Chapter 3
Advanced Materials for Aerospace Applications

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1 Introduction

The word stealth relates to all the techniques that make it difficult to observe or detect an object. There are multiple ways of identifying objects, such as direct observation using our eyes or by using devices such as radars, sonars, and infrared sensors. In military areas, detection and counter detection methods are vital and particularly applicable as it can make a difference of detecting and planning for an adversary airship 200 km away or watching it destroy one's base. Since the improvement of the radar frameworks, the importance of stealth has reached out from microwave stealth to different parts of the electromagnetic spectrum. There has been a constant battle between the two systems of detection and stealth, where the development in one field immediately elicits a response from the other. The significant developments in detection techniques are related to active devices such as radars, sonars, IR imaging systems, and other such methods. These advancements have had such a high impact that a large number of the cutting-edge fighter aircraft are produced with a radar signature decided beforehand.

The stealth techniques came into the picture only after the detection systems were in full-fledged use. The beginning of advanced detection technologies can be attributed to the invention of the radar. The development can be traced back to 1904 when a German inventor by the name Christian Hulsmeyer patented a device which could detect and measure the distance of metallic objects far away using

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radio waves. After that, many advancements were made to the radar, but the military use was non-existent until the Second World War. The rapid development phase took place before and after the war with most of the participating countries having some or the other form of radar. The working principle of radar is echolocation. It consists of an emitter and a receiver, both usually located next to each other. The emitter sends radio waves in a particular direction, and on encountering an object, these waves are reflected, scattered, or absorbed based on the target material. The waves that are reflected or scattered back in the direction of the emitter are the ones detected by the receiver and enable the calculation of distance and velocity of the object with respect to the radar. The observability of the object depends on its size, shape, material, and the frequency of the radar which can range from 3 MHz to 100 GHz. There is an equivalent version of the radar called sonar which uses sound waves instead of electromagnetic waves to locate objects. The effectiveness of the two varies drastically depending on the medium being air or water; sonars are preferred in water because of the poor transmissivity of radio waves in water. The two techniques suffer limitations due to clutter and interference such as reflections from ground, sea, and rain. There is another method of detection which is termed infrared sensing and can account for most of the aerial combat losses for the USA in the past quarter-century. This technique uses the heat signature of an object to locate it in space and is widely used as a guidance tool for accurately hitting targets with missiles. It is a relatively modern technology as it requires sophisticated electronics for it to be small and light enough to be fitted onto missiles.

There were parallel advancements in stealth to maintain an edge over the previously mentioned detection systems. The primary device that stealth innovations aimed to counter was the radar, the reason being its widespread use and the lack of alternatives. Today, all military equipment takes into account low observability principles, trying to be discreet in all aspects such as reducing acoustic, radar, and infrared emissions, and trying to blend into the surrounding environment. When using the term low observability, one does not mean complete disappearance from the radar screens; rather it means to make objects tough to distinguish from background noise or insignificant sources such as birds and clouds. The two most often employed low observability techniques are modifying the shape and coating of outer surfaces; both are limited by aerodynamic considerations. The last three decades have seen more developments happening in shaping and are extensively used in the design of fighter aircrafts. Current design techniques commonly go for a balance between shaping and other L.O. techniques. After exhausting the possible advances in stealth with the help of shapes, radar absorbing materials (RAM) have come into the spotlight of stealth research. RAM absorbs a part of the received radar energy and converts it to heat, reducing the reflected power. RAM has been at the forefront of radar cross-section (RCS) reduction efforts since the beginning of stealth attempts, the first one being the construction of a German aircraft *Horten Ho-229*, built a little before the end of Second World War. The design included wings of plywood sandwiched around a mixture of glue, sawdust, and granulated charcoal.

A significant breakthrough in stealth came when the aircraft used a thinly curved extension for the nacelles, leading edges, and fuselage. This created a continuously curving airframe with sharp edges and a mostly flat underside that reduced RCS up to 90%. The first stealth aircraft *F-117* employed a fully faceted shape, and RAM was used to deal with cavities and surface waves. Initially, the material came in linoleum-like sheets of a ferrite-loaded polymer. They were bonded to the airframe's skin with change in thicknesses at different locations. The subsequent stealth aircraft, *Northrop Grumman's B-2*, was said to depend more on shape and less on RAM than the *F-117*. As the stealth fighter's fully faceted shape only dealt well with specular reflections, surface-wave suppression needs to be addressed. The "*fibermat*" technology used in the *B-2* aircraft is considered a technological breakthrough. The fibermat would replace many RAM structures by being cured into the composite skin, making it durable [1]. In the twenty-first century, a large amount of research has been done for materials relating to stealth using multi-disciplinary techniques, and the recent challenges and progress are detailed ahead.

