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High Temperature Antennas: A Review

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Abstract—The advent of space exploration and space warfare along with the deployment of advanced missiles, unmanned aircraft systems, and modern nuclear reactors has reignited the field of high temperature antennas. In this context, this article surveys the field of antennas that operate under harsh environments that are often characterized by high temperature. In this context, this article surveys the field of high temperature antennas. The choice of the substrate and the conductor for antenna implementation are discussed with emphasis on their thermal and electrical properties. Further, the different fabrication techniques to realize the antenna are discussed. The performance comparison of the different types of high temperature antennas are presented. Finally, the future prospects and inherent challenges in advancing research on antennas for extreme environments are detailed. The article concludes with insights into the new developments in the field of flexible antennas operable in hostile conditions.

1. INTRODUCTION

Increased implementation of electronics in new applications has mandated devices with specific characteristics. Applications in the field of energy systems [1–4], satellite communication, internet of things (IoT) [5–7], industrial and manufacturing processes such as furnaces, boilers, and heat pumps [8–10], combustion chambers, and turbines in automobile and aerospace crafts [11, 12], sensor systems, different military systems such as unmanned vehicles, ship, rail, and ground-based systems, as well as environmental monitoring systems require quite a modified set of device features. The devices in these applications need to be robust against rough environment such as high temperature, high pressure, high radiation, high rotational speed [2], high velocities, corrosive chemicals [13], corrosive gases [5], and lightning strikes. Examples include high temperature hydrogen safety monitors for the new gas cooled nuclear reactors, strict automotive emissions control requirements via tailpipe sensors, requirement of flexible antennas and antenna radomes with extreme thermal shock resistance for missile applications, high temperature substrates for hypersonic antennas, communication solution for beyond line-of-sight on small to medium scale unmanned aircraft systems, and wireless physiological and environmental monitoring system for first responders.

Industry's demand for flexible high temperature sensors and antennas stems from the need to monitor combustion turbines, combustion engines, gasifiers, combustion reactions, power plants, agricultural waste processes (such as pyrolysis), and chemical manufacturing plants. In the era of internet of things and wearable devices, one of the current needs of Federal agencies and industry is a platform that can withstand extreme environments for sensing and communication applications. Such harsh environmental setups often degrade the efficiency and usability of various sophisticated electronics. The critical need for devices operable in high temperature and harsh conditions is evident from various Federal agencies' future budget plan, priorities, call for proposals and funding opportunities [14, 15].

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Examples include the new gas cooled nuclear reactor and strict emissions control requirements from the Department of Energy (DOE); requirement of antennas and antenna radomes with extreme thermal shock resistance for missile applications and high temperature substrates for hypersonic antennas for the Department of Defense (DoD); communication solution for beyond line-of-sight communications on small to medium scale unmanned aircraft systems (UAS) for National Aeronautics and Space Administration (NASA); and Wireless Physiological and Environmental Monitoring (WiPEM) system requirement (for first responders) from Department of Homeland Security (DHS).

High temperature measurement and interrogations are critical in many applications to improve efficiency, quality, maintain stability [13], maintain accuracy and improve reliability [5], optimize operational parameters [16], expand materials' life expectancy [3], prevent wearability and defects [1], improve designs [2], maintain healthy performance, and many more. However, the operating environment can be toxic and harmful for direct human interaction. As one of the most important elements of wireless devices, it has thus become necessary to design improved and robust antenna with high temperature tolerance. Researchers are engaged in passive wireless sensing systems rather than active ones where the antenna works as both the sensing and communication elements of the system. The goal is to adapt wireless passive sensing methods that require no power supply, no transmission lines, or cables, and can still withstand harsh environments [13].

Recent advancements in materials and fabrication technologies have enabled improved antenna designs to meet such stringent requirements. As an an integral part of the microwave systems, the other pertinent criteria arises from antenna's deployment in satellite communication, energy harvesting, RADAR, phase shifters, power dividers and couplers [17–19]. Different fabrication techniques with the help of modern optimization algorithms and machine learning have made designing complex antennas achievable [20]. Since temperature affects and changes the dielectric constant of the material, and since the resonant frequency of an antenna is coupled to the dielectric constant, microstrip antennas can be used as sensors via monitoring the resonant frequency as a function of temperature [21]. The geometry and physical dimensions of an antenna also affect the antenna's resonant frequency as temperature changes [8]. Microwave-based sensing technology has been widely investigated in high-temperature and harsh environments [13, 21–23].

2. MATERIALS SELECTION FOR ANTENNA

A high temperature antenna usually consists of a dielectric substrate and a conductive patch. The operating temperature plays a crucial role in materials selection as the dielectric constant of a substrate and the electrical properties of the conductor can change as a function of temperature and can alter the device's performance. The combination of the substrate, conductive patch, and the operating temperature dictates the device performance in harsh environments. While the substrate is chosen based on dielectric constant or relative permittivity, dielectric loss tangent, coefficient of thermal expansion, flexibility, and melting point, the choice of conductive material is based on electrical and thermal conductivities.

2.1. Dielectric Substrates

Substrates for high temperature antenna implementation need to possess resilient characteristics to harsh environments. If the dielectric permittivity is constant over the operational temperature range, a linear antenna response can be expected [8]. The hard limitation on the choice of the dielectric substrate is its compatibility with microwave designs and its mechanical robustness during use [21]. Materials with high temperature tolerance and stability [9], low thermal conductivity, low dielectric loss, and superior mechanical and chemical properties [24] are typically preferred for high temperature applications. Various types of substrate materials such as ceramics, polymer-derived ceramic (PDCs), glass, sapphire, polymers, composites, semiconductors, and oxides have been explored in recent studies.

Ceramic materials are the most popular substrates for the development of devices for extreme environments. They are attractive due to their varied dielectric constants, superior mechanical strength, high stability, ability to be flexible, low thermal conductivity, and tolerance to high temperatures. Recently, E-Strate (a thin flexible ceramic substrate) that can withstand temperature up to 1000°C used in [24] for implementing flexible devices like a Coplanar Wave Guide (CPW)-fed antenna and a capacitive interdigitated sensor for IoT applications was reported. Hexagonal Boron Nitride (hBN) is another ceramic material that has great potential for high temperature antenna as it possesses thermal stability up to 900°C. It also has low-loss polaritons which makes it an excellent candidate for high temperature infrared photonics [9]. Moreover, aluminum oxide (Al_2O_3) or alumina ceramic is one of the strongest ceramic substrates for high temperature wireless sensors applications since it can withstand temperatures up to 1600°C [14]. Alumina has been identified as a robust material for harsh environment applications by researchers at the NASA Glenn Research Center in recent years. It has been found that the dielectric constant of alumina is temperature dependent and can increase monotonically up to 1600°C desirable for wireless temperature sensing applications [25]. For this purpose, another ceramic composite referred to as $La(Mg_{0.49}Ca_{0.01}Sn_{0.5})O_3$, a mixture of multiple chemicals such as MgO, $CaCO_3$, $SrCO_3$, and SnO_2, was proposed in the same study with a dielectric constant of 19.9.

