5G Antenna Materials and Ensuing Challenges

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Abstract. Fifth Generation (5G) communication tools are extremely important for the modern society, especially when more and more of our activities are organized in such a way as to be carried out rapidly and more efficiently even if they are to take place from a distance. There are many possibilities, using different advanced materials, to fulfill the high demand of the antennas with different functionalities. Investigation on the characteristics of the material used in this application is a starting point to be really able to manage in a proper way the performance of the antenna. Understanding the most important characteristics allows designing material with low or even controlled dispersion that intrinsically will increase the performance of the antenna. The present chapter reports some fundamental elements belonging to such a wide-ranging topics used up to date, even if it does not target to fully cover all features about any material used in this field. The aim of the present chapter is to present different challenges in designing 5G communication tools, starting from the selection of the appropriate material up to their production methods. It also includes some aspects related to the multidisciplinary face

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of such research developments in order to highlight the necessity of the participation of many scientific figures to attain enhanced characteristics of the future communication systems. Additionally, an insight into future communication networks from material point of view is provided. Some of the major challenges in THz communications, body implant antennas and wearable antennas are discussed also.

Keywords: DRA · 5G Communication · Milimeter Wave · THz · Implant Antenna · Nanoantenna · Antenna Materials· Antenna Materials Properties

1 Introduction

5G communication network always rely on performance of the antennas involve in the communications. Significant progress has been achieved during the time in terms of better quality joining, quantity of the transmitted data, widespread coverage, etc. All of these features have been realized using better quality materials in order to be able to provide some consistent implementations to the existing one [1], [2]. High speed data transfer is major attribute in wireless communication technology which is upgraded to an unprecedented level by introduction of Multiple Input Multiple Output (MIMO) concept in 5G communication systems. By using multiple antennas for transmitting or receiving the electromagnetic signal at a time, undoubtedly MIMO antenna system passed Shannon's limit. These antenna systems with the ability to suppress fading, high throughput, low latency,increased coverage & connectivity, play crucial role in the development of various RF and microwave communication system. Role of material in antenna design cannot be denied as it is partially responsible for various performance attributes of the antenna. With the advancement of material science, antenna designers are able to think about unconventional applications like wearable antennas, On/Off body antennas, Milimeter wave and THz antennas. The 5G network can be characterized by some typical features viz: ever-present connectivity, particularly low latency and high-velocity data transfer. With 5G technology being set up, the common tendency for high-speed wireless communication is to move the functional frequency toward the millimeter-wave spectrum (30-300 GHz) and to exploit the available high bandwidth [3], [4], [5].

The approach to reach excellent functionalities in 5G communication tools are directly correlated to the exploration of the various materials used for such devices. The connection between its structure, composition, morphology, shape, electric characteristics and others properties has to be considered and analysed before their implementation for the considered application. Understanding these characteristics allows designing materials with enhanced properties, in particular low or even controlled dispersion that intrinsically will increase the antenna performances. Compared to the current 4G network, 5G supports high frequencies and spectrum, proposing remarkable data proficiency, unlimited call volumes and data transmission. One can talk about an important development as signal, management and accounting process concerns [6], [7], [8]. The present chapter does not aim to completely cover all features about any material used in this applications, but it reports some essential elements belonging to such a wide-ranging topic used up to date with the intentions to present different challenges in designing 5G communication tools. It also includes some aspects related to the multidisciplinary face of such research development in order to highlight the necessity of the participation of many scientific figures to attain enhanced characteristics of the futuristic wireless communication network and of its compatible contemporaries.

2 Role of Dielectric Material in the Development of Antennas

Dielectric means “a substance or medium that can sustain a static electric field within it or a substance in which an electric field gives rise to no net flow of electric charge but only to a displacement of charge” [9]. Dielectric materials are insulating materials with characteristics of electric polarization. It means positive and negative charges displace themselves in accordance to Electric Field (EF) applied. Dipole moment of material is also disturbed due to applied EF. These dielectric materials can be distinguished on the basis of their 'dielectric constant' or 'relative permittivity' expressed as Eq. 1.

$$\epsilon_r = \epsilon/\epsilon_0 \tag{1}$$

where ϵ_0 -permittivity of free space and ϵ -permittivity of the medium

The dielectric constant of any material helps in evaluating its ability to carry ac current in respect to that of free space or vacuum. Whenever a potential is applied to material, dielectric constant also relates with how much amount of energy is stored by the material in respect to vacuum. It is the reason why dielectric material used previously in condensers to up their storage capacity, in microwave filters, resonators etc. In 1888, German physicist Heinrich Hertz demonstrated concept of electromagnetic radiation using metallic rod experimentally following James Maxwell's Electromagnetism theory. After that, myriad of successful antennas were built by using metallic conductor. Due to increase in regular demand and need of future, operating frequency was kept increasing which eventually stagnate because of excessive metallic losses in those metallic antennas at high frequency. With the advent of wireless communication, movement towards higher frequency spectrum became the necessity. In 1939, R.D. Richtmyer [10] unveiled the fact that dielectric materials can also be used as resonators. A Dielectric Resonator (DR) indulge into resonance for a steep set of frequencies and this action finds similarity between cavity resonator, with major difference that, definition of boundary condition in DR wholly governed by abrupt change in permittivity instead of conduction as in cavity. The resonant frequency of DR largely depends upon physical dimensions, dielectric constant of DR and immediate surrounding. In 1960s, [11,12,13] discussed working of dielectric microwave resonator for different applications. Important dielectric properties of Dielectric Resonators (DR) include i) the Quality factor (Q) which is approximately equal to inverse of loss tangent ($\tan\delta$), ii) the relative permittivity of material (ϵ_r), iii) the temperature coefficient of resonant frequency (τ_f). For different applications researchers seek desirable combination of these three properties i.e., Q,

ϵ_r, τ_f. For example, to make an efficient TE_{10} mode waveguide filter DR having following parameters is desirable i.e., $Q \simeq 8000$ at 4 GHz, $\tau_f \simeq 20\ ppm/^0C$ and $\epsilon_r > 35$. Some of the materials used as DR are given in Table-1. From the inception of DR, it was majorly used in applications such as microwave filters and oscillators until in 1983, an experiment was reported in which DR successfully used as a radiator. The radiator which used DR as main radiating element termed as Dielectric Resonator Antenna (DRA). In 1980s, [14,15,16,17,18,19] have undergone a systematic and purposeful study of DRA. Dielectric resonator antenna can be visualized as a leaking resonator and this leaking energy can be used as efficient radiation. Due to absence of metallic losses at high frequency, DRA become prominent option for microwave and millimeter wave radiation applications. In general, there are three most important characteristics sought in a low loss dielectric material to be suited as efficient radiator. These are: well optimized value of ϵ_r, low $tan\delta$ signifies less dielectric losses and low τ_f. In the forthcoming sections, focus is on the material used in DRA and their effect on the antenna performance.

Table 1: Some of materials used as DR

Material Composition	Qxf GHz	ϵ_r	$\tau_f\ (ppm/^0C)$
$Ba_2Ti_9O_{20}$	32000-40000	40	$+2$
$(Zr,Sn)TiO_4$	32000-40000	34-37	± 20
$(Sr,Ca)[(Li,Nb),Ti]O_3$	30000-36000	38-46	$\pm 30 \sim 70$
$BaTi_4O_9$	28000-40000	38	$\pm$ 15, ± 3
$(Ca,Sr)(Ba,Zr)O_3$	22000-33000	29-32	$\pm$ 50
$MgTiO_3 - CaTiO_3$	55000	21	$\pm$ 10
$Ba(Sn,Mg,Ta)O_3$	200000	25	$\pm$ 5
$Ba(Zr,Zn,Ta)O_3$	100000	30	± 5
$BaO - PbO - Nd_2O_3 - TiO_2$	5000	90	± 10

Human nature is to run before speed whether it is high speed car racing or high data rate communication system. The advent of modern communication has now become essence of human communication system. There are various means of wireless communications such as 4G/5G cellular networks, Wireless- Fidelity (Wi-Fi), Wireless Local Area Network (WLAN), Worldwide Interoperability for Microwave Access (WiMAX), satellite communication, RADAR, SONAR, Direct to Home (DTH) broadcast etc. In 1970s, one of the major reforms in the microwave antennas was:- introduction of printed antenna technology. It needs a dielectric substrate for propagation of electromagnetic signal which eventually excite the microstrip patch antenna (MPA). Performance of patch antennas can be enhanced up to a limit by choosing a low loss substrate. Most popular substrate used for patch antennas is FR-4 (Flame Retardant-4) glass reinforced epoxy laminate material (ϵ_r=4.4) manufactured by various companies. It is a composite material made of woven fiberglass cloth and an epoxy resin binder. It is available in different configurations and thicknesses, and primarily preferred for Printed Circuit Boards (PCB) in electronics industry. This epoxy laminate is low cost but having high loss tangent around 0.02 which makes it a difficult choice for millimeter wave and THz applications but [20] used FR4 DRA with patch antenna for mm wave sensor applications. There are a number of manufactures like Rogers Corp., Isola, Taconic, Arlon, Accumet, Park Electrochemical Corp., Nelco, Maruwa etc. which provide various other substrate laminate with different sizes (of the order of multiple of 10 mils), dielectric constant (ϵ_r= 2-11) and loss tangent ($\tan\delta$=0.0001-0.01) suitable for various applications in microwave, millimeter wave frequency range. These substrates are generally made up of ceramics, glass fiber, poly vinyl chloride (PVC), silicon, polyurethane and other chemical composite material in different ratios to fulfill the application. After more than a decade of the introduction of MPA, Long et. al. [14] successfully demonstrated radiation characteristics of DR which impacted on high frequency antenna design techniques. DRA can be described as a transitional structure made up of dielectric material and excited by various means to, work as efficient radiators for different applications.