2 Challenges in Developing Stealth Materials

It is a common practice in engineering to have multiple disciplines collaborating and leading up to the development of novel technologies. This is mostly applicable in the case of stealth as it requires in-depth knowledge of electromagnetism, aerodynamics, material science, electronics, manufacturing, and numerical simulation. It is a tough task to achieve mastery in all these fields within a lifetime to realize true stealth; there is an added layer of difficulty on considering that the area is continuously evolving. This makes it clear that any significant development in the direction of practically achieving stealth requires collaboration between researchers and engineers in vastly different fields. A good example to understand this would be the development of RAM. The first task is to know what types of radars are used for aircraft detection and how they work. Then one requires a model for understanding the interaction of radio waves with aircraft and how this interaction will affect its observability using radar. This task itself requires knowing electromagnetism and numerical simulation techniques. Next, there is the task of modeling material behavior such as coatings on aircraft, along with experimental verification at each step. The materials also need to be tested for their compatibility with aircraft standards such as thermal stability, mechanical durability, and low mass density. This is a challenging task for implementing principles such as design for manufacturing as the disciplines involved are not simply related.

The multiple ways of detection also pose a challenge for developing an all-encompassing stealth material. Even if one considers a narrow outlook of focusing only on radars, one discovers the numerous frequencies of its operation, demanding the RAM to have a broadband capability. Especially at lower frequency bands, the RCS of a low observable aircraft is expected to increase significantly. This is because the wavelength becomes comparable in size with parts of the plane, and light follows the Mie scattering model. The permittivity and permeability of a material dictate its electromagnetic behavior, and these properties usually vary with frequency and polarization of the electromagnetic wave. This leads to inevitable trade-offs between broadband capability and the radar cross-section reduction (RCSR). There is another incompatibility that arises because of the nature of microwave and infrared stealth. Microwave stealth requires the incident microwaves to be absorbed to fool simple radars, whereas infrared waves need to be dealt with by caging the internal thermal radiation sources and selectively absorbing or reflecting the atmospheric infrared (IR) waves. It is possible for powerful radars to heat the RAM and create hotspots of thermal radiation increasing its IR signature.

Advancements in stealth technologies have always instigated the development of similar anti-stealth technologies, leading to constantly evolving challenges. There have been many reports relating to developments in counter the stealth technologies. Among these, the potential counter-stealth approaches include passive radars, multi-static radars, very low-frequency radars, over-the-horizon radars, and sensitive IR systems. Since stealth aircraft work primarily by deflecting radar signals in directions away from the source, the immediate answer for detecting them is to capture those deflected signals. A multi-static radar system works by using numerous radars all networked together. If a signal sent out by one radar is diverted, then the second radar is in a position to capture it and uses that information to deduce the aircraft's location. The main idea of the multi-static radar is to have one or more receiver antennae in a position to receive the scattered echo. Such multi-static systems have higher reliability, due to the redundancy of the receivers and their passive operation [2].

Another upcoming technology in anti-stealth is the quantum radar. The working principle involves one of the most exciting aspects of quantum physics called entanglement. Entangled pairs of particles are distinguishable from other similar particles, just like a lock and key. A particular key can be identified from a group of related keys by checking it with the corresponding lock. Once the entangled pairs of particles are created, one of them is kept idle with the detectors, and the other one is modulated and sent out by the radar. The brilliance of the system is that when the received signals are being analyzed, one can use the first idle particle to filter out the noise and figure out which wave corresponds to the one originally emitted. This makes it physically impossible to use any kind of signal jamming to spoof or confuse the radar. It also allows for even the weakest signal reflected by the stealth aircraft to be distinguishable from the noise and reveal its location.

3 Sub-domains of Stealth

When one thinks about light, one probably only considers what our eyes can see. In reality, the light to which our eyes are sensitive is just a part of the whole spectrum, similar to the frequencies of sound we cannot hear; there is an entire spectrum of light that human eyes cannot see. This whole range of electromagnetic wave that exists is named as the electromagnetic spectrum. There exist various detection techniques to detect these waves, such as radio receivers used for microwaves, cathode ray

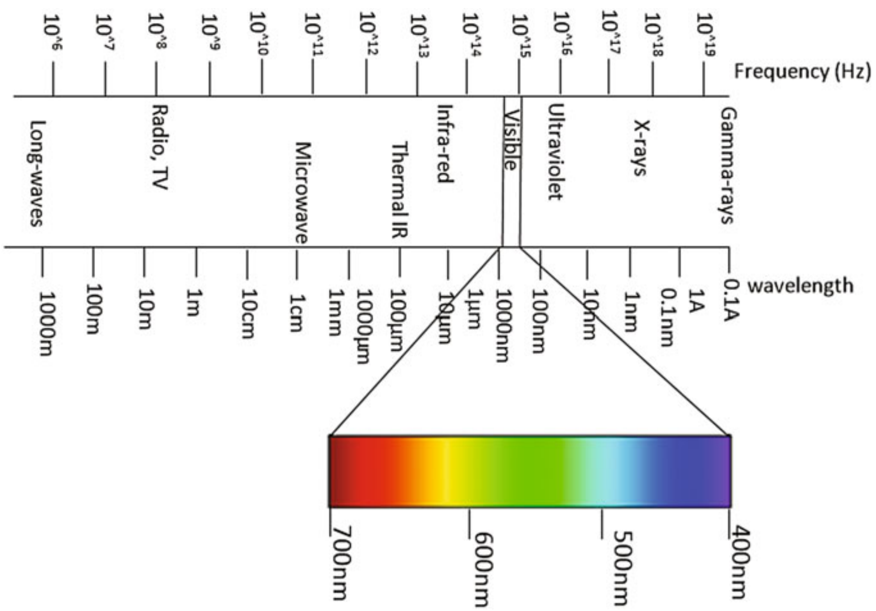

Fig. 1 Electromagnetic spectrum

oscilloscope (CRO), IR sensors, and thermal imaging cameras for infrared waves, and visible light can be detected by light meters and human eyes. The entire range of the electromagnetic spectrum and its detection techniques are described below (Fig. 1 and Table 1).

3.1 Microwave Stealth

Microwave stealth materials

Microwaves are a part of the electromagnetic spectrum most commonly used in radars. The detectability of a target in the microwave region is quantified using the RCS defined as the ratio of backscattered power per steradian to the incident power on the target. RCS depends on the objects shape, size, and material. It also varies with the frequency and direction of the incident waves and the direction in which it is being measured. For example, objects which are electrically large result in scattering including diffraction and specular reflection which enhances its detection by increasing its RCS. In this sub-domain, stealth equates to the reduction of RCS. Radar absorbing material (RAM) is the term used to describe all classes of materials that aim at reducing RCS by absorbing incident microwaves. RAMs generally exhibit selective absorption in the microwave region and often have a peak absorbance at a frequency. There may be a misconception that RAM make objects invisible to radars,

Table 1 Regions of the electromagnetic spectrum with its detection techniques

Type of wave	Example of a detector (sensor)	Approximate wavelength	Typical users
Microwaves	Antenna (aerial), RADAR, crystal detectors, solid-state diodes	1 cm	Communications satellites, telephony, Cooking in microwave cookers In speed cameras
Infrared (IR)	Thermopile, bolometer, black-bulb thermometer, photographic film	0.1 mm	Photography, Burglar alarms, night vision missiles, cooking, heating, in remote controls for TVs and VCD/DVDs
Visible light	Eye, photographic film, electronic components (e.g., LDR) photocell	0.001 mm	Photography, vision (sight), optical fiber, laser beams, weapon aiming systems, CD players, laser surgery

but in reality, they only reduce the RCS at specific frequencies such that they become indistinguishable from the background clutter.

Radar cross-section reduction techniques include shaping, active loading, passive loading, and distributed loading. Shaping aims to counter monostatic radars by avoiding surfaces perpendicular to the incoming waves such that reflected waves do not go in the same direction as the source. Passive and active loadings reduce the scattering from hotspots through the use of resistive sheets or jamming techniques, respectively. In active loading, the object detects the incoming electromagnetic wave and sends an electromagnetic wave with equal magnitude and opposite phase to cancel the incoming EM wave, while in passive loading, the material with a surface resistance is considered to modify the surface impedance of the structure to cancel the scattered signal. Radar absorbing material comes under distributed loading, in which the surface is covered by using RAM material. In this section, an attempt is made to review the RAM with consideration of the materials property required, current developments, and upcoming absorbing materials.

RAM—properties of the material needed

Microwave absorbing materials are a type of functional materials which can dissipate electromagnetic energy by converting it into thermal energy and is found applications in radar absorbers. The concepts behind the design of radar absorber are matched characteristic impedance and matched wave impedance. That is, the characteristic impedance of front face of an absorber should be equal to that of free space and is the criteria for zero reflection. While the matched wave impedance means the input impedance of the front face should be equal to the impedance of free space, it ensures that entire energy is transmitted into the absorber structure. So it is necessary to select the permittivity and permeability of the material to minimize both reflection and transmission through a material simultaneously.

Electromagnetic energy absorption can be increased by adequately choosing the intrinsic characteristics of the material such as permittivity, permeability, and loss tangents. When permittivity, permeability, and loss components increase, EM energy absorption in RAM improves. However, when waves reach a boundary between two mediums, energy can be reflected rather than absorbed. And the amount of reflected energy depends on their impedance and is given regarding materials permeability and permittivity. For perfect matching, the ratio of relative permeability to relative permittivity should be equal to unity. The imaginary parts of permeability and permittivity indicate the losses in the dielectric material. So for minimum transmission value, the imaginary parts of the material properties might be as large as possible. RAM design must have a balance between absorptivity and surface reflectivity to achieve maximum absorption because if an impedance change occurs more energy is reflected rather than absorbed.

RAM constitutes a matrix material and a filler. The matrix material is considered to be a low loss dielectric material with significant permittivity and negligible permeability and is transparent to EM waves. Insulating polymers like plastic, glass, resin, polyurethane, and rubber are most commonly used as the matrix material. The RAM filler is usually particles composed or coated with a lossy material.

Researchers are always in search of new materials to substitute the existing high-density RAM for stealth applications. Conventional absorbers are generally either magnetic or dielectric types. The working principle of magnetic absorbers is based on the magnetic hysteresis effect using magnetic substances such as ferrites. The disadvantages of a magnetic RAM material are its high density and narrow bandwidth. Instead, dielectric materials are lightweight but do not have the absorption capability as good as magnetic RAM. So both these have benefits and downsides when used as absorbers. Both of these can be used as a composite with magnetic material as the bottom one and dielectric material as top one, though the high density of the material remains a significant challenge in RAM designs.

3.1.1 Carbon-based Material

Many materials have been proposed to meet microwave stealth requirements, with carbon-based materials being one of the most promising candidates. Carbon is a suitable material for dielectric absorption because its electric loss is proportional to conductivity and carbon's conductivity lies below metals but above insulators. Carbon-based materials are abundant in nature and are synthesized or retrieved from organic and inorganic compounds. By controlling the parameters such as temperature and pressure during the processing, the physical, mechanical, electrical, and thermal properties of carbon material can be altered. Usually, researchers are in search of highly efficient, thermally conducting, mechanically stable, and lightweight material with high values of dielectric and magnetic losses for RAM application.

Carbon Foam

Carbon foam is a high-performance, sponge-like rigid material in which carbon ligaments are interconnected to each other. The electric conductivity of the material directly depends on its carbonization temperature, enhancement in carbonization temperature increases the conductivity of a material, and conductivity directly influences its absorbing character. As the electric conductivity changes from 0.02 to 1.03 S/m, the foam changes its characteristics from transmitting to reflecting [3]. The best microwave absorption obtained was for the carbon foam with an electric conductivity of 0.46 S/m, with absorption exceeding 7 dB across the measured frequency range of 4–15 GHz [4]. To enhance microwave absorption, the material is heat treated at a lower temperature to make it a dielectric or a material with low electrical conductivity. However, to utilize carbon foam as a RAM in stealth applications, it is also required for it to be thermally stable and conductive for quick dissipation of heat. As it turns out, the carbon foam treated at low temperature does not have sufficient thermal stability or conductivity, and one needs to infuse the foam with other materials such as magnetic or dielectric nanoparticles to match the standards.

Carbon foam was first prepared using heat treatment of thermosetting polymeric materials in a controlled environment. Later, coal tar and petroleum pitches were used for production. Carbon foam obtained from the above technique gives low thermal conductivity and is primarily considered as a thermally insulating material. High electrical and thermal conductivity can be achieved in crystalline carbon foam by using meso-phase pitch with high-temperature and high-pressure foaming techniques.

Carbon Fiber

Carbon fibers are fibers of carbon atoms about 5–10 μm in diameter. Carbon fibers are widely used in civil and military applications because of its high tensile strength, high stiffness, low weight, high chemical resistance, high heat tolerance, and small thermal expansion. While comparing similar fibers, such as glass fibers or plastic fibers, with carbon fiber it has superior tensile strength but comes with a high price.

Carbon fibers as such are not used in any of the applications. Usually, it is used as a composite by combining the fiber with other materials. The most commonly used carbon fiber composite is a carbon-fiber-reinforced polymer (CFRP), which is obtained by infusing the fiber with a plastic resin. This is often called as the carbon fiber, exceptionally rigid material with a very high strength-to-weight ratio. CFRP consists of two parts: a matrix and a reinforcement. The matrix is used to keep the reinforcement together, whereas the reinforcement should be a high strength material. In CFRP, carbon fiber acts as the reinforcement and a polymer resin, such as epoxy, is used as the matrix which is mixed with a hardening agent to form a solid. Carbon fibers are also used as composites of graphite to former in forced carbon–carbon composites with superior heat tolerance. Untreated carbon fiber is a strong radar reflector, and it is a specially treated carbon fiber that absorbs microwaves. Thus carbon fiber processing methods improve its electromagnetic parameters.

Carbon fiber (CF)/FeCoNi composites, another type of carbon fiber composite, are composed of carbon fibers and magnetic material, like Fe_3O_4, $NiFe_2O_4$, $CoFe_2O_4$, and Ni_3Fe. The magnetic particles in these composites are spread equivalently along the axial direction of the material and electromagnetic waves undertake numerous reflections in the fiber. CF/FeCoNi composites exhibit also excellent performances by uniting the properties of carbon fiber and magnetic loss materials [5]. These composite materials can also be used as lightweight and high-performance radar absorbing materials, by adjusting their treatment parameters such as temperature and time.

The most recently introduced carbon fiber-based composite is the frequency-selective fabric composite (FSFC), which is fabricated by weaving carbon fibers and dielectric fibers in periodic patterns. This is similar to the frequency selective surface (FSS), where carbon fibers correspond to metal parts due to its high electrical conductivity, and reflects the incident waves, and glass fibers with low permittivity, corresponding to aperture parts, transmit most of the incident waves. Therefore, FSFC is used as an inductive frequency selective surface (FSS) and is a promising candidate for radar absorbing structure (RAS). Carbon fiber production is done mainly using two components: (i) poly acrylonitrile (PAN) and (ii) pitch.

Carbon Nanotubes (CNT)

Nanostructured materials have been broadly researched for radar absorbing properties. The carbon nanotube is used as a conductive element in RAM design due to its material characteristics. CNTs have a pipe-like structures with walls made of carbon atoms linked neatly together. The carbon nanotube is 1 nm in diameter. When compared with carbon fiber it is 2000 times smaller than a carbon fiber filament. There is a significant difference between carbon nanotubes and carbon fiber based on its crystal structure and physical properties. The carbon nanotube's superior atomically bonded crystal structure is what makes it the strongest and stiffest material, nearly 20 times stronger than carbon fiber. CNT displays high mechanical resistance, low-density, and excellent electrical and thermal properties. Studies have demonstrated that CNTs can exhibit good microwave absorption when integrated with polymeric matrices and in multi-layer structures. The aforementioned properties of CNT make it a suitable candidate, both in the microwave and infrared stealth technologies.

The method of production greatly defines the properties of CNT, such as diameter, length, density, and purity. Recent studies show that a higher amount of absorption is observed when CNT with fewer nanotubes and the increased length is considered. Composite is made up of CNT, and polymeric structure presents a RAM with enhanced absorption characteristic. George et al. proposed a nanostructured composite made of small portions of multi-walled CNT (0.086 wt%) in natural rubber. The interconnected network in nanostructured composite gives rise to a high value of

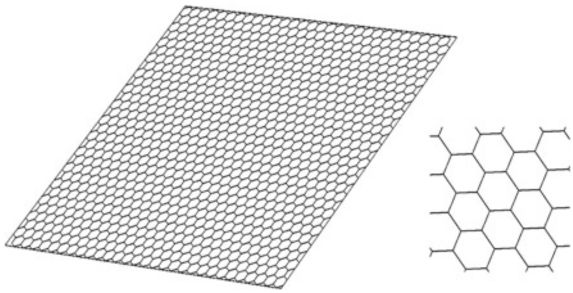

Fig. 2 Illustration of graphene

electrical conductivity and dielectric constant with improved mechanical properties such as elastic modulus and tensile strength [6].

Currently, the CNT coating on an airplane is not feasible due to the limitations in the fabrication processes. One hypothesis to overcome these restrictions is to cover small particles with the nanotubes and suspend them in a medium, for example, paint, which would then be applied to the aircraft.

Graphene

Graphene (G) is a trending material of vast research interest for a wide variety of applications in the field of engineering, especially at microwave and terahertz frequencies. It is a 2D layer of graphite with hexagonal geometry (Fig. 2). It was first observed through an electron microscope in 1962 and was studied only on metal surfaces. It was later rediscovered by Andre Geim and Konstantin Novoselov at the University of Manchester in 2004 [7]. Graphene is a semi-metal which comes under the category of zero bandgap materials; these materials have a small overlap between its valence and conduction band. Graphene possesses some attractive features, such as low density, large specific surface area, high chemical stability, tunable surface conductivity, and outstanding electronic properties.

Developing a composite with distinct morphologies like the ferrite graphene (FG) which consists of magnetic- and carbon-based elements will contribute a lot to the research of RAM. Disperse graphene into magnetic materials like ferrite to introduce free charge carriers in graphene and to improve its absorption effect. Research with a focus on the particle size, shape, concentration, temperature, and so on is going on to improve absorption properties of graphene and its composite materials. The interfacial electronic interactions between ferrite and graphene will lead to a phenomenon of charge transfer, and it alters the electronic properties of graphene. This results in the formation of ferrite graphene heterogeneous nanocomposites with some novel EM properties [8]. Composites with graphene show a significant reduction in weight as well as thickness and hence suitable for high-speed aircraft. The composition and structural integrity of the absorbers are also of great concern. It is necessary to choose the optimal weight fraction of ferrite and graphene and adjust the dielectric, magnetic, and EM wave properties of the composite to obtain the required absorbing properties. Multi-layering and frequency selective surfaces (FSS) along with proper material selection can play a vital role in the field of research for thin and broadband EM wave absorbers. The radar absorption property of the ferrite graphene-based composites strongly depends on the internal structure, morphology, and its composition [9].

Graphene and graphene-based hybrids are extensively studied over the years while considering its superior electromagnetic absorption and shielding properties. Examples for graphene-based hybrids are G/CNTs, G foams, G/ZnO, and G/magnetic nanoparticle composites [10].

3.1.2 Ferrite-Based RAM

First, RAM that was employed is the iron ball paint consists of carbonyl iron or ferrite. In iron ball paint the alternating magnetic field in the incident electromagnetic wave produces magnetic oscillations, and it leads to conversion of electromagnetic energy into heat and is dissipated.

Ferrite is a metal oxide which comes in the category of a magnetic material, which contains magnetic ions arranged in such a manner that it produces spontaneous magnetization while maintaining good dielectric properties. Ferrites are extensively used for microwave absorption as they use inexpensive raw materials and have simple fabrication methods. Absorbers based on these ferrites are now commercially available under the trade name Eccosorb and are operable at frequencies below 1 GHz. Such absorbers in practice are, however, heavy and brittle and are usually 6–8 mm in thickness.

Among the variants, spinel ferrites are gaining momentum because of their magnetic properties and high electrical resistivity for the broad frequency range. Nickel ferrite ($NiFe_2O_4$) has the highest absorptivity among spinel ferrites leading to its applications as RAM. Spinel ferrites such as nickel–zinc ferrites have also been used as absorber materials [11].

More recently, hexagonal ferrites have entered the scene as they allow better absorption at higher frequencies (X-band) with thinner layers. Absorption mechanism in hexagonal-type ferrite is characterized by its lossy interaction of the magnetic field of the wave with their distinct magnetization. The hexagonal-type ferrite materials exhibit a significant value of permeability (>1), the high value of magnetization, and planar anisotropic behavior in microwave frequencies. Several types of hexagonal ferrites are reported with complex crystal and magnetic structures. The magnetic ions can be replaced by substituting divalent ion and the magnetization increases with increasing amount of non-magnetic substitution [12]. Mostly reported hexaferrites RAM are based on barium. Barium hexaferrite possesses great magnetic properties due to its slightly altered crystal structure and the presence of large barium ions. Through external doping of divalent ions (Zn, Co, Ni, etc.) [13], the magnetization and the anisotropy of barium hexagonal ferrite can be further boosted.

The thickness of the absorber is an imperative criterion in stealth applications, especially for aircraft where weight considerations are very important. Therefore, maximum absorption with the minimum thickness of absorber is desirable. Absorbers capable of responding to a wide frequency bandwidth of radar signals are required. Large bandwidths are easily achieved by stacking some absorber layers of varying thickness. This increase in bandwidth also increases the absorber thickness. Single-layer absorbers would be more useful in applications where weight is a major consideration.

3.1.3 Silicon Carbide (SiC)

Vast research is going on in the field of carbon and conducting polymer-based absorbers for the last few years. Unfortunately, carbon materials have difficulty in attaining impedance matching because of their significant permittivity and negligible permeability. However, individual conductive polymer materials lack a broad absorption bandwidth. Also, under extreme temperature and stringent working environments, the thermal and chemical resistance of carbon materials and conductive polymer materials is unacceptable, and it restricts their application in the aerospace domain. Nevertheless, SiC stands out for its exceptional properties regarding EM wave absorption and high-temperature stability.

SiC, a semiconductor, consists of silicon and carbon used only as structural ceramic for a long time, and also have high microwave absorption capability. SiC is a high strength and hardness materials. Along with its absorption ability, it possesses good corrosion resistance and excellent dielectric property. Because of its high thermal stability and thermal conductivity properties, it is commonly used in high-temperature environments. Hence for the electromagnetic wave absorption, SiC can be considered as a promising absorber candidate with relatively large bandwidth [14].

Different type of SiC structure is available; it can be zero dimensional (e.g., nanocrystals or particles), 1D (e.g., wires, tubes, and whiskers), 2D (e.g., flakes, platelets), and 3D (e.g., more complex structures). Excellent chemical and thermal properties are achieved in SiC because of its strong covalent bond between Si and C atoms. Si/C atom is surrounded by four C/Si atom to form a tetrahedral sp^3 hybridized bonds. Single intrinsic electric dipolar polarization in SiC reduces the dielectric loss of this material which in turn reduces the electrical conductivity; hence the possibility for its broader applications is limited. This can be overcome by altering the phase, or structural features of SiC to improve its polarization and multi-reflection of the incident EM waves [15].

Modified SiC is used extensively in the design of radar absorbing material and they are SiC modified with carbon-based materials such as CNT, carbon black, and graphene, or with polymeric materials such as PANI, PVDF, or with inorganic materials such as Si_3N_4, SiO_2, or with metal such as Fe, Co, Ni, or their oxides [14, 16].

3.1.4 MXenes

MXenes are a class of attractive compounds which came into the picture in 2011. Material science describes MXenes as a class of two-dimensional inorganic compounds with few atom-thick layers of transition metal carbides, nitrides, or carbonitrides. MXenes are hydrophilic because of their hydroxyl or oxygen-terminated surfaces. MXenes combine its hydrophilic nature and metallic conductivity of transition metal carbides. MXenes are synthesized by etching a layer from MAX phases, and the name “MXenes,” MX came from the MAX phases, and “ene” is added to show the similarities of MXene with graphene. MAX phases are a large family (60+ members) of layered hexagonal structure with a composition of $M^{n+1}AX^{n}$, where M stands for an early transition metal (such as Ti, V, Cr, Nb, etc.), A stands for a group A element (such as Al, Si, Sn, In, etc.), X stands for carbon or nitrogen, and $n = 1$, 2, or 3 [17].

Major attractive applications of MXenes are lithium-ion and sodium-ion energy storage systems, electromagnetic interference (EMI) shielding, and RAM. MXenes are extremely important in electromagnetic field due to their good flexibility, easy processing, and great conductivity with minimal thickness.

Since the discovery of Ti_3C_2 MXenes, it has attracted tremendous attention in the field of fuel cells, lithium-ion batteries, and supercapacitors. In the ordered Ti_3C_2MXene, $(n + 1)$ layers of Ti cover n layers of C. Single or double layers of tip are sandwiched between the layers of a second Ti. EM absorbing materials should have increased polarizations and moderate conductivity for achieving the dielectric loss and impedance match. One can improve the dipole polarization by introducing an intrinsic defect in the structure by using a surface functional group and will result in decreased electrical conductivity. Two-dimensional Ti_3C_2Tx MXenes are extensively studied for its absorption characteristics; an enhanced absorption characteristic is present in this material because of the presence of chemically active surfaces combined with the native defects and its metallic character [18].

3.1.5 Metamaterials

Metamaterials are materials displaying definite properties that are not available in naturally occurring materials, the most important one being the capability to exhibit a negative refractive index. Metamaterial was proposed by Rodger M. Walser of the University of Texas. The name metamaterial comes from the word “meta,” which in Greek means beyond, so metamaterial means beyond the material. Even though metamaterials are fairly new, Victor Vesel ago predicted the presence of doubly negative materials in 1968. Doubly negative materials are also known as left-handed materials (LHM). Metamaterials are not naturally occurring material with a negative value of permeability, permittivity, and negative refractive index. Metamaterial structure is fabricated by etching the metallic patterns on a dielectric substrate. Some patterns can be fabricated; such as electric ring resonators with wires, graphene-based films, stacked rings, a combination of FSS, and I-shaped rods.

Electromagnetic absorption characteristics of metamaterial-based RAM depend on its distinct material properties, geometry, and dimensions of the metallic patch and thickness of the substrate. If the cell size is equal to a quarter of a wavelength, then it is called effective-homogeneity limit where refraction dominates scattering/diffraction when the wave propagates through a metamaterial.

Generally, metamaterials are categorized into resonant and non-resonant metamaterials. The material properties such as permeability and permittivity possess a dynamic range adjacent to the resonant frequency, then it is known as a resonant metamaterial. The plot of permittivity versus frequency and permeability versus frequency is seen to follow a Drude–Lorentz relationship as it displays a particular response. The major disadvantage of this kind of metamaterial structure is the narrow bandwidth as well as high loss in the resonant frequency region. Therefore, observing the material parameters, such as ε and μ provides insight into the performance of a metamaterial. But obtaining these material parameters is quite challenging.

Some literature is already available regarding the broadband radar absorbers. Wakatsuchi et al. [19] presented a lossy cut wire pair broadband metamaterial absorber for arbitrary polarization. A periodic unit of lossy cut wire pair with altered lengths is combined and placed adjacent to PEC. The paired cut wire works for both polarizations by exhibiting both electric resonance and magnetic resonance with an absorption peak of 0.76 at 27 GHz [19]. In 2011, Grant et al. presented broadband metamaterial absorber with a stacked metal-insulator layers of different structural parameters in terahertz frequency. The absorption of the structure improved more than 60% with a bandwidth of 1.86 THz [20].

Liu et al. [21] proposed a broadband metamaterial absorber with high absorption capabilities. The proposed structure consists of three layers; the first layer being the ground plane and a dielectric spacer is placed as the second layer and circular metallic patches are etched on the top layer. Broadband resonance characteristics are achieved with the multi-band resonance of each metallic patch, and bandwidth of 2.8 GHz is achieved [21]. Yuan et al. [22] designed and experimentally validated lumped element broadband metamaterial absorber. The designed composite metamaterial behaves as polarization and angle of incidence independent absorber with an improved absorption characteristic in the frequency band of 2.85–5.31 GHz with a relative bandwidth of 60.3% [22].

3.1.6 Conducting Polymer

Conducting polymers are one of the new additions in RAM. They are organic polymers that conduct electricity and such composites may have metallic conductivity or can be semiconductors. Polymer works as a small bandgap semiconductor because of its conjugated π-system. The main drawback of conventional metallic materials, such as copper, steel, and metallic powders is that their conductivity cannot be controlled. Here comes the new conducting material, that is, conducting polymer in which their conductivity can be controlled during its processing phase. The intrinsic conducting polymers with a wide range of electric conductivity can be used as an

EM wave absorbing the material. Along with its ability to control the electrical conductivity, it also has control over its coating thickness, and is transparent, and has a simple and effective surface coating [23].

The thickness and complex permittivity of the material defines the reflection loss of material. Controllability over the electrical conductivity and coating thickness makes conducting polymer a suitable dielectric loss component for RAM. Phonon-assisted hopping between the randomly distributed localized states contributes to the conductivity of a conducting polymer. Conductivity is achieved in a polymer such as polypyrrole (PPy) by the partial oxidation of the polymer (doping), and during the process polarons and bipolarons are formed as the charge carriers along the chains [24, 25].

Polypyrrole–Polymer Composites

Polypyrrole shows high electrical conductivity along with environmental stability and ease of production. However, its practical applications in the aerospace domain are limited due to its mechanical properties, such as high brittleness and low processability. Incorporating PPy within an electrically insulating polymer overcomes the poor mechanical properties and has opened a new door toward the development of conducting polymer composites. Hence most of the useful materials are composites of polypyrrole and other materials such as latex, fibers, or polymer blends. At frequencies above 1 GHz, because of the hopping mechanism of charge transport in the conducting polymer, the conductivity is dominated by the AC conductivity and is dependent on the frequency. Conductivity in the composite does not depend on the material concentration, making it an intrinsic characteristic of the material. Though, processing has a great effect on its material properties such as permittivity, conductivity, and reflectivity. A resonant Dallenbach layer can be easily made from a melt injected polypyrrole/PVC composite, but making a tuned absorber from a compressed sheet of polypyrrole/PVC composite is a difficult task [25].

Polypyrrole Fabric Composites

Polymerizing pyrrole in the presence of fabric or fibers gives rise to different materials which are of interest in the engineering field. By changing the chemical proposition and deposition time, the electrical conductivity of the composite can be tailored. The use of polypyrrole-coated fabrics enables the formation of structural RAM. The properties of the fabric-coated materials were modeled and made used in Salisbury screens and Jaumann layers. By varying its conductivity, it can be used in a wide variety of applications [25].

Polyaniline (PANI)

Polyaniline (PANI) comes under the family of conducting polymers with a 1000 repeat units of polymers and was first reported in 1862. Among conducting polymers, it got attention due to its superior electrical conductivity. Controllability over its electromagnetic parameters and coating thickness improves its EM absorption over a broader bandwidth. Hence it can act as an ideal candidate for radar absorbing material. Polyanilines are produced by oxidative chemical polymerization with three different oxidation states, namely the completely reduced leucoemeraldine base, the completely oxidized pernigraniline base, and the emeraldine base. Different types of polyaniline structure can be produced such as bulk powder, cast films, or fibers and it can also be used in conjunction with glass fiber textiles and PET textiles. Apart from its capabilities, feasibility of low-cost and large-scale production makes it a suitable replacement for a RAM [25].

3.1.7 Hexagonal-BCN (h-BCN)

Graphene discovery has accelerated the research and development of numerous 2D materials, and among them, more studies have been carried out for hexagonal boron nitride (h-BN). h-BN is also having honeycomb structure and contains boron and nitrogen atoms in equal number which are bonded by sp^2 hybridization. Although h-BN and graphene have similar atomic structure, bond strength, and physical properties, h-BN is an insulator due to its wide bandgap of 5.971 eV. Further research has been conducted to identify other possible hexagonal structures similar to graphene and h-BN, and scientists have successfully synthesized structures like graphitic carbon nitride g-$C_3N_{44}C_3N$ and hexagonal graphitic BCN (h-BCN). Properties of these structures are inclined to graphene; for example, h-BCN is more conductive compared to h-BN with a bandgap of 1.5 eV which is greater than gapless graphene and less than insulating h-BN.

Since hexagonal BCN (h-BCN) has exceptional thermal stabilities, chemical stabilities, and adjustable dielectric property, it falls under the promising class of EM wave absorption materials. B and N dopants in h-BCN enhance the lattice polarization and by controlling the N dopant lowest reflection loss can also be achieved, resulting in a highly efficient frequency tunable radar absorber. The mostly used magnetic and dielectric absorbers fail at high temperature, especially above 850 °C. SiC nanomaterials are proposed at high temperature due to its high temperature stability and excellent electromagnetic wave absorption, but its non-tunable complex permittivity and relatively high absorption frequency (in higher GHz) moderates its use in microwave region. In this case h-BCN can replace all these materials due to its extraordinary thermal stability and strong polarization. Also, by adjusting their chemical composition and changing the complex permittivity through the adjustment of B:N:C atom ratio in the hexagonal lattice, we can easily control the dielectric properties of h-BCN materials [26].

Mass production of h-BCN is still a challenging task because matching the theoretical requirement of high thermal stability and low density requires a lot of effort. Precursor pyrolysis, laser ablation hot-filament chemical vapor deposition (CVD), laser vaporization process, aerosol-assisted CVD, and arc discharge using different B, C, and N sources are some of the methods to produce different BCN architectures [27].

3.2 *Infrared Stealth*

Every object above zero Kelvin radiates energy in the form of electromagnetic waves; these waves are precisely what one needs to look to reveal an object. The important detail to be noted here is that the radiation is distributed non-uniformly across the spectrum, having the maximum intensity within a small band. Detection is effective only when probing for the particular frequency at which radiation has the maximum intensity. For thermal radiation it lies in the band ranging from 1 to 20 μm. This infrared signature is tracked to guide heat-seeking missiles. The countermeasures would require eliminating the thermal signature by either reducing the temperature or by using specialized coatings with low IR emissivity. In a broad sense, stealth requires removing any form of signature going into the surroundings, and on considering the various detection techniques, the most effective and prominent would be radar, sonar, and IR sensing. Microwave stealth is being investigated with the help of RAM and cloaking techniques. This leaves acoustic and thermal signatures as the remaining detection criteria, among which infrared invisibility is more prominent as most of the military detection techniques use IR to locate and identify features of their targets.

The multiple aspects of infrared stealth include absorbing IR waves, reducing IR emissivity, and reducing surface temperature. The infrared band ranges from visible to microwave, but while developing stealth technology one has to narrow it down by taking a few key factors into account. The atmospheric window is the most important factor one has to consider when working on infrared stealth technology. The atmosphere has a composition of materials which ascribe it to its absorption characteristics. Based on this, the infrared sensors should be aiming for the high transmittance regions lying between 3–5 and 8–14 μm. Next, one has to look at are the sources of infrared radiation and find the overlap of bands in the atmospheric window, because any radiation other than this would be absorbed within the atmosphere. The internal sources of IR in an aircraft are mainly the engine, heat exterior surfaces, and the exhaust. Among these sources, the IR signature from the exhaust gases is such that it cannot be mitigated by using any sort of coatings but by using alternative strategies such as mixing cool air with the hot exhaust to reduce the temperature. The ones that has to be considered for coating-related stealth would be the former two. These can also be tackled individually as the different directions of viewing give access to different sources of IR; for example, the rear view will primarily expose the engine parts, and hence its particular IR signature must be considered whereas the signature for other viewing directions would be based on the hot outer surfaces [28].

After this, one can consider the reflection of IR waves that originate from outside the aircraft, which are namely the earthshine, the sky shine, and the sunshine. These sources each have a different distribution with some having peaks in the 3–5 μm range and some intermediately within the 8–14 μm range. These details can be used to make coatings for daytime aircraft specialized in reducing sunshine IR reflectance and the night-time aircraft aiming to reduce the earthshine reflectance. They can also be selectively applied to reduce costs such as the sunshine coating being applