can withstand high temperature and can be used in flexible applications. Such a limitation can be overcome by embedding very thin metallic nanowires on the surface of elastomers like PDMS to make it highly conductive and stretchable. Because of the fabrication and design complexity, it is not very suitable for low-cost, flexible applications. Instead of solid metal wire, if Liquid Metal (LM) is used in the microfluidic channel created by elastomers, it will give the antenna re-configurability, an exciting feature of antenna that is needed in many applications.

PDMS is the most popular commercial elastomers to make the microfluidic channel for the flexible antenna. Different liquid metals such as mercury, Carbon Nanotubes (CNT), Galinstan, Gallium Indium (GaIn), and Eutectic Gallium Indium (EGaIn) are injected into the channel to form the antenna. Besides PDMS, Eco Flex silicone rubber and Thermoplastic Polyurethane (TPU) based Ninja Flax are also used as an elastomer for creating microfluidic channel, and are usually 3-D printed to realize a specific pattern. Another challenge of designing flexible antennas is identifying suitable conducting materials that sustain different bending and twisting conditions and have reasonable resistance value as not to affect the antenna radiation efficiency. Various methods have been considered to find the conductive substrates, such as chemically modifying fabrics surface or physical mixing of several conductive materials. The material with high dielectric constants are used to miniaturize the size of the antenna. Most common elastomeric materials have low dielectric constants.

Future Scope

Flexible antennas for future wireless solutions are expected to work in a broad range of frequencies due to the increased demand for wireless applications such as the Internet of Things (IoT), Body Area Network (BAN), and biomedical devices. There are different antenna methodologies, single-band antenna, multiband antenna, and reconfigurable antenna. Multiband design is often necessary, for example, devices in wireless LAN should operate in both 2.4 and 5 GHz range. In addition, the design should ensure that the antenna's characteristics stay consistent under bending conditions. A low-cost inkjet-printed multiband antenna was developed in an earlier article. A novel triangular iterative design with Coplanar Waveguide (CPW) feed printed on Kapton polyimide-based flexible substrate was used to achieve multiband operation with wide bandwidth. The antenna covers the GSM 900, GPS, UMTS, WLAN, ISM, Bluetooth, LTE 2300/2500, and WiMAX standards. Concave and convex bending was used to evaluate the antenna. Convex bending shows no significant resonance frequency shift, while during concave bending, there is a maximum 3% shift. A Planar Inverted-F Antenna (PIFA) made of a Flexible Printed Circuit (FPC) with multi-band operation available for Bluetooth and IEEE 802.11a/b/g standards were developed earlier.

The antenna's characteristics stay consistent while the angle of folding is less than 90 degrees. Flexible and wearable antennas were designed in .for wireless and satellite-based Internet of Things (IoT) and Wireless Body Area Network (WBAN) applications. The antenna operates in the C-band (4-8 GHz) for satellite communication to avoid congestion in lower frequency satellite bands. There are different types of reconfigurable antennas, including polarization, frequency, and reconfigurable pattern antenna. The significant benefit of a reconfigurable antenna is its capability to switch bands based on the end-user's application requirements. In a previous work, a flexible, spiral-shaped frequency reconfigurable antenna is developed that covers aeronautical radio navigation, fixed satellite communication, WLAN, and WiMAX standards. Frequency reconfiguration is achieved by the incorporation of a lumped element in the strip so that the antenna can switch between different resonances. A flexible, reconfigurable antenna using polarization was proposed in earlier work .The intended use for the antenna is in biomedical applications as a remote patient monitoring system operating in WBAN and WiMAX standards. Future flexible antennas should feature low profile, low loss, easily integrable with RF front end system, ability to control/ manipulate radiation pattern, and eventually circular polarization for wider bandwidth.

Conclusion

The field of flexible antennas is fascinating and interdisciplinary involving electrical engineering, materials science, and mechanical engineering. Flexible antennas are one of the critical components in the realization of flexible electronic devices. The flexible antenna is ideal for current and futuristic wireless communication and sensing applications primarily due to its lightweight, reduced form factor, low-cost fabrication, and ability to fit non-planar surfaces. The choice of materials for antenna fabrication is based on application preferences such as environment, seamless integration with rigid and non-rigid devices, cost, and mass manufacturing aspects of the fabrication process. Highly conductive materials such as Ag nanoparticles inks, Cu tape or clad, conductive polymers, PDMS embedded conductive fiber, and graphene-based materials have been typically used to implement the conductive patterns in the antenna. Kapton polyimide, PET, PEN, PANI, liquid crystal polymer, electro-textile, and paper have been preferred as flexible substrates. Metamaterial based flexible antenna is a relatively new development and has found its way in the commercial market because of its characteristics like lightweight, robustness, and re-configurability. It has the potential to be cheaper and smaller. The co-design of antenna and RF system on a flexible substrate has made breakthroughs in biomedical implantable devices. Improvement in the design techniques and introduction of new materials will help make this co-design system more viable for many other applications.

Metamaterial has a natural ability to couple with the radiation and converts it from one type of energy to another. This feature of the metamaterial can be used to flexible rectenna for energy harvesting. Applications of flexible antennas in the different frequency band below and above 12 GHz indicates the versatility of flexible antennas. Different miniaturization techniques have been discussed, along with challenges and limitations. Flexible antennas for biomedical applications with implantable and ingestible functionality shows the promising nature of the electromagnetic devices in health care. Bending, stretching, and proximity to the human body's impact on flexible antennas performance have been discussed. Corrective measures such as increasing the bandwidth or symmetry of the designed antenna can help account for deviations caused by deformation and other spurious factors. Finally, challenges for designing and realizing a flexible antenna has been discussed considering material challenges for the substrate and the conducting material. Flexible antennas for the future wireless system as a part of IoT, BAN, and biomedical devices have been reviewed with the citation of recent literature. The latest research on flexible antennas with emphasis on power sustainability via energy harvesting is discussed. Despite the limitations of flexible antennas, these non-rigid devices can be engineered to meet the futuristic demand for a compact wireless solution to fit the surface of any curvature.

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