In last few decades, dielectric materials are also preferred in antennas because of several disadvantages of metallic antennas and advantages of dielectric as radiators. Some of the characteristics of DRAs have been stated here which makes them preferable against traditional low gain antennas such as MPAs, monopoles and dipoles.

a. Design and Dimensional Flexibility: Unlimited shape and dimensional flexibility available while designing a DRA. Some of traditional shapes like rectangular, cylindrical, spherical, cross and corner shapes are shown in Fig. 1.
b. High Temperature Tolerance: At high temperatures, high metallic losses can perturb the antenna performances which is not possible in DRAs, so these are more suitable for adverse circumstances which includes warfare, fire etc.
c. Wide Impedance Bandwidth: In comparison to MPAs, DRAs yield wider impedance bandwidth.
d. Integration with other antennas is easier: One important advantage of DRA is its ease and simplicity of joining or combining with other structures.
e. Minimal metallic losses: DRAs are nothing but a model of dielectric material which are non-conducting unlike metals. So, while working as radiators, there is less conductor losses in DRAs as compared to other metallic antennas such as patch antennas. This characteristics of DRAs yields appreciable radiation efficiency at higher frequency in comparison to their counterparts.
f. Flexibility in excitation of DRA: There are various methodologies discussed in the literature to excite different modes in the DRA. Basic feed mechanism are probe feed, microstrip line feed, aperture coupled feed, conformal feed and coplanar feeds as shown in Fig. 1.

Material science played very important role in finding out various dielectric materials for many ambitious applications. Initial trend to use very high permittivity materials (ϵ_r>70) as DRAs shifted to medium permittivity (ϵ_r<20) materials in recent times because of induction of new materials with desired properties by the scientists. In 1990s, Foschini [21,22] presented concept of multi-antennas which later revolutionized as MIMO antenna system. In 1999, Telatar [23] found that there is increase in channel capacity of isotropic MIMO channel with the in-

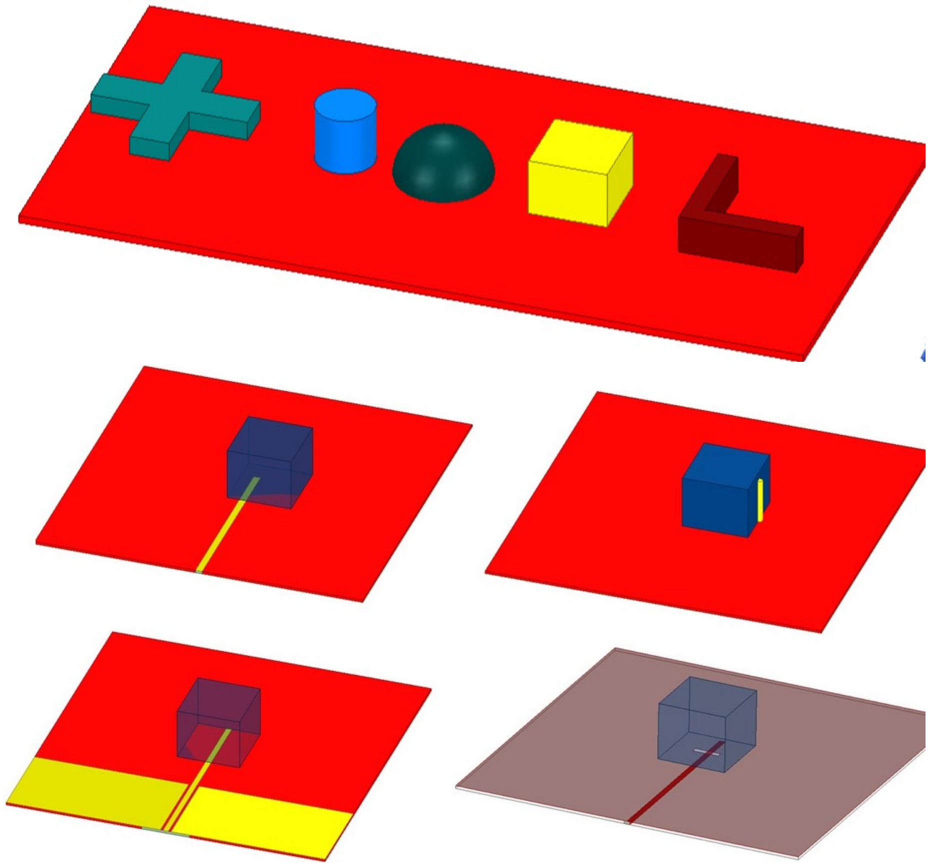

Fig. 1: Different shapes and feeds used in DRA

crease in the number of radiators, so the channel capacity is directly proportional to the number of radiators used to transmit. This study boosted emergence to MIMO communication system which was later on practically tested by Bell laboratory. Today, MIMO system is inevitably important in implementation of 4G and 5G communication networks. In 2008, Ishimiya et. al. [24,25] combined advantages of MIMO technology with DRA and proposed a MIMO antenna using DRA which opened new era of DRA based MIMO antennas. Researchers reviewed progress and advancement of DRA. In 2010, Petosa et. al. [26] rigorously reviewed various DRA which were followed by critical analysis in 2015 [27] and 2021 [28], for Circularly Polarized (CP) DRA and MIMO DRAs, respectively.

Abstracts of these analytical articles [26,27,28] from dielectric material point of view are demonstrated in Fig.2, Fig.3 and Fig.4, respectively, which provides a rich conclusion that various mixtures of Alumina Ceramic discussed in [29], Laird's Eccostock HIK series [30] and Roger's TMM series [31], materials with relative permittivity ($8<\epsilon_r<13$) and low loss tangent ($\tan\delta<0.01$) have been preferred in recent times for designing DRAs whereas high permittivity ($\epsilon_r>50$) materials have been used to design compact DRA at microwave frequencies. Table 2 show some of the dielectric manufacturers and suppliers.

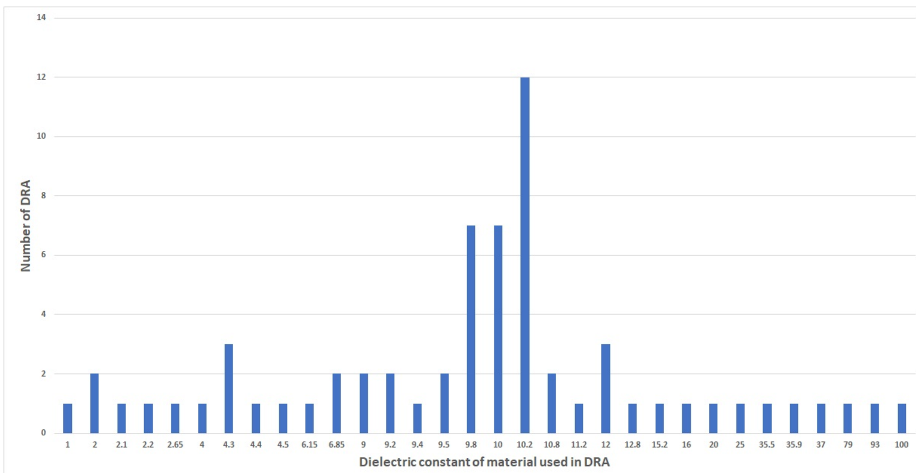

Fig. 2: Dielectric Materials used in DRA [26]

Table 2: Some of the dielectric resonator manufacturer and supplier [32,33,34,35]

Manufacturer	Type	Dielectric constant(ϵ_r)	Loss Tangent($\tan\delta$)
Laird	Eccostock Hik and Eccostock HIK500	3-30	0.002
Skyworks	D-series and MCT-series	4.5-140	$<$ 0.015
Maruwa	M-series, A, Q, F, E	6.8-110	-
Preperm	(PPE, RS, Rb, H, PEEK, LCP, FLX)-series	2.58-23	0.001- 0.0047