For even higher dielectric constant ceramic choice (dielectric constant of 37), zirconium tin titanate (ZST or $Zr_{0.8}Sn_{0.2}TiO_4$) was reported earlier [26]. ZST can withstand temperature up to 2000°C making it an ideal substrate for the miniaturization of high temperature devices. Low-Temperature Co-fired Ceramics (LTCC) can be effective for environments up to 600°C, whereas High-Temperature Co-fired Ceramics (HTCC) are effective for environments above 600°C [27]. Further, polymer-derived ceramic silicoaluminum carbonite (PDC-SiAlCN) was used to make a cavity resonator and an integrated slot antenna in another study [5]. The PDC-SiAlCN material showed stability and corrosion resistance up to 1400°C making them a suitable choice for wireless temperature sensor applications. Another PDC material made with iron-containing silicon boron carbonitride (SiBCN) monolithic ceramic was reported earlier [28] which had excellent high temperature resistance up to 885°C for the use in electromagnetic wave absorption.

Selecting the right substrate is directly related to the intended device application. Quartz glass has been the desired dielectric material for lens antennas in the microwave transmission diagnosis of plasma [11]. It has excellent light transmission and a melting point of 1715°C, and can be used as a high-temperature resistant material for optical focusing lens antennas due to its high focusing resolution [6]. Other materials such as fabrics, linen, and polyester have been widely used for wearable devices due to their flexibility. Advanced devices are getting embedded in clothes for personal body monitoring in high-risk occupations such as mining and firefighting. However, these materials usually have low tolerance to very high temperature. In a prior study [29], a dipole antenna was fabricated on a 65/35 polyester cotton fabric which was cured at a temperature up to 225°C. A study [30] used linen material to fabricate a QR code antenna for Wi-Fi applications that operated under 200°C. Another flexible material, polyamide laminate, was used to fabricate a wearable flexible antenna for personal monitoring in wireless body area work [31]. The antenna showed great thermal and mechanical resistance characteristics up to 250°C, and its radiating fields were evaluated by the specific absorption rate (SAR) test on human body which showed minimal penetration in human tissues.

Composites, oxides, and semiconductors like silicon were also used as substrates for high temperature antennas and sensor. A wireless antenna strain sensor was implemented in a prior study [8] on a laminate substrate made by Rogers (RO3006). It consisted of ceramic-filled polytetrafluoroethylene (PTFE) composites that can operate up to 250°C. Further, a study conducted an investigation on gallium arsenide, silicon, aluminum oxide, and a graphene oxide-based Roger RO3210 substrate (which can withstand a very high temperature of 4237°C) to fabricate an electromagnetic wave absorber integrated with a patch antenna array [4].

In summary, the dielectric substrate must be carefully chosen for high temperature antenna applications taking into account the mechanical, electrical, and coupled mechanical-electrical properties. The high demand for monitoring devices under high temperature has ignited the resurgence of materials such as titania, zirconia, yttria-stabilized zirconia (YTZ), silicon dioxide, indium tin, alumina, hafnia, magnesia, and magnesium aluminate spinel oxide, to name a few. Table 1 summarizes the commonly used dielectric substrate materials for antenna applications.

2.2. Conductive Materials

Patch antennas used for high temperature applications have metallization patterns as the radiating materials due to their high conductivity. High conductivity enhances the antenna's gain, efficiency,

Table 1. Common dielectric materials with some of their properties.

Material Type	Substrate Materials	Dielectric Constant (ε_r)	Loss tangent ($\tan\delta$)	Melting Point (°C)
Ceramic	E-Strate [24]	23	0.001	1000
	Hexagonal Boron Nitride (hBN) [9]	6.76	-	900
	Aluminum Oxide (Al_2O_3) [4]	9.8	0.0003	1600
	$La(Mg_{0.49}Ca_{0.01}Sn_{0.5})O_3$ [14]	19.9	0.00012	1600
	Zirconium Tin Titanate (ZST or $Zr_{0.8}Sn_{0.2}TiO_4$) [26]	37	0.0002	2000
	Silicoaluminum Carbonite (PDC-SiAlCN) [5]	3.053	0.026	1400
	Silicon Boron Carbonitride (SiBCN) [28]	6.11	0.32	885
Glass	Quartz [11]	3.78	-	1715
Crystal	Sapphire [32]	11.4	0.0001	2000
Laminate	Polyamide Laminate [31]	3.4	0.04	225
	Rogers (RO3006) [8]	6.5	-	250
Others	Graphene Oxide-based Roger RO3210 [4]	10.2	-	4237
	Silicon [4]	11.9	0.005	1414
	Gallium Arsenide [4]	12.9	0.0004	1238
	Teflon [11]	2.1	0.00028	327

and bandwidth. Solid metals, metal-based nanoparticle inks, and alloys are common materials used to pattern the antenna's radiation patch. Solid metals such as copper, silver, gold, chrome, steel, nickel, aluminum, platinum, palladium, rhodium, and iridium have been successfully used in high temperature environments. Other metals such as molybdenum and tungsten, which have high melting points, are slowly emerging as applications in extremely high temperature gain traction. As nanoparticle inks are concerned, silver nanoparticle inks exhibit superior electric conductivity and low bulk resistivity and are often preferred due to simple fabrication techniques associated with the ink. Copper nanoparticle ink is not as commonly used due to low conductivity and high rate of oxide formation [7].

Some alloys have been successfully used such as silver-palladium, brass, and bronze. The advantage of using an alloy is the ability to mix desired percentages of metals to achieve certain characteristic to meet specific antenna performance standards. More alloys will be used and investigated in the future as the demand for antenna and wireless sensors for harsh conditions increases. Table 2 shows the common conductive materials used in antenna along with their thermal and electrical properties.

3. ANTENNA FABRICATION TECHNIQUES

Prior to fabrication, it is important to optimize the device's design parameters to maximize performance and efficiency. There are many software programs built upon the fundamental equations of electromagnetic theory that are available for antenna simulation and analysis. Such programs like Ansys HFSS, ADS, CST, and IE3D are constantly getting improved with the help of artificial intelligence (AI) and machine learning (ML). Fabrication techniques influence antenna performance. Common antenna fabrication techniques include screen printing, chemical etching, aerosol printing, 3D printing, and inkjet printing. A few of the techniques are described in the following sections.

Table 2. Common conductive materials and some of their electrical and thermal properties.

Material Type	**Name of Material**	**Electric Conductivity (10^6 Siemens/m)**	**Electric Resistivity (10^{-8} Ohms/m)**	**Thermal Conductivity (W/m·K)**	**Melting Point (°C)**
Solid Metals	Silver	62.1	1.6	420	961
	Copper	58.7	1.7	386	1083
	Gold	44.2	2.3	317	1064
	Aluminum	36.9	2.7	237	660
	Nickel	14.3	7.0	91	1455
	Steel	10	9.61	80.4	1538
	Chromium	7.9	12.5	93.9	1907
	Molybdenum	18.7	5.34	138	2623
	Tungsten	8.9	11.2	174	3422
Nanoparticles	Silver	21.3	-	-	≈ 961
	Copper	1	-	-	≈ 1083
Alloys	Silver-Palladium	-	-	-	-
	Brass	15.9	6.3	150	900
	Bronze	-	-	-	-

3.1. Screen Printing

Screen printing is a preferred fabrication method due to its simplicity, cost-effectiveness, and speed of mass-producing devices. Many types of antennas have been reported using this fabrication method [33–36]. The screen-printing process starts with a screen encompassing the desired pattern. The screen is then placed on the substrate. It is important for the screen to be aligned with the substrate for selective printing of the conductive material. After alignment is made, a desired conductive paste is applied at one end of the substrate across its width and is spread through the entire substrate with the help of a squeegee blade [7].

The conductive paste goes through the patterned screen onto the substrate, and then the screen is lifted off. Finally, the patterned substrate is sintered at high temperature. In a prior study [34], platinum paste is applied through a patterned screen to form the conductive patch antenna on top of an alumina ceramic substrate as seen in Figure 1 below. Another study [35] reported sintering in a

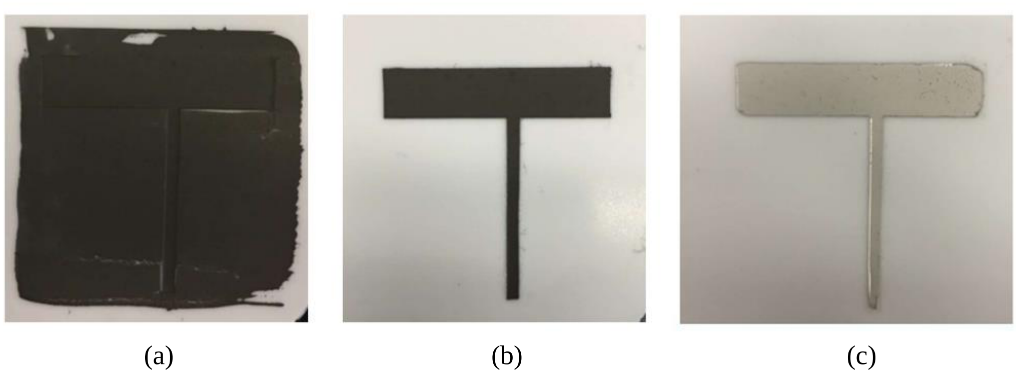


Figure 1. (a) Applying platinum paste through a patterned screen, (b) lifting screen to leave a patterned Pt patch, and (c) sintering Pt patch 8°C/min from room temperature to 1000°C with a hold time of 10 minutes [34].

muffle furnace from room temperature to 850°C at a rate of 10°C/min in order to solidify and form a dense silver-palladium metal layer. Yadav et al. [37] reported silver sintering in a furnace at 850°C at a rate of 20°C/min, holding it for 30 min at 850°C. Li et al. [36] reported sintering silver paste in a muffle furnace at a peak temperature of 850°C for one hour.

3.2. Chemical Etching

While screen printing is an additive process, chemical etching is a subtractive process where materials are removed selectively. There are many ways to chemically etch conductive materials in order to form a desired conductive patch on a dielectric substrate. The most common etching technique found in recent research is the PCB print-etching technique (Figure 2). The desired pattern that forms the conductive patch is designed using a Computer-Aided Design (CAD) and then printed with PCB ink using laser or other printing techniques on a thin film sheet, usually made of paper. The PCB transfer film is then aligned on top of the substrate, and thermal compression is applied to transfer the resistive PCB ink onto the conductive layer of the substrate. After the transfer is completed, the paper film is removed, and the entire substrate is submerged into chemical solution to etch all conductive areas that are not covered by the PCB resistive ink. Finally, the resistive ink is removed, leaving a fine pattern of conductive patch on the dielectric substrate. Many investigations [16, 38–41] reported antenna patterns drawn using CAD software and printed on PCB transfer paper films. The films were then transferred onto the substrates using clothing irons as thermal compression sources. Copper etching was performed using ferric chloride.

Another etching process utilizes photolithography techniques. The photolithography technique uses photoresists and masks to form a patterned layer on top of the substrate. The photoresist will cover the metallization layer thus preserving metal under it. Then the entire substrate is submerged in a

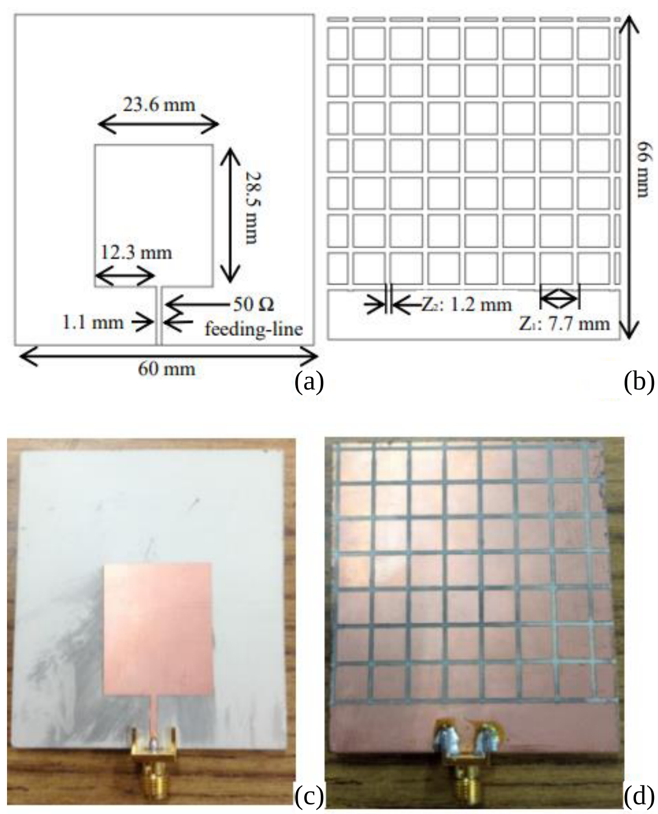


Figure 2. Dimensions of the (a) radiation patch and (b) ground plane intended to be printed on PCB transfer thin films, (c) top view and (d) bottom view of antenna after printing and etching [16].

chemical etching solution to remove exposed metals. Finally, the photoresist is removed leaving only the desired metal pattern. An alternative way to execute this etching process is through lift-off. Lift-off is performed by applying photoresist first on a substrate in a form of a "negative pattern", then a desired metal is deposited on the substrate by physical evaporation or sputtering. Photoresist etching is carried out by submerging the substrate in photoresist etching solution to lift-off photoresist and the undesired metal on top of it leaving the rest of deposited metal in a form of a fine "positive pattern". In a prior study [1], a 0.3-µm-thick chromium layer was first evaporated on a silicon carbonate substrate.

Second, a photoresist layer was added to cover the CPW feeding lines of the antenna. Third, a 7-µm-thick layer of gold was deposited on top to minimize conductor loss due to skin depth effect. Finally, lift-off technique was carried out to remove unwanted gold leaving fine patterned chromium CPW feeding lines as shown in Figure 3 below.

Figure 3. CPW fed antenna layered with chromium and gold using physical evaporation on a silicon carbonate substrate for high temperature sensing [1].

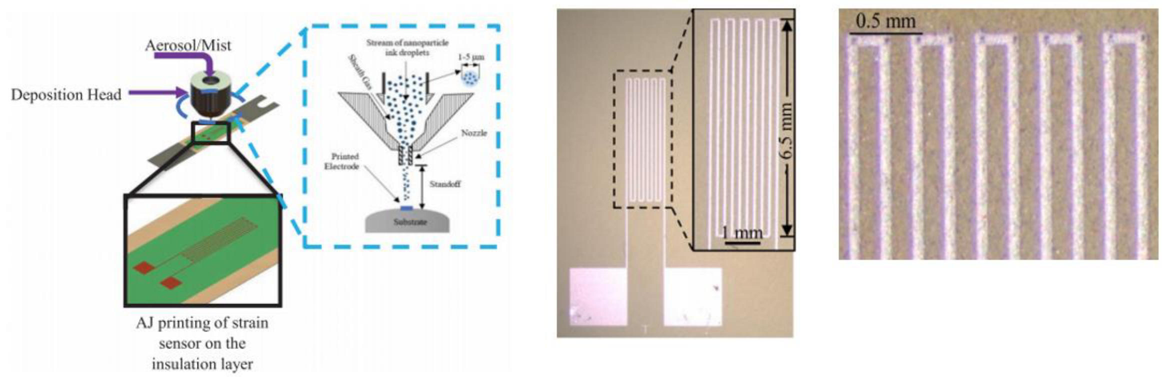
3.3. Inkjet Printing

Inkjet printing technique uses nanoparticles ink to print predesigned conductive patterns on a wide range of desired substrates (Figure 4). Inkjet printing is highly desired to use and pattern the conductive patch on antenna substrates because the design is directly printed without the use of masks, screens, or any etching process. This allows for less materials to be used and wasted, thus decreasing materials cost and environmental factors. The printing process using this technique, from design to fabrication, is low cost and simple. It requires an inkjet printer which comes with a complimentary software to control the printer. The software allows the user to insert a predesigned pattern and optimize printing parameters to provide the best printing quality. The most common nanoparticle inks used is silver nanoparticles.

Figure 4. Inkjet printer — Dimatix Materials Printer, DMP-2800 (FUJIFILM Dimatix Inc., Santa Clara, CA, USA), and a PC which contains the software that is used to control the printer.

The quality of the printing is dependent on many common factors such as the conductivity of the ink, voltages of jetting nozzles, jetting waveform, frequency, temperature, and resolution of the pattern [7].

Rahman et al. [42] reported printing a microstrip strain sensor using Aerosol jet printer for high temperature applications (Figure 5). The sensor was printed three times using silver nanoparticle ink to form three layers of deposited ink on a rectangular cantilever beam substrate made from stainless steel. After printing, the silver layers were sintered at 200°C for 6.5 hours in a programmable oven to ensure stable electrical performance of the conductive electrodes of the strain sensor.



(a) (b) (c)

Figure 5. (a) Schematic of AJ printed and strain sensor, (b) printed sensor with silver nanoparticle ink, and a closer look at sensor gages [42].

4. APPLICATIONS

Technological advancement in every sector of modern engineering has enlarged the scope of applications for modern devices operating under benign and extreme environments. High temperature applications are prevalent in industries using boilers, heat pumps, furnaces [8–10], as well as in combustion chambers of automobiles, aerospace crafts [11, 12], ships, and various military equipment and vehicles [43], where general human interaction or intervention is not feasible. High temperature compatibility has always been at the center for wireless applications in extreme environments. Researchers are more interested in the passive wireless sensing systems in such environments, rather than active ones, where the antenna works both as the sensing and communication elements of the system. Most of the passive wireless sensing techniques utilize the antenna performance parameters such as gain, resonant frequency, dielectric constant, and Q-factor to indicate the temperature of the system [26, 43–45]. Aluminum based ceramic substrates were successfully implemented as passive wireless sensors [44, 46, 47]. Different microstrip patch antennas and RFID tags made of ceramic substrates and various complex compounds have been used for high temperature wireless sensing applications [26, 48–53]. Besides, different ceramic radomes are used in military navigation applications where the temperature can rise up to 400°C [43].

Apart from sensing the temperature (Figure 6), passive wireless devices have been used to monitor pressure at high temperatures [54, 55]. For pressure sensing applications, Tan et al. [55] proposed a microstrip antenna using DuPont 951PT LTCC tapes made of ceramic, glass, and organic binder materials as the substrate which can withstand temperature up to 400°C. Another patch antenna for pressure sensing application was developed using Sapphire substrate that can withstand up to 600°C when measuring pressure from 20 KPa to 600 KPa as a function of the resonant frequency from 420 MHz to 370 MHz [32]. Su et al. [56] provided a similar solution by developing a slot antenna for pressure sensing applications in harsh environment (using Alumina substrate). The resonant frequency is a constant at 2.1065 GHz for the entire temperature variation from 24°C to 800°C, which is one of the promising aspects of this antenna.

With the advent of IoT framework, wireless devices have been investigated to operate under extreme environments (Figure 7) without performance degradation over time [57, 58]. High temperature

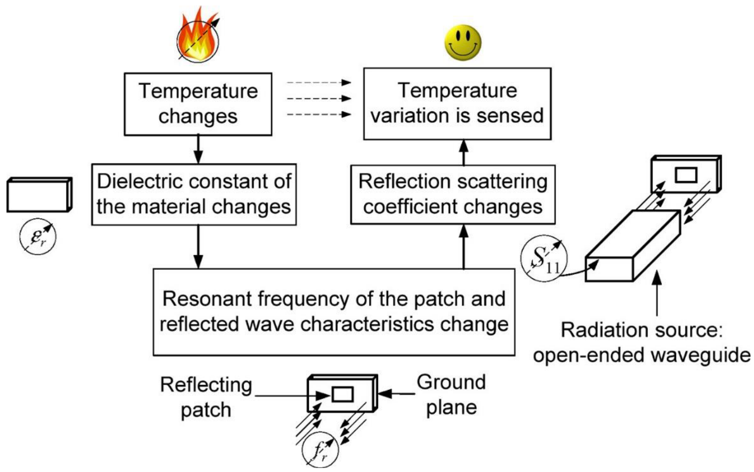
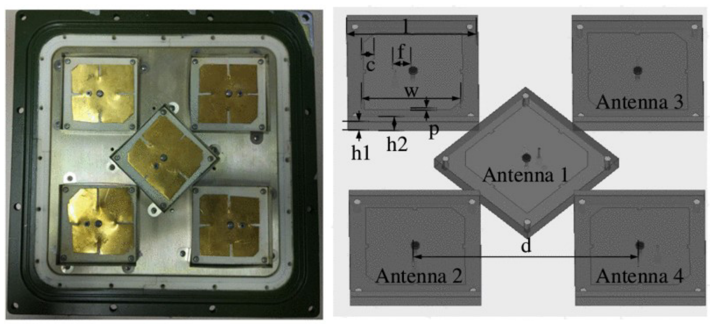


Figure 6. Passive temperature sensing mechanism utilizing reflective patch [44].



(a) (b)

Figure 7. Stable high temperature antenna for navigation applications [43].

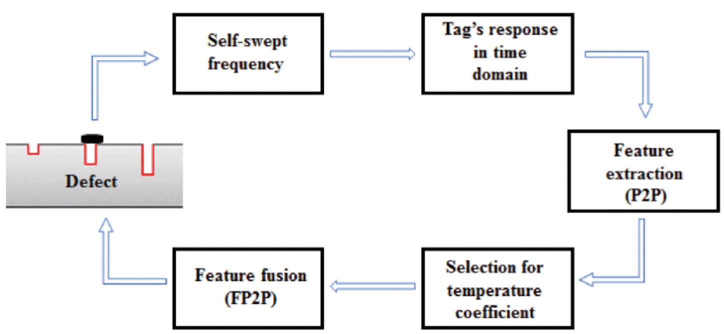


Figure 8. Workflow diagram of defect detection using high temperature antenna [51].

antenna technology is becoming prevalent in research areas such as detection of the characteristics of electromagnetic waves in plasma environment [6, 11]. A point focusing lens antenna with quartz material as substrate was reported earlier [6], which can withstand temperature up to 1100°C, used in plasma characterization. In different corrosion and crack detection applications, high temperature antennas are currently showing consistent performance unaffected by the temperature of the environment (Figure 8) [51]. Some commercially available RFID tags such as 231 Volcano LF RFID is used in detecting cracks in several materials. A constant resonant frequency is a necessity in the above situation for uninterrupted communication by any means. Research indicated that this RFID tag can handle temperature up to 160°C while keeping the resonant frequency constant at 125 kHz [51].

5. ANTENNA PERFORMANCE

Antenna performance is usually characterized by resonance frequency, impedance, gain, aperture or radiation pattern, polarization, efficiency, and bandwidth [59]. The resonant frequency and electrical resonance are related to the electrical length of the antenna. Antennas are generally tuned at a certain frequency and are effective in a frequency band centered on this resonant frequency [59]. Gain refers to the ratio of the power density of the signal generated by the actual antenna and the ideal radiating element at the same point in space under the condition of equal input power [59]. Antenna gain is a passive phenomenon. The antenna does not increase excitation, but only redistributes it to radiate more energy in a certain direction. The radiation pattern is a three-dimensional graph representing gain, but usually, only the horizontal and vertical two-dimensional sections of the radiation pattern are considered. The bandwidth of an antenna refers to the frequency range in which it works effectively, usually centered on its resonant frequency. Regardless of whether it is a transmitting antenna or a receiving antenna, they always work within a certain frequency range (bandwidth). Normally it is considered at 10 dB value of return loss or standing wave ratio SWR ≤ 2 [59].

There are many critical parameters that affect the antenna performance, and these indicators are mostly conductivity of the radiation element, dielectric substrates, and different design considerations which can be usually adjusted during the antenna design process. The physical dimensions, design of the patch antenna, along with the parameters of the conductive material constitute the patch. The dielectric material is used to form the antenna's substrate. The parameters of the conductive material and its geometry play a crucial role in determining the resonant frequency of the antenna and in turn, the intended applications. To specifically operate in the high temperature regime, one of the most important parameters is to choose a suitable dielectric material which could withstand the harsh environmental conditions. Dielectric constant, thickness, stiffness, as well as loss tangent are important factors for substrate selection. A higher value of loss tangent of the dielectric substrate results in low efficiency and gain [60]. Additionally, dielectric permittivity (ϵ_r) affects the bandwidth and resonant frequency. Apart from the above-mentioned factors, the antenna performance can be significantly affected by antenna patch design, array configurations, and transmission lines. Patch elements come in various regular shapes or irregular patterns [61]. The shapes affect polarization patterns, resonant frequencies, return loss, gain, and directivity. To evaluate the design and simulated performance of the antenna with different radiating materials and substrate combinations, the indispensable requirement is a computer-aided design (CAD) software combined with an electromagnetic wave solver, preferably HFSS or CST.

In an earlier report [27], the operating antenna is an inductively coupled LC resonance circuit consisting of a multi-turn planar square loop which shows the relative frequency shift over a temperature range of room temperature to 900°C. Three different devices follow the same pattern with a decrease in frequency up to 300°C, then a slight increase between 400 and 600°C, and finally equalizing above 600°C. This is shown in Figure 9. In another study [25], the resonant frequency is sensed by an

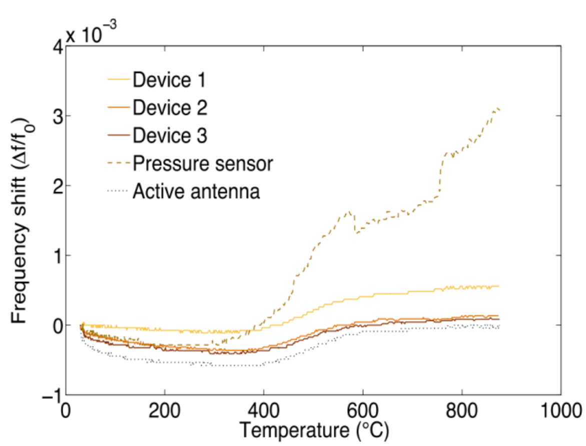


Figure 9. Frequency shift versus temperature for the loop antenna [27].

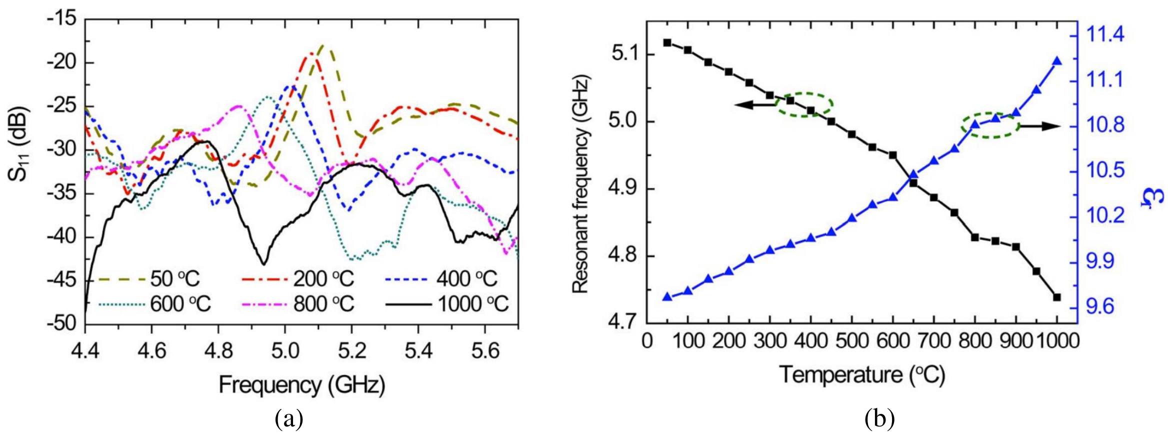


Figure 10. Measured responses of the OEWG for different temperatures: (a) Shift of resonance frequency; (b) Shift of dielectric constant of alumina [25].

open-ended waveguide (OEWG) antenna through the integrated slot antenna. Figure 10 represents the measured responses of the OEWG for several temperature values. It is observed that a unique peak exists with the highest signal level at each temperature. This peak corresponds to the resonant frequency of the integrated cavity/resonator. In the temperature range of 50°C–1000°C (shown in Figure 10), the resonant frequency decreases from 5.12 to 4.74 GHz, and the dielectric constant of alumina increases from 9.7 to 11.2 which indicate a measured sensitivity of 0.4 MHz/°C less than the 8% resonant frequency change in this temperature range.

A similar trend was observed in a prior report [62] where the resonance peak is evident in the spectrum (shown in Figure 11). An average absolute sensitivity of 307 kHz/K and an average temperature coefficient of 104 ppm/K were found when the resonant frequency increases continuously from 2.92 GHz to 3.03 GHz.

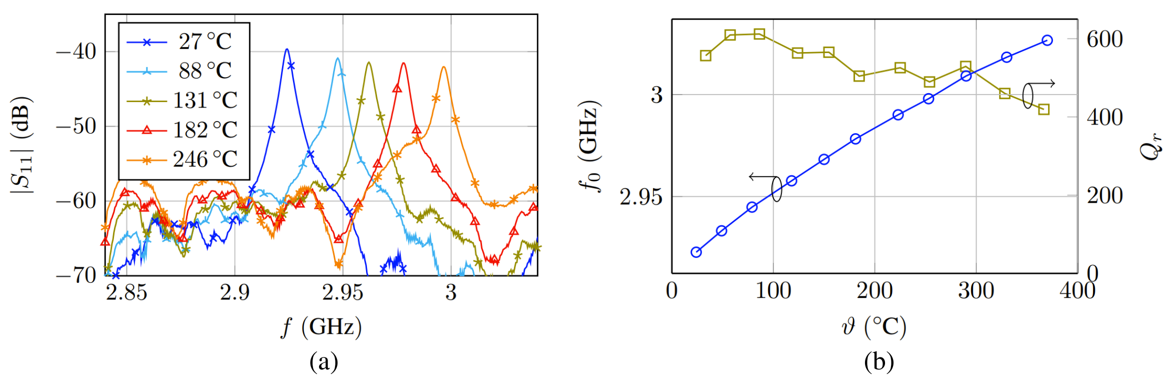


Figure 11. Measured resonance frequency and quality factor of the sensor tag versus temperature responses: (a) Differential spectral signals; (b) Shift of quality factor [62].

Simultaneously, there was a decrease in resonance quality factor which took place due to the increase in metallic, dielectric, and connector losses as temperature increases.

Generally, the sensitivity to temperature changes is dictated by the nature of a dielectric material when it is used in a wireless passive temperature sensor. Thus, it is imperative to have a linear relationship between resonant frequency (or ϵ_r) and temperature. The observation from an earlier report highlights [45] the temperature dependence of dielectric loss at various frequencies with the TE_{011} resonant mode from 100 Hz to 1 KHz depicted for the TiO_2 ceramics sintered at 1250°C for 4 hrs. Further from another study [44], the change in dielectric constant was observed as the dominant contributing factor influencing resonant frequency variations.

When the measured resonant frequency monotonically decreases from 5.07 to 4.58 GHz, the sensor sensitivity is extracted to be within the range of 0.41–0.58 MHz/°C, and the dimensional change of the substrate is 0.82% from 50 to 1050°C as shown in Figure 12.

Using a similar working principle [5], it was seen that wireless passive temperature sensors have

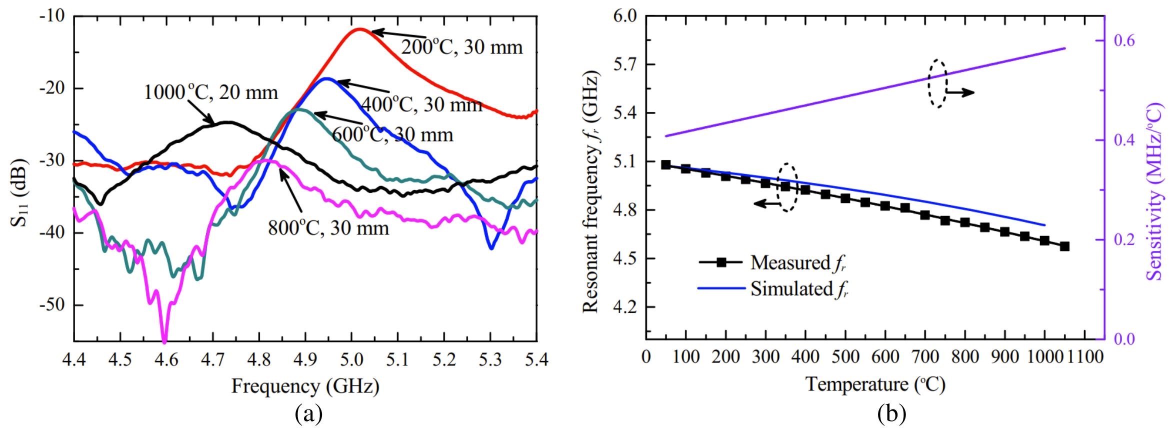


Figure 12. Measured resonant frequencies of the patch sensor versus temperature; (a) S_{11} at different temperature: (b) Sensitivity at different temperature [44].

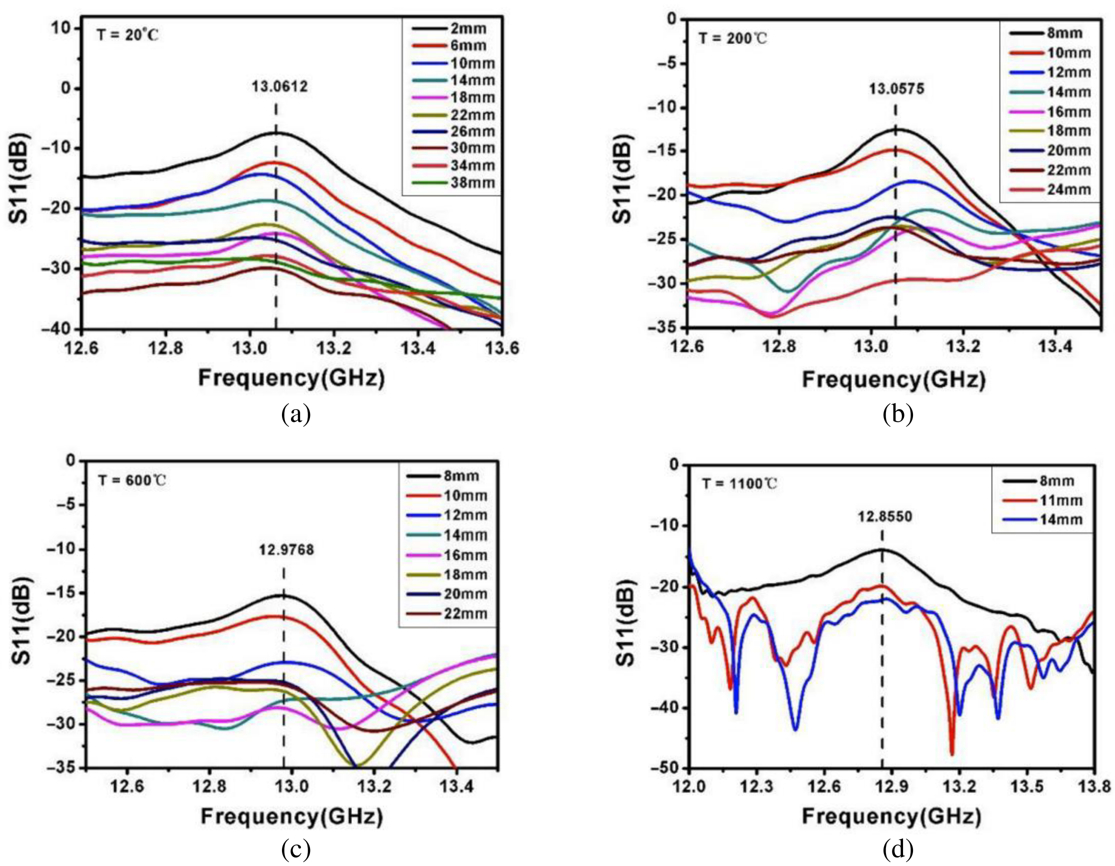
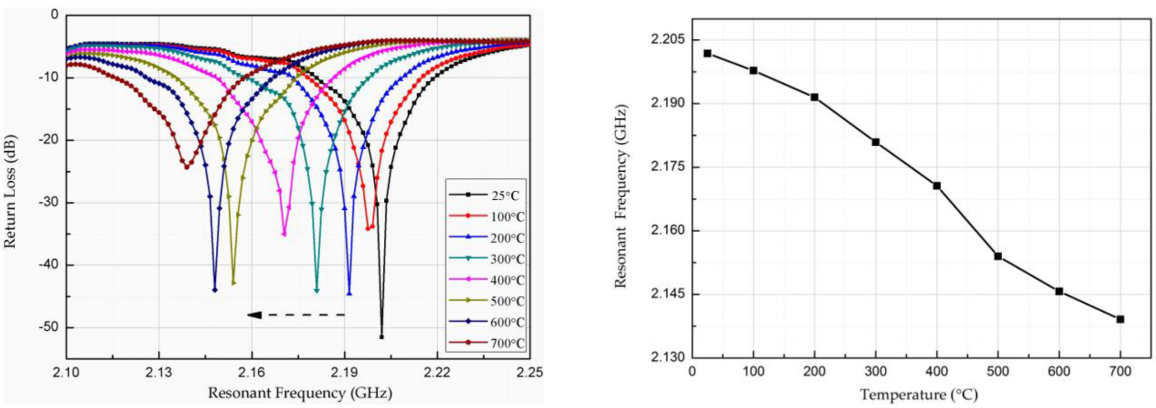


Figure 13. Measured S_{11} responses of the sensor STC-2 in frequency domain for different test temperatures and different sensing distances (a) 20°C; (b) 200°C; (c) 600°C; (d) 1100°C [5].

been proposed to utilize a cavity resonator and an integrated slot antenna, made from high-temperature stable PDC-SiAlCN ceramics. The test results proved that the sensors can be used up to 1100°C with excellent reliability and repeatability.

The responses were measured in frequency domain after TD gating for different test temperatures and different sensing distances as shown in Figure 13. Between 20°C and 1100°C, the transmission distance decreases from 38 mm to 14 mm.

It can be inferred from various reports that high temperature affects the resonant frequency of the antenna. Figure 14 shows the experimental data recorded in a prior report [35] showing resonant frequency of the designed antenna versus temperature. It can be seen from Figure 14(a) that the performance of the antenna changes as temperature increases, but it is not obvious to assume a relationship between them. For example, the performance decreases when temperature increases from 25°C to 100°C, but performance increases when temperature increases from 400°C to 500°C and then dramatically decreases around 700°C. However, a relationship between resonant frequency and temperature can be observed from Figures 14(a) and (b). The figures show that the resonant frequency decreases as temperature increases.



(a) (b)

Figure 14. (a) Shows the return loss vs frequency at different temperatures, and (b) plots resonant frequencies vs temperatures [35].

However, in an earlier report [40] an increase in resonant frequency was observed as temperature increased (Figure 15), opposite to the results found in a prior study [35].

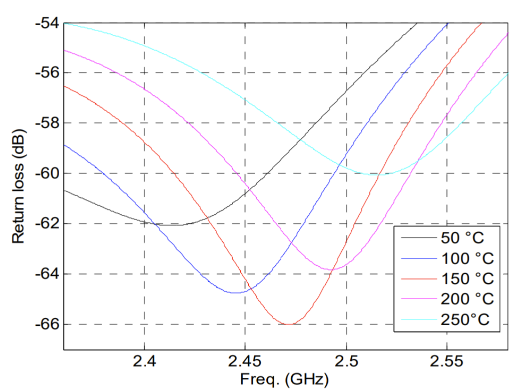


Figure 15. Shows the return loss in dB of the designed antenna versus frequency in GHz [40].

As for the performance of the antenna, it seems to increase at first and then decrease as temperature increases, so no direct relationship can be found [18].

The obtained results seem consistent with those of existing literature [4, 6, 27]. It can be concluded that the antenna performance at different resonant frequencies will vary as temperature changes, and for every new antenna design and related materials choice, there is a relationship between the change in resonant frequencies versus increase in temperature. There is no empirical formula by which the

Table 3. High temperature antenna performance comparison derived from recent investigations.

Ref.	Antenna Type	Material	Dimensions (mm^3)	Band Range (GHz)	Gain (dB)/ Sensitivity (MHz/°C)	Highest measuring Temp (°C)
[63]	Reconfigurable double-patch	Rogers 5880 laminate	$99 \times 31 \times 0.79$	0.84–0.91	-	40
[52]	Microstrip patch	FR4	$56.2 \times 70 \times 1.6$	2.38–2.43	-	125
[4]	Microstrip	Rogers RO3210	$55 \times 58 \times 2.5$	9.80–10.8	5.985/-	187
[4]	Microstrip	Aluminum oxide	$55 \times 58 \times 2.5$	10.3–11.3	10.52/-	187
[64]	CSA	SYRON™ 7000	-	2.4–3.7	-	210
[31]	Microstrip Fractal	Polyamide laminate	-	1–5	5.53/-	225
[12]	Planar antenna (microstrip)	Copper	$105 \times 105 \times 44$	2.1–4.8	-	350
[65]	LC Resonator	DuPont 951	$22 \times 22 \times 1.5$	-	-/0.24	400
[43]	Microstrip Array	Ceramic radome	$200 \times 200 \times 21$	1.56–1.57	4/-	400
[32]	Patch	Sapphire	$10 \times 10 \times 0.42$	0.37–0.42	-	600
[13]	Dielectric Resonator	$(Mg_{0.93}Ni_{0.07})_2SnO_4$	-	7.35–15.04	-	600
[26]	Microstrip	ZST	$5 \times 5 \times 2$	2–2.50	-	700
[66]	Microstrip patch	AIN ceramic	$22.4 \times 34 \times 1$	2.13–2.20	-	700
[67]	Dielectric Resonator	Alumina	$29 \times 29 \times 5$	2.29–2.44	-/0.194	800
[68]	Microstrip patch	Sapphire	$10 \times 10 \times 0.05$	-	-	1000
[25]	OEWG	Alumina	$22.86 \times 5.93 \times 1.016$	4.74–5.12	6/0.4	1000
[69]	Slot Antenna	Si_6B_1	$a = 4.47$, $h = 4.50$	8–12	6/0.78	1050
[44]	Microstrip	Alumina (ADS 96R)	$21 \times 21 \times 0.635$	4.58–5.07	-/0.58	1050
[6]	Lens	Quartz	$r = 100$, $h = 72.82$	26.5–40	-	1100
[5]	Patch	PDC-Silicon Ceramic	$r = 5.355$, $h = 0.9$	12–13.8	-	1100
[70]	RFID tag	Alumina	$(r = 14) \times 0.1$	2.32–2.42	-	1100
[48]	Closed ring resonator	Alumina	$Ø = 13$, $h = 0.1$	2.32–2.42	-/0.096	1100
[47]	Microstrip patch	Alumina (ESL 44007-G, USA)	$51 \times 51 \times 0.3$	0.08–0.11	-	1400

relationship between resonant frequency and temperature can be defined. A performance comparison of the high temperature antennas in the last 9 years is shown in Table 3.

6. FUTURE PROSPECTS AND CHALLENGES

The field of high temperature antennas is rapidly evolving with paradigm shift towards new rigid and flexible materials for dielectric substrates along with multiband operation. Advancements in antenna design and improvements in long distance wireless communication will result in new applications. Microstrip antennas operable at high temperature, typically have smaller bandwidths, and work on a single frequency band. It is highly desired for an antenna to have dual bands, triple bands, or an ultrawide band frequency which can cover wider range of applications. In addition, dual testing abilities that can be performed using a single antenna like monitoring temperature and strain or temperature and pressure at the same time are highly desired. The investigation of advanced conductive and dielectric materials can yield new designs and modalities. Recently, various forms of hexagonal Boron Nitride (hBN) have been used for RF-transmitting heating systems suitable for the use with the radomes of drones, unmanned aerial vehicles, aircraft, and spaceships in extremely cold environments [71].

For professional practice in harsh environments such as firefighting, mining, and underwater welding, wearable technologies are necessary to monitor workers' health and safety. Many existing flexible substrates have limitations that include temperature resistivity, fatigue, and their ability to retain conductivity. Other than E-Strate, there are other flexible substrates, such as textiles, paper, and polymeric substrates that include PET (Polyethylene terephthalate) and PEN (Polyethylene naphthalate). Paper is not ideal for wireless sensor applications due to low dielectric permittivity and high loss tangent.

Paper substrate is suible for environments up to 200°C [72, 73]. Further, PEN and PET are only suitable for temperatures up to 270°C. For harsh high temperature environments above 600°C, beside the lack of suitable flexible substrates, signal and power transfer also raise challenges [27]. Signal and power transfer will need to be further investigated along with new flexible substrate materials for extreme environments. Another limitation for flexible substrates is their flexibility (bending) since it can alter the resonant frequency of the antenna.

In addition, the temperature rise can also alter the resonant frequency, which can then affect the performance of the antennas. Investigating new flexible substrates that will allow the conductive material and substrate to expand at a constant rate will be vital for future high temperature applications. Wireless temperature sensing and pressure sensing are two of the most popular applications for high temperature antenna and sensor design [2, 35, 47, 52, 56, 68, 74]. With space exploration, geothermal research, and combustion engines, the investigations into high temperature antennas is on the rise [27].

7. CONCLUSIONS

Antennas are becoming essential components for communication in applications centered around harsh environments. The combination of conductive materials and dielectric materials influences the antenna performance characteristics. In this review, common conductive and dielectric materials adopted for implementing high temperature antennas along with some of their properties are presented. The choice of fabrication technique is a critical factor that dictates antenna performance. Technique such as chemical etching is found most suitable for cladded substrates, screen printing for conductive pastes, and inkjet printing for conductive nanoparticles ink like silver or copper. The need for high temperature antennas operable in harsh environments is emerging in numerous applications such as automobiles, space and aerospace crafts, military, and industry. Comparison of high temperature antenna performances in the last 10 years is highlighted. The future prospects of high temperature antenna is discussed along with the emerging area of flexible substrates for high temperature antenna implementation. The challenges in utilizing the flexible substrates for high temperature antenna is reported.

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