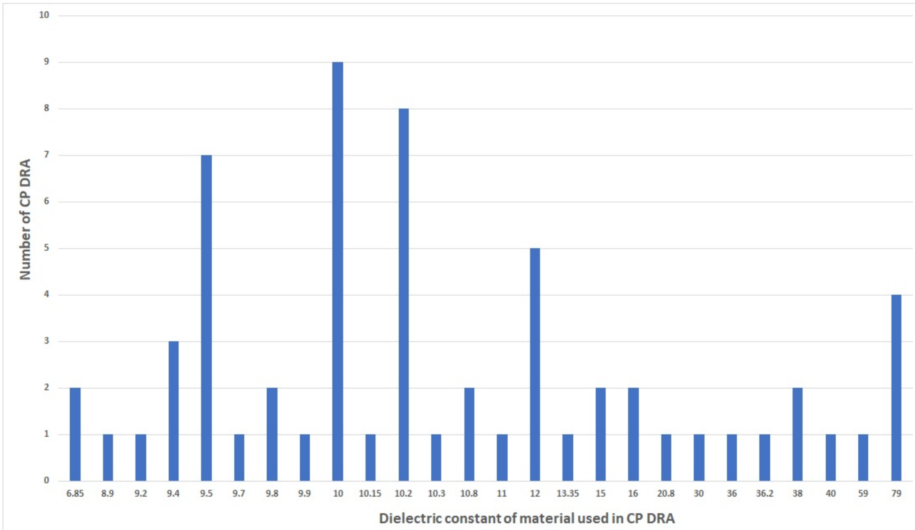

Fig. 3: Dielectric Materials used in CP DRA [27]

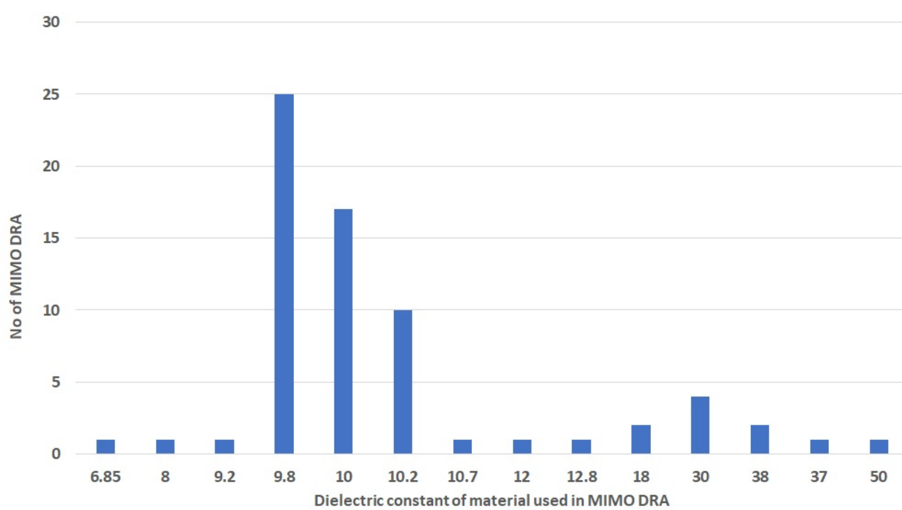

Fig. 4: Dielectric Materials used in MIMO DRA [28]

3 Role of Material in 5G Contemporary Antenna Technologies

The higher data rates and the exponential growth of data transfer, the reduced inactivity connected to higher connectivity between people and different equipment too, constrain the scientists to find appropriate solutions able to satisfy such requirements. Actually, other important issues in this sense are related to have as much as possible reduced size and easily managed device with the possibility to reuse it when necessary, in case of the development of a similar tool and functions in future [36], [37]. From materials viewpoint, there are, at least, two directions to be followed: one of these is related to reach this essential technical feature by choosing and using the most suitable materials for the application. This task is directly associated with the knowledge of the properties of the material and its limits. The other way is to employ innovative technologies which are able to develop material with enhanced properties and finally excellent end-product able to fulfil the actually need in our modern, information-oriented society. Generally, the research in this field is focused to find advanced materials that avoid any signal losses and at the same time can protect the signal reliability with the purpose to arrive at an effective communication structures and to an enhanced performance tools [38]. Among other properties, flexibility connected to wearable and implantable characteristics is another feature that is difficult to overcome. Current improvements in this area are moving to enlarge the field of flexible materials with additional benefits. Such advantages have to include the use of lightweight, green/reusable, transportable and economically convenient type of materials, since they have to be exploited also for biomedical purpose as health-monitoring structures (detect vital functions, using for drug delivery, etc.) and/or for daily-life wireless devices (computer, phones, etc.). In communication application, the selection and the development of the antenna is of primary importance and it is governed by the surroundings, the transmission strength and/or frequency range [39], [40], [41], [42]. Up to now, in the manufacturing of various kinds of antennas, which have fluctuating functionalities, different advanced materials have been used. As for example, graphene, which make available high frequency and bandwidth, advanced ceramic materials assuring the possibility to achieve the preferred characteristics when used in the form of fiber or composite material, meta-material, dielectric substrate material and non-metallic substrate material. Another example is plastic materials because of their improved workability and low dielectric constant. Furthermore, Mn, Zn, Fe_2O_3 substrate material are only some of the materials which have been exploited during the time for such applications. Generally, any employed material show some benefits and some weaknesses at the same time with respect to other materials and their use in a direct relation with the conditions that one has to satisfy in a particular use [43], [44].

Here, some valuable materials will be considered and presented, based on the data offered by the current scientific literature. Advanced ceramic materials play an important role in many communication systems because of their advanced electrical properties, like medium/high dielectric constant, low dissipation loss and good temperature stabilities, which make possible their use for high frequency transmission [45], [46], [47]. Functional ceramics, like piezoelectric ceramics, belong to this class of materials. These materials are based on the lead zirconate titanate $Pb(Zr1 - xTiO_3)$ system (PZT), in a perovskite $(A2 + B4 + O3)$ structure, where $A2+$ or/and $B4+$ positions can be replaced by different dopants capable to modify the dielectric and piezoelectric properties leading to obtain new material in a simple and low cost manner. Generally, these materials are prepared by sintering procedure starting from high purity uniaxially pressed powders. The procedure for piezoelectric materials development can be considered particularly favorable because it is a low-cost processing method and there is no need of protection against Pb volatilization [48], [49], [50]. The sintering temperature, in such cases, is usually above 1000°C, which can be considered sometimes as a drawback. To overcome this inconvenience, Low Temperature Co-fired Ceramics (LTCC) or glass-ceramics, ultra-low sintered ceramics with ferrite and dielectric materials $((Mg, Fe)_2Al_4Si_5O_18$, Li_2MgSiO_4,

Mg_2SiO_4, Zn_2SiO_4, $BaAl_2Si_2O_8$, $MgAl_2O_4$ and Al_2O_3) and materials with ultra-loss tangent properties are Ba-based perovskites with small amount of Ta, W, Nb, has been used as particularly interesting for wireless communication. As far as the LTCC are concern, they can be defined as a multi-layer glass ceramic substrate co-fired (at temperatures low-er than 1000 °C) with low resistance metal conductors. The low manufacturing temperature, determine a lower energy consumption, low-cost investment of the heating system employed and does not determine the volatilization of lead (due to the sintering temperature situated below 500 °C), it makes possible 3D micro-structures where micro-cavities and/or channels can be accommodated [51], [52], [53].

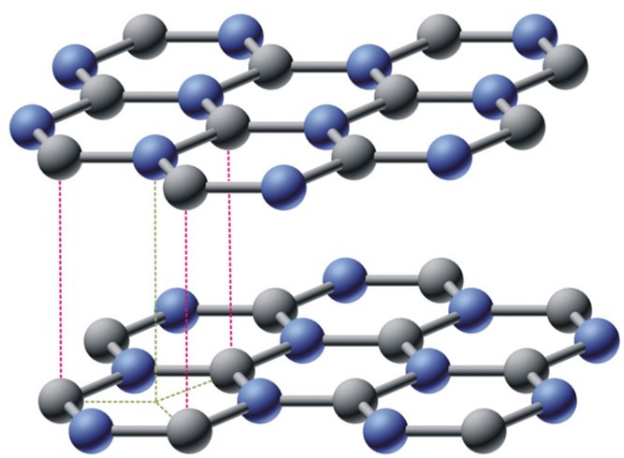

Fig. 5: Crystal Structure of Bilayer Graphene [54]

Graphene, is a very challenging material, often called a "super-material". Good chemical stability, light-weight, high surface area (2630 m^2g^{-1}), excellent flexibility, electrical and thermal conductivity (5000 $Wm^{-1}K^{-1}$) characterize such material. For its exceptional switching characteristics and tunable properties, it is attractive for the development of ultra-high-speed electronics. Using graphene is possible to create a smaller size and thinner dimensions' antenna able to release high frequencies. As for conductivity concerns, it can be controlled via an applied bias voltage and different doping procedures, described more in details later on. Graphene is a two-dimensional single layer material that can be considered as defect-free too, where the $sp2$ bonded carbon atoms are organized in a hexagonal lattice structure leading to a great freedom to be pack-aged into different forms. Such structures, with an atomic monolayer, can with-stand very high electron concentrations [54], [55], [56], [57], [58], [59],[60]. Figure 5 shows crystal structure of bilayer graphene. The graphene surface complex 'conductivity can be controlled by chemical doping or by varying the gate voltage. And this specific situation can be exploited to realize tunable frequency response and to employ such behavior in development of different type of antennas, like reconfigurable, reflactarray, beam scanning, etc. Generally, graphene-based nano-antennas have the benefit that they are smaller with respect to a conventional microstrip antennas and show higher bandwidth and gain as compared to metallic nanoantennas. Anyway, graphene shows some difficulties often related to the procedures used for obtaining high quality product and this task can limit its use at large scale. Epitaxial growth of graphene on some carbide (Si, Ti, Ta) and one such metal (Ni, Cu, Pt, Co, etc.), growth from carbon nanotubes, synthesis by thermal and organic methods, development by chemical vapor deposition techniques, oxidation of graphite are some of the procedures which can be used in relation to the preferred performance to be obtain [61], [62].

Micromechanical cleavage is the simplest way to obtain graphene: graphite fragments are positioned in the middle of the adhesive tapes and the surface is constantly peeled off, the tape is then dissolved in acetone and the graphite deposition can takes place on Si wafer and then it can be used for the desired application. Liquid phase exfoliation is another method to exfoliate graphite in various liquid environment (N-methylpyrrolidone, N,N-dimethylformamide, different polymers, nonionic and ionic surfactants, ionic liquids, etc.) with the condition that this later have to show comparable surface energy for minimizing the interfacial tension among the solvent and the graphene sheets. This method involves the exfoliation of initially oxidized graphite, leading to graphene oxide (GO), which is chemically and/or thermally reduced to graphene, typically called

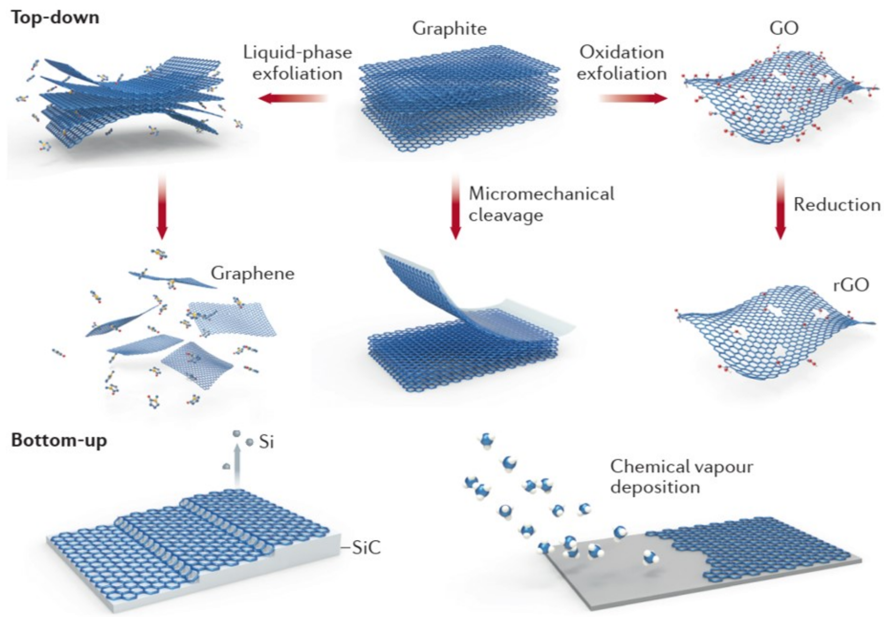

Fig. 6: Major fabrication methods of graphene [99]

reduced GO (rGO). As far as its weaknesses are concerned, one can mention that graphene concentration growths as processing time increases, determining the appearance of lateral graphene sheet sizes and decrease of the purity of graphene occurs. Using this method, one has to pay attention to the exposition time, in order to avoid the generation of the larger defects determining smaller sheet size, which occur during excessive exposition. Reduction of graphite oxide is another common option to obtain graphene and represent a low-cost procedure, involving intercalation of graphite with an oxidant on the surface of graphene sheets. Figure 6 shows major fabrication methods of graphene. Introduction of the defects to the graphene sheets can be considered as negative feature of the method, even if some of these can be reasonably removed. Most of the materials used in chemical reduction are unsafe, however thermal and microwave treatment can replace such method, but locally determine an increase of the temperature on the surface, that is a critical issue in case of flexible substrates. Mechanical milling is an economically convenient and simple route and it can be useful also for large scale production. However, it is time-consuming, needs high energy for the realization and the development of defects creates some difficulties to the extensive use of such procedure. Additionally, graphene can be used as a new nanoscale building blocks, it can be chemically modified to produce composites with added-value characteristics by dispersion in a polymer, inorganic matrix. The graphene sheets can be dispersed in water, developing a paper like material, which revel higher stiffness and strength properties, absence of electrical conductivity, it can be corrected by thermal annealing process. As far as the electronic properties of the graphene are concerned, it is governed by the number of the graphene films in the graphene sheets and the overall properties are modulated in these different situations. It is possible to modify the charge carriers from holes to electrons and in the case of higher number of layers, the dependence turns out to be weaker due to the electrical field screening realized by the other layers [65], [66], [67], [68], [69], [70]. Figure 7 shows a graphene based reconfigurable pattern antenna..

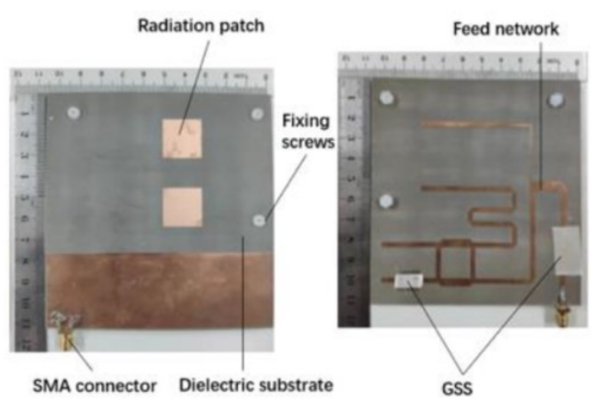

Fig. 7: Graphene Sandwitch Structure (GSS) based reconfigurable pattern antenna [64]

Carbon Nano Tubes (CNTs) are one-dimensional materials, with a defect-free structure showing rare electronic and electromagnetic properties (aligned axial transition dipoles, large absorption cross-sections, and high quantum efficiencies, etc.) and particularly high conductivity determining very low resistive losses in the antenna. The electron movement in CNTs is produced by ballistic transport over the nanotubes. Using such material one can have an antenna with low power dissipation, obtaining high efficiency with respect to a metal cable with identical dimension. Based on the CNTs properties, CNT-based nanoantennas are able to efficiently mould the energy flow with respect to its intensity and direction [71], [72], [73]. This can be realized by a suitable selection of the material to be introduced in the gap, like a metallic sphere which can be an efficient field converter, supporting a considerable field improvement in the antenna volume, hence also contributing to its miniaturisation. Employing more nanotubes in parallel the transmission power can be intensified. Compared to graphene, CNT-based nanoantennas allow higher heat because of their higher thermal conductivity, which facilitates the nanoantennas to dissipate heat by the antenna surface. In the presence of high temperature, oxidation of CNTs and graphene occurs. Such oxides can still be employed for nanoantennas which reveal good microwave absorption, but temperature higher than 900°C considerably disturb the electromagnetic properties. To avoid such aspects CNTs are combined with ceramic material, like SiO_2, or by coating the CNT surfaces with nanoparticles, like CdS. Other possibility is optimizing the topology of the nanoantennas array to improve the efficiency of heat dissipation (linear irregular array, spiral array, thinned array, circular ring array); using some metal plates with heat dissipation functions (which are electromagnetically transparent to specific radio wave frequencies without disturbing the radio waves of the nanoantennas), but miniaturization of the whole structure became difficult to be realized [74], [75], [76], [77], [78].

Metallic nanomaterials can be used efficiently for nanoantennas in the 5G network, producing interesting properties, like directivity/gain, polarization control, intensity improvements, decay rate enrichment, and spectral shaping. Such nanostructures support surface plasmon resonances and generate extremely limited electromagnetic fields at the interface between the metal and the dielectric material in a particularly reduced volume. The frequency of localized surface plasmons, is determined by the size, the shape, the composition of the nanoparticles in addition to the sensitivity to the dielectric environment. The structural geometry and the refractive index of the surrounding medium have an important effect on the resonance wavelength and on the intensity of the localized fields in the nanoantenna [79], [80], [81], [82], [83]. Metamaterials, due to their special electromagnetic properties, are able to increase the performance of nanoantennas and their use in such application significantly decreases the dimension of the antenna improving its performance, in terms of bandwidth, gain and by producing multiband frequencies. Metamaterials can be defined as an engineered, synthetic structures starting from different materials with electromagnetic properties, which are not offered by the nature. Modulating the profile, dimension and arrangement path of single metamaterial resonators or by manipulating the near-field interactions between them, tunability of electromagnetic properties can be reached. For what regards the properties, metamaterials can have negative permittivity and permeability at equal frequency. The electromagnetic wave can be refracted in the opposite direction with the wave propagation in such material. Based on the properties named before (permittivity and permeability), which are generated by different structures, we can name electric negative metamaterials, magnetic negative metamaterials and double-negative metamaterials, which all exploit such differences for multiple choices. The electric negative metamaterials can use the metallic thin wires to obtain the negative permittivity values, and the parallel metal wires display high pass behavior for an incoming plane wave. Their electric field is parallel to the wires. The magnetic negative metamaterials with a negative permeability value can have a structure of split ring resonator, made of two concentric metallic rings and separated by a gap. The double-negative metamaterials possess a negative refractive index, and their structures are a combination of thin wire-based and split ring resonator-based structures [84], [85], [86].

Polymeric materials play an important role in 5G network development and they can be considered indispensable for high speed and stable signal transmission at microwave frequency, as substrate materials, because of their good properties, such as lightweight, adequate mechanical resistance, dielectric constant, loss tangents range and excellent flexibility. Engineering thermoplastics, like liquid crystal polymer, polyphenylene sulfide, polybutylene terephthalate and thermal conductive polymers are also promising materials for 5G network. Epoxy/fiberglass, polyacetal,acrylonitrile-butadiene-styrene, polyamide-66, polyetherimide, polystyrene, polycarbonate, ultra-high molecular weight polyethylene are some of such materials that can be employed in 5G communications. Polycarbonates are mechanically strong, lightweight, transparent to radio frequencies and appropriate for injection molding, useful technology for plastic material production. Some grades also show good weather resistance and thermal conductivity [87], [88], [89], [90], [91], [92]. As for example, an investigation on the realization of a triband antenna is presented in [90], starting from a thick and reduced size liquid crystal polymer substrate. The authors have developed a simple design, flexible, compact and multi-band performance antenna which is appropriate for incorporation in flexible 5G front ends and mm-wave wearable devices. The manufacturing of the antenna is carried out by laser-milling and inkjet printing on a thin film of flexible liquid crystal polymer. Polymer composites reveal high dielectric permittivity and usually ceramics with perovskite structure can be employed as reinforce material using conventional manufacturing route. Addition of the conductive elements determines the realization of an ultrahigh dielectric permittivity, which goes with a high dielectric loss. In [93] the possibility to adjust the dielectric performance of polymer composites materials by embed-ding silver particles in $(Ba0_6Sr0_4)TiO_3$ fibers is presented by electrospining procedure. Tunable Bragg grating filters based on polymeric optical waveguides are offered in [94] in order to produce wavelength filters which are adequate for communication application, with 20 dB bandwidth of 1.0 nm and a side mode suppression ratio of 35 dB, over the whole wavelength-tuning range considered.

4 Role of Material in 5G/6G Futuristic Communication Networks

Fifth generation and other forthcoming communication networks essentially require a group of compatible antennas in all applications such as military, security, sensor, biomedical, telemetry etc. Some of these futuristic antennas which need to be compatible with 5G networks are THz antennas, biomedical equipment, wearable radiators and nanoantennas.

4.1 THz Antennas

Expanding demands of bandwidth in wireless communication pushed human to enter in this 'blank area' between microwave and infrared light, called THz wave defined from 0.1-10 THz. There are following characteristics of THz waves which make researchers more attractive towards it [95].

a) High spectral resolution: Because the size of the most molecules corresponds to THz wavelength, so analyzing and detecting viruses, bacteria, explosives is even easier for THz waves.

b) Wide bandwidth: To achieve unprecedented data rate of Tbps, such a wide bandwidth of THz band is required.

c) Low damage: In biomedical field, THz waves are able to provide greater efficiency because its single photon energy is much lower than presently used X-rays which can affect human organism during disease treatment and body scanning.

d) Visualization: As the wavelength of THz waves is roughly from 3 millimeter to 30 micrometer which can easily penetrate plastic and non-polar materials, resulting better visualization of the object or body and making good choice in sensor or scanner applications at high risk area like airports.

In recent times new material is widely experimented for THz antennas which resulted in photoconductive material ($GaAs, InP$), carbon nanotubes and graphene material based antennas. Advantages of the photoconductive antennas are simple structure, compactness, miniaturization can be achieved at relatively low cost but certainly improvement in substrate material is the future issue. The carbon nanotube antenna exhibits resonances within lower THz frequencies. Graphene, another recent material used in THz antennas, posses invariably great dynamic control characteristics by managing bias voltage and surface plasmons.It can achieve a wide range of light regulation and light absorption. Graphene demonstrated superior characterstics at THz frequency that by metal, such as it has complex conductivity at THz band which result slow wave propagation in plasma mode at THz frequency. Moreover, surface plasma of this recently used material in THz communication, has higher binding and lower loss which supports continuous electrical tuning in THz band [95]. Figure 8 shows four THz horn antennas.

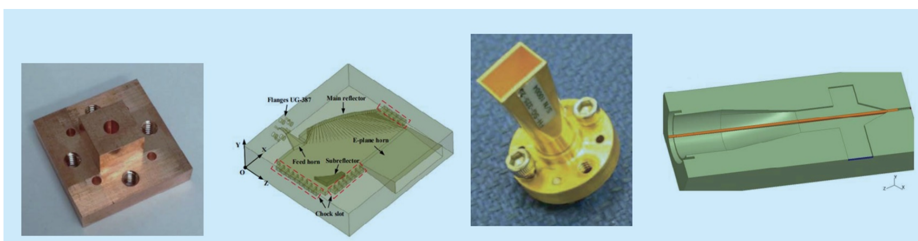

Fig. 8: Four THz horn antennas: multi-angle horn [96], E-plane horn [97], rectangular horn [98] and dual-band horn [99] (from left to right), combined photograph taken from [95]

4.2 Antennas in IMDs

Human has always desired to cure disease and malfunctioning of body by technological means which developed on or off body bio-medical implantation of antennas in recent times. Biomedical telemetry is the measurement of physiological signals from a distance, generally outside the body through wired and wireless communication. Implantable Medical Devices (IMD) such as cardiac pacemakers, Implantable Cardiac Defibrillators (ICD), coronary stents are used to monitor body functions or to provide support to organs and tissues. But wired communication has several physical limitations which eventually resolved by means of induction of On/Off body antennas.These implanted devices provide unique opportunity to sense and detection of early diseases and timely treatment of those diseases. Some of recent devices has been used for glucose monitoring, blood pressure monitoring and blood oxygen monitoring. Implanting antennas On/Off body has several challenges such as lossy human body, bounding Specific Absorption Rate (SAR), compactness, low battery consumption, stability and many others depending upon the body conditions. One of the major concern, the implant antenna engineers face is biocompatibility. Generally a super-

Fig. 9: Implantable patch antenna and measurement while implanted in a rat body [101]

strate dielectric layer of Teflon (ϵ_r=2.1, $\tan\delta$=0.001), alumina ceramic (ϵ_r=9.4, $\tan\delta$=0.006) and MACOR® (ϵ_r=6.1, $\tan\delta$=0.005) are used to preserve the biocompatability of the antenna. Another technique to achieve biocompability in implant antennas is introducing a thin layer of low loss coating of material like zirconia (ϵ_r=29, $\tan\delta\simeq$0), PEEK (ϵ_r=3.2, $\tan\delta$=0.01) and Silastic MDX-4210 Biomedical Grade Base Elastometer (ϵ_r=3.3, $\tan\delta\simeq$0) [100]. Zirconia is preferred by designers because of its high permittivity and low loss tangent which allows near field of the implanted radiator to concentrate inside the encapsulation layers and to reduce power loss. Figure 9 shows an implantable patch antenna with measurement setup while implanted in a rat body.

4.3 Nanoantennas

Dielectric Resonator Nanoantennas and optical DRAs are some of the emerging fields in the world of antennas in recent times. At optical frequencies, electromagnetic waves interact with electrons causing plasma oscillations which is termed as plasmonics by physicists. Behaviour of metal at optical frequencies is governed by complex permittivity, complex conductivity and complex wave impedance. As the frequency crosses microwave region, real part of conductivity dramatically decreases and even goes below the imaginary part of conductivity whereas the absolute real and imaginary parts of the complex permittivity decline sharply in metals. This action drastically escalate the ohmic losses and increased phase retardation between electric field and oscillating electrons resulting in unacceptably low radiation efficiency of metallic antennas in the optical frequencies. Properties of DRA viz low dielectric loss, absence of metallic losses and multiple resonance modes, attracted the attention of researchers. Using scalability of Maxwell's equations, antennas can be scaled corresponding to optical wavelength as long as the material's property does not vary. In the recent times, few materials have been reported such as Silicon, Titanium Dioxide and Gallium Phosphide with acceptable performance as nanoantennas [102]. Currently, exploration to find different low loss dielectric material is in progress.

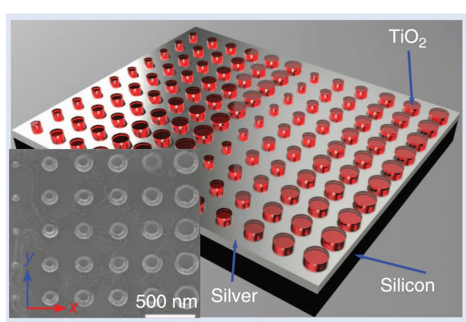

Fig. 10: A DRA-based visible light reflectarray nanoantenna [103]

Besides availability of desired material, adopting low cost nanofabrication technology is another area of interest. Presently, deep-ultraviolet photolithography, nanoimprint lithography and atomic layer deposition are technologies available for large area fabrication of optical DRAs. Figure 10 shows a DRA based nanoantenna at optical frequencies.

4.4 Wearable Antennas

Body wearable antennas and Body Area Network (BAN) with 5G and futuristic 6G communication networks are also major area of research. Different types of fabrics and paper have been tried for wearable sensor applications for example denim has been used as substrate as shown in Fig.11.

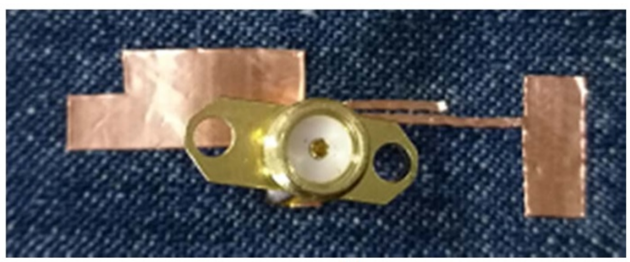

Fig. 11: Wearable antenna on denim substrate [104]

Dielectric properties of some major fabrics are shown in Table 3. Millimetre wave systems may be designed using system-on-chip (SoC) and system-on-package (SoP) methodologies. SoC is an integrated design approach with components on the wafer whereas SoP incorporates components into multilayer dielectric material and integrates chips within the same dielectric packaging material [105]. For SoC approach gallium arsenide is preferred for various advantages like low substrate loss and high cutoff frequency performance. Silicon germanium (SiGe) on high resistivity Si is another lower cost alternative of pricey GaAs for chosen applications as SiGe is lossy substrate than GaAs. In 5G communications network, demand of cost-effective antennas with wide bandwidth and low dielectric constant of material can be fulfilled by polymers and ceramic-filled polymers antennas. Additionally, polymer is conformal and easily takes the desired shape in low temperature process also. In comparison to polymers, ceramic material has low dielectric losses, improved and stable temperature characteristics, ability to provide wide range of dielectric constants, better mechanical stability and ease of metallization. LTCC materials are preferred in integrated MIMO antennas [106].

Table 3: Dielectric Properties of some major textiles [107]

Material	Dielectric constant (ϵ_r)	Loss Tangent ($\tan\delta$)
Fleece	1.17	0.0035
Silk	1.75	0.012
PTFE	2.05	2.57
Leather	1.82-2.39	0.049-0.071
Denim	1.4-2	0.014-0.07
Cotton	1.6	0.04
Polyester	1.9	0.0045

5 Conclusion

The aim of the present chapter was to present different challenges in designing 5G communication tools, starting from the selection of the appropriate materials up to their production methods. Some aspects related to the multidisciplinary face of such research development was highlighted to underline the necessity of the participation of various scientific figures to achieve higher performances of the future communication systems. Further and continuous research in this field is very important, since some of the limitations of 5G communication originates from the technologies and from the cost of the materials to be used. An extensive application can be reached when the cost of the technology and of the materials will be reduced. The antennas, indispensable elements for 5G communications system, has to sustain the variation toward the new setup shift with flexible and implantable, reduced size structure. 5G communication network is very high speed data transfer between all present applications and futuristic applications. It provide backbone to other networks like BAN, Sensors, nanoantennas, IMDs, wearable radiator, military/security networks etc. In this chapter, 5G communication network has been discussed from material point of view. Present antenna material and futuristic material has been studied for various wireless communication applications. As material science is itself a very vast field and antennas are its one of applications, so covering the whole spectrum of material science may be out of scope of this chapter. Present 5G communication is in sub-6 GHz band and mm wave band but in future it may encroach the so called blank area (THz) band. Some of the important material in context of 5G communication networks and compatible networks may be iterated here such as polymer and ceramic based material, graphene, carbon/silicon nanotubes and semiconductor material (III-V group).

References

1. Wang, D., Chen, D. Song, B. Guizani, N. Yu, X. Du, X.: From IoT to 5G I-IoT: The Next Generation IoT-Based In-telligent Algorithms and 5G Technologies. IEEE Commun. Mag. 56, 114–120 (2018).
2. Jilani, S.F. Munoz, M.O. Abbasi, Q.H. Alomainy, A.: Millimeter-Wave Liquid Crystal Polymer Based Conformal Antenna Array for 5G Applications. IEEE Antennas Wirel. Propag. Lett. 18, 84–88 (2019).
3. Simko M, Mattsson MO.: 5G wireless communication and health effects – a pragmatic review based on available studies regarding 6–100 GHz. Int J Environ Res Public Health. 16, 3406 (2019).
4. Kanerva M, Lassila M, Gustafsson R, O'Shea G, Aarikka- Stenroos L, Hemila J. Emerging 5G technologies af-fecting markets of composite materials. Vantaa, Finland: Exel Composites (2018).
5. Hong Y., Choi J.: 60 GHz patch antenna array with parasitic elements for smart glasses. IEEE Antennas Wireless Propag. Lett., vol. 17 (7) 1252-1256 (2018).

6. Wang M, Ma HF, Zhang HC, Tang WX, Zhang XR, Cui TJ. Frequency-fixed beamscanning leaky-wave antenna us-ing electronically controllable corrugated microstrip line. IEEE Trans Antennas Propag 66(9),4449–57 (2018).
7. Choi S-A, Lee S-H, Choi H-K.: Design of the ESPAR antenna with improved DC bias. Microw Opt Technol Lett. 57(10), 2281–6 (2015).
8. Othman A, Barrak R, Abib GI, Mabrouk M.: A varac-tor based tunable RF filter for multistandard wireless commu-nication receivers. AEU – Int J Electron Commun 102, 69–77 (2019).
9. Collin Website: https://www.collinsdictionary.com/dictionary/english/dielectric last accessed 2021/2/9
10. Richtmyer R. D.: Dielectric resonators. J. Appl. Phys., 10, 391-398 (1939).
11. Okaya A. K., Barash L. F.: The dielectric microwave resonator. Proc. IRE, 50, 2081–2092 (1962).
12. Karp A., Shaw H. J., Winslow D. K.: Circuit properties of microwave dielectric resonator. IEEE Trans. Microwave Theory Tech., MTT-16, 810–828 (1968).
13. Iveland T. D.: Dielectric resonator filters for application in microwave integrated circuits. IEEE Trans. Microwave Theory Tech., MTT-19, 643–652 (1971).
14. Long S. A., McAllister M. W., Shen L. C.:The Resonant Cylindrical Dielectric Cavity Antenna. IEEE Transactions on Antennas and Propagation, 3(31), 406-412 (1983).
15. McAllister M. W., Long S. A.: Rectangular Dielectric Resonator Antenna. IEE Electronics Letters, 19(6), 218-2l9 (1983).
16. Kajfez D.: Basic Principles Give Understanding of Dielectric Waveguides and Resonators. Microwave Syst. News, 13, 152-161 (1983).
17. Glisson A. W., Kajfez D., James J.: Evaluation of Modes in Dielectric Resonators Using a Surface Integral Equation Formulation. IEEE Trans. Microwave Theory Tech., , MIT-31, 1023-1029 (1983).
18. McAllister M. W., Long S. A.: Resonant Hemispherical Dielectric Antenna. IEE Electronics Letters, 20(16), 657-659 (1984).
19. Kajfez D., Glisson A. W., James J.: Computed Modal Field Distribution for Isolated Dielectric Resonators. IEEE Trans. Microwave Theory Tech., MTT-32, 1609-1616 (1984).

20. Singhwal S. S., Kanaujia B. K., Singh A., Kishor J.: Novel circularly polarized dielectric resonator antenna for microwave image sensing application. Microw Opt Technol Lett., 61(7), 1-7 (2019).
21. Foschini G. J.: Layered space–time architecture for wireless communication in a fading environment when using multiple antennas. Labs Syst. Tech. J. , 1(2), 41–59 (1996).
22. Foschini G. J., Gans M. J.: On limits of wireless communications in a fading environment when using multiple antennas," Wireless Personal Commun. , 6, 311–335 (1998).
23. Telatar I. E.: Capacity of multi-antenna gaussian channels. European Transactions on Telecommunications, November , 10, 585-595 (1999).
24. Ishimiya K., Ying.,Z., Takada J.: A Compact MIMO DRA for 802.11n application. IEEE International Symposium on Antennas and Propagation (APS), CA, USA, (2008).
25. Ishimiya K., Långbacka J., Ying Z., Takada J.: A compact MIMO DRA antenna. iWAT, Chiba, Japan (2008).
26. Petosa A., Ittipiboon A.: Dielectric Resonator Antennas: A Historical Review and the Current State of the Art. IEEE Antennas and Propagation Magazine, 52(5) (2010).
27. Kumari R., Gangwar R.K.: Circularly Polarized Dielectric Resonator Antennas: Design and Developments. Wireless Personal Communication, 86, 851–886(2016).
28. Singhwal S. S., Matekovits L., Kanaujia B. K., Kishor J., Fakhte S.,Kumar A.: Dielectric Resonator Antennas: Application and Development in Multiple Input Multiple Output Technology. IEEE Antennas and Propagation Magazine, May, 2021.(Accepted)
29. Sebastian M. T., Ubic R., Jantunen H.: Low-loss dielectric ceramic materials and their properties, International Materials Reviews, 60(7), 392-412 (2015).
30. Laird website https://www.laird.com/products/microwave-absorbers/low-loss-dielectrics/eccostock-hik-500 last accessed 2021/2/9.
31. Rogers website https://rogerscorp.com/advanced-connectivity-solutions/tmm-laminates last accessed 2021/2/9.
32. Laird Website https://www.laird.com/products/ last accessed 2021/2/9
33. Skyworks Website https://cm-sitecore.skyworksinc.com last accessed 2021/2/9

34. Maruwa Website https://www.maruwa-g.com/e/products/ceramic/powdery-molding-goods-1.html last accessed 2021/2/9
35. Preperm Website https://www.preperm.com/products/ last accessed 2021/2/9
36. Oh SS, Park WK, Jung YB, Il Choi T, Lee YH.: Fre-quency-tunable open-ring microstrip antenna with optimally-positioned varactors for radiated-power in situ measurements. AEU – Int J Electron Commun 68(9), 841–5 (2014).
37. Alazemi AJ, Avser B, Rebeiz GM. Low-profile tun-able multi-band LTE antenna with series and shunt tuning devices. AEUE – Int J Electron Commun, 110,152-155 (2019).
38. Ghasemi, A.; Sousa, E.S. :Spectrum sensing in cog-nitive radio networks: Requirements, challenges and design trade-os. IEEE Commun. Mag., 46, 32–39 (2008).
39. Singh, R., Singh, E., Nalwa, H.S.: Inkjet-printed nanomaterial based flexible radio frequency identification (RFID) tag sensors for the internet of nano things. RSC Adv., 7 48597–48630 (2017).
40. Abhinav K, V.; Rao R, V.K.; Karthik, P.S.; Singh, S.P. Copper conductive inks: Synthesis and utilization in flexible electronics. RSC Adv., 5, 63985–64030 (2015).
41. Corchia, L.; Monti, G.; Tarricone, L. Wearable An-tennas: Nontextile versus Fully Textile Solutions. IEEE Antennas Propag. 61, 71–83 (2019).
42. Masihi, S.; Panahi, M. Maddipatla, D.; Bose, A.K.; Zhang, X. Hanson, A.J. Narakathu, B.B. Bazuin, B.J. Atashbar, M.Z. : Development of a Flexible Tunable and Compact Mi-crostrip Antenna via Laser Assisted Patterning of Copper Film. IEEE Sens. J. 20, 7579–7587 (2020).
43. Arif, A.; Zubair, M.; Ali, M.; Khan, M.U.; Mehmood, M.Q. A Compact, Low-Profile Fractal Antenna for Wearable On-Body WBAN Applications. Antennas Wirel. Propag. Lett. 18, 981–985 (2019).
44. Rmili, H. Miane, J.-L. Zangar, H. Olinga, T.: Design of microstrip-fed proximity-coupled conducting-polymer patch antenna. Microw. Opt. Technol. Lett. 48, 655–660 (2006).
45. Ali, U. Ullah, S. Shafi, M. Shah, S.A.A. Shah, I.A. Flint, J.A.: Design and comparative analysis of conventional and metamaterial-based textile antennas for wearable applica-tions. Int. J. Numer. Model. Electron. Netw. Devices Fields 32, 2567 (2019).
46. Roy, S.; Chakraborty, U.: Metamaterial Based Dual Wideband Wearable Antenna for Wireless Applications. Wirel. Pers. Commun. 106, 1117–1133 (2019).

47. Okabe, K.; Jeewan, H.; Yamagiwa, S.; Kawano, T.; Ishida, M.; Akita, I. Co-Design Method andWafer-Level Pack-aging Technique of Thin-Film Flexible Antenna and Silicon CMOS Rectifier Chips forWireless-Powered Neural Interface Systems. Sensors 15, 31821–31832 (2015).

48. Dumitru A.I., Pintea J., Patroi D., Dumitru T.G., Matekovits L., Peter I.. "Investigation of Multiferroic Properties of Fe3+ and (La3+, Fe3+) doped PbZr0.53Ti0.47O3 Ceramics", 192-196 (2020).

49. Dumitru A.I., Velciu G., Pintea J., Patroi D., Marinescu V., Clicinschi F., Peter I., "Structural and piezoelectric characterization of Pr3+ MODIFIED (1-x)Pb(Zr1-yTiy)O3 – xPb(Mn1/3Sb2/3)O3 ceramic", The Scientific Bulletin of VALAHIA University, MATERIALS and MECHANICS, Vol. 17, No. 17, 7-10 (2019).

50. Dumitru A.I., Velciu G., Pintea J., Patroi D., Marinescu V., Clicinschi F., Matekovits L., Peter I., "Investiga-tions on the Doping Effects on the Properties of Piezoelectric Ceramics", Advanced Materials Research, ISSN: 1662-8985, Vol. 1158, pp 105-114 (2020).

51. Mirzaee, M., Noghanian, S., Wiest, L. Chang, I.: Developing flexible 3-D printed antenna using conductive ABS materials. In Proceedings of the 2015 IEEE International Sym-posium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, Vancouver, BC, Canada, 19–24 July 2015; IEEE: Vancouver, BC, Canada, 1308–1309 (2015).

52. Dwivedi, R.P. Kommuri, U.K.: Compact high gain UWB antenna using fractal geometry and UWB-AMC. Mi-crow. Opt. Technol. Lett. 61, 787–793 (2019).

53. Govaert, F., Vanneste, M. Preparation and Applica-tion of Conductive Textile Coatings Filled with Honeycomb Structured Carbon Nanotubes. J. Nanomater., 651265 (2014).

54. Novoselov K.S., Nobel Lecture: Graphene: Materi-als in the Flatland, Rev. Mod. Phys. 83 837–849 (2011).

55. Geim A.K., Nobel Lecture: random walk to graphene, Rev. Mod. Phys. 83 851–862 (2011).

56. Novoselov K.S., Blake P., Katsnelson M.I., Graphene: Electronic Properties, in: K.H. Veyssière, W. Jürgen Buschow Robert, C. Cahn Merton, J. Flemings Bernhard Ilschner Edward, Kramer Subhash Mahajan Patrick (Eds.), En-cyclopedia of Materials: Science and Technology, second ed., Elsevier, Oxford, 1–6 (2008).

57. Allen M.J., Tung V.C., Kaner R.B., Honeycomb carbon: a review of graphene, Chem. Rev. 110 132–145 (2010).
58. Yoo E., Kim J., Hosono E., Zhou H.S., Kudo T., Honma I., Large reversible Li storage of graphene nanosheet fam-ilies for use in rechargeable lithium ion batteries, Nano Lett. 8 2277–2282 (2008).
59. Soldano C., Mahmood A., Dujardin E., Production, properties and potential of graphene, Carbon 48 2127–2150 (2010).
60. Sur U.K., Graphene: a rising star on the horizon of materials science, Int. J Electrochem. 12 (2012).
61. Avouris P.,Dimitrakopoulos C., Graphene: synthe-sis and applications, Mater. Today 15 86–97 (2012).
62. Jiao L., L. Zhang L., Wang X., Diankov G., Dai H., Narrow graphene nanoribbons from carbon nanotubes, Nature 458 877–880 (2009).
63. Wang, X.-Y., Narita, A., Müllen, K., Precision synthesis versus bulk-scale fabrication of graphenes. Nat. Rev. Chem. 2, 00100 (2017)
64. Wang J., Lu W., Liu Z., Zhang A. and Chen H.: Graphene-Based Microwave Antennas With Reconfigurable Pattern. IEEE Transactions on Antennas and Propagation, 68(4), 2504-2510 (2020).
65. Kosynkin D.V., Higginbotham A.L., Sinitskii A., Lomeda J.R., Dimiev A., B.K Price, J.M. Tour, Longitudinal unzipping of carbon nanotubes to form graphene nanoribbons, Nature 458 (2009) 872–876.
66. Shinde D.B., Debgupta J., Kushwaha A., Aslam M., Pillai V.K., Electrochemicalunzipping of multi-walled carbon nanotubes for facile synthesis of highquality graphene nanorib-bons, J. Am. Chem. Soc. 133 4168–4171 (2011).
67. Fan X., Chang D.W., X. Chen, Baek J., Dai L.: Functionalized graphene nanoplatelets from ball milling for energy applications, Curr. Opinion Chem. Eng. 11 52–58 (2016).
68. Ullah M., Ali M.E., Abd Hamid S.B.: Surfactant-assisted ball milling: a novel route to novel materials with controlled nanostructure – a review. Rev. Adv. Mater. Sci. 37 1–14 (2014).
69. Chen S., Moore A.L., Cai W., Suk J.W., An J., Mishra C., Amos C., Magnuson C.W., Kang J., Shi L., Ruoff R.S.: Raman measurements of thermal transport in suspended monolayer graphene o f variable sizes in vacuum and gaseous environments, ACS Nano 5 321–328 (2011).

70. Balandin A.A.: Thermal properties of graphene and nanostructured carbon materials, Nat. Mater. 10 569–581 (2011).
71. Das S., Irin F., Tanvir Ahmed H.S., Cortinas A.B., Wajid A.S., Parviz D., Jankowski A.F., Kato M., Green M.J.,:Non-covalent functionalization of pristine few-layer gra-phene using triphenylene derivatives for conductive poly (vinyl alcohol) composites, Polymer 53 2485–2494 (2012).
72. Hu H., Wang X., Wang J., Wan L., Liu F., Zheng H., Chen R., Xu C.: Preparation and properties of graphene nanosheets–polystyrene nanocomposites via in situ emulsion polymerization. Chem. Phys. Lett. 484 247–253 (2010).
73. Wang X., Hu Y., Song L., Yang H., Xing W., Lu H. : In situ polymerization of graphene nanosheets and polyurethane with enhanced mechanical and thermal properties, J. Mater. Chem. 21 4222 (2011).
74. Qiu J., Wang S.,:Enhancing polymer performance through graphene sheets, J. Appl. Polym. Sci. 119 3670–3674 (2010).
75. Wang J., Yang S., Huang Y., Tien H., Chin W., Ma C.M.: Preparation and properties of graphene oxide/polyimide composite films with low dielectric constant and ultrahigh strength via in situ polymerization, J. Mater. Chem. 21 13569 (2011).
76. Yoonessi M., Gaier J.R.,:Highly conductive multifunctional graphene polycarbonate nanocomposites, ACS Nano 4 7211–7220 (2010).
77. Potts J.R., Murali S., Zhu Y., Zhao X., Ruoff R.S.: Mi-crowave-exfoliated graphite oxide/polycarbonate composites, Macromolecules 44 , 6488–6495 (2011).
78. Qi X.Y., Yan D., Jiang Z. , Cao Y.K., Yu Z.Z., Yavari F., Koratkar N.: Enhanced electrical conductivity in polystyrene nanocomposites at ultra-low graphene content, ACS Appl. Mater. Interfaces. 3 3130–3133 (2011).
79. Dash S: Patnaik A. Graphene loaded Frequency Reconfigurable Metal Antenna. In: 2017 IEEE Int. Conf. Antenna Innov. Mod. Technol. Ground Aircr. Satell. Appl.. p. 1–4 (2017).
80. Alzoubi K., Hamasha M. M., Schadt M., Lu S., Sammakia B., Poliks M.: Effect of lamination on the bending fatigue life of copper coated PET substrate," Proc. SPIE 7956, 79560X-179560X (2011).
81. Mantash M., Tarot A. C., Collardey S., Mahdjoubi K.:Wearable monopole zip antenna, Electron. Lett. 47 (23), 1266-1267 (2011).

82. Li G., Huang Y., Gao G., Wei X., Tian Z., Bian L. A.: A handbag zipper antenna for the applications of body-centric wireless communications and Internet of Things, IEEE Trans. Antennas Propag.. 65(10), 5137-5146 (2017).
83. Wu D., Cheung S. W.,: A cavity-backed annular slot antenna with high effciency for smartwatches with metallic housing," IEEE Trans. Antennas Propag., vol. 65(7), 3756-3761 (2017).
84. Canet-Ferrer J. Metamaterials and Metasurfaces. London, UK: IntechOpen; (2018).
85. Zheludev N.I., Kivshar Y.S. From metamaterials to metadevices. Nat Mater. 11, 917–24 (2012).
86. Dong Y, Itoh T.: Metamaterial-based antennas. Proc IEEE. 100(7), 2271–85 (2012).
87. Tang L., Zhang J., Tang Y., Kong J., Liu T., Gu J.,:Polymer matrix wave-transparent composites: A review. Journal of Materials Science and Technology 75, 225-251 (2021).
88. Wu, B., X. Mao, C. Wang, T. Deng, R. Li, Y. Xu: Different Organic Peroxides that Cure Low-k 1,2-PB/SBS/EPDM Composites for High-Frequency Substrate", Journal of Vinyl and Additive Technology 26(4), 524-535 (2020).
89. De Wit M., Ooms S., Philippe B., Zhang Y., Reyn-aert P.: Polymer Microwave Fibers: A New Approach That Blends Wireline, Optical, and Wireless Communication", IEEE International Symposium on Phased Array Systems and Tech-nology, Volume 2019-October (2019).
90. Li X., Du C.: Compact Triple-Band Liquid Crystal Polymer Based Flexible Antenna for WiMAX/WLAN/5G Ap-plications, IEEE Antennas and Wireless Propagation Letters 18(1), January 2019, 84-88 (2019).
91. Jilani S.F., Munoz M.O., Abbasi Q. H., Alomainy A.: Millimiter-Wave Liquid Crystal Polymer Based Confromal Antenna array for 5G applications" Annual Technical Conference-ANTEC, Detroit, US, Conf. Proc. Volume 2019.
92. Brar R.S., Vaughan R.G., Felipe M.: Phased Arrays and MIMO: Wideband 5G End Fire Elements on Liquid Crystal Polymer for MIMO", 2019 IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition, iWEM (2019).
93. Gao C., Luo S., Yu S,, Sun R.: Hybrid particles of Ag nanoparticles embedded in (Ba0.6Sr0.4)TiO3fibers as fill-ers in polyvinylidene fluoride composites leading

to excellent dielectric property", 21 st Int. Conf. on Electronic Packaging, ICEPT 2020 August, Guangzhou, China, 12-15 August 2020.

94. Park T.H., Kim S.M, Oh M. C.: Polymeric tunable wavelength filter with two-stage cascaded tilted Bragg gratings", Optics Express, Open Access, Volume 28(7), 10145-10152 (2020).
95. He Y., Chen Y., Zhang L., Wong S., Chen Z. N.: An overview of terahertz antennas. China Communications, 17(7), 124-165, (2020).
96. Chahat N. et al., 1.9-THz multiflare angle horn optimization for space instruments. IEEE Transactions on Terahertz Science and Technology, 5(6),914-921, (2015).
97. Fan K., Hao Z. C., and Hong W. A 325-500 GHz high gain antenna for terahertz applications. Proc. 2016 International Symposium on Antennas and Propagation (ISAP), 780-781, (2016).
98. Sawada H., Kanno A., Yamamoto N., Fujii K., Kasamatsu A., Ishizu K., Kojima F., Ogawa H., and Hosako I., High gain antenna characteristics for 300 GHz band fixed wireless communication systems. Progress in Electromagnetics Research Symposium, 1409-1412, (2017).
99. Wang X., Deng C., Hu W., Lv X., and Ligthart L. P., Dual-band dielectric-loaded horn antenna for terahertz applications, Proc. International Applied Computational Electromagnetics Society Symposium (ACES), 1-2, (2017).
100. Kiourti A., Nikita K. S.: A Review of Implantable Patch Antennas for Biomedical Telemetry: Challenges and Solutions [Wireless Corner]. IEEE Antennas and Propagation Magazine, 54(3), 210-228, (2012).
101. Karacolak T., Cooper R., Butler J., Fisher S., and Topsakal E., In Vivo Verifi cation of Implantable Antennas Using Rats as Model Animals. IEEE Antennas and Wireless Propagation Letters, 9, 334-337 (2010).
102. Zou C., Withayachumnankul W., Bhaskaran M., Sriram S., Fumeaux C.: Dielectric Resonator Nanoantennas: A Review of the Theoretical Background, Design Examples, Prospects, and Challenges. IEEE Antennas and Propagation Magazine, 59(6), 30-42 (2017).
103. Zou L., Withayachumnankul W., Shah C.M., Mitchell A., Bhaskaran M., Sriram S., and Fumeaux C., Dielectric resonator nanoantennas at visible frequencies. Opt. Express, 21 (1),1344–1352, (2013).
104. Wang K. and Li J., Jeans Textile Antenna for Smart Wearable Antenna. International Symposium on Antennas, Propagation and EM Theory (ISAPE) (2018).

105. Huang K. C., Edwards D. J.: Advanced Antenna Materials. Millimetre Wave Antennas for Gigabit Wireless Communications: A Practical Guide to Design and Analysis in a System Context , Wiley, 227-253, (2008).

106. American Ceramic Society Website http://ceramics.org/wp-content/bulletin/2019/pdf/August2019.pdf last accessed 2021/2/9.

107. Ashyap A. Y. I. et al.: An Overview of Electromagnetic Band-Gap Integrated Wearable Antennas." IEEE Access, 8, 7641-7658 (2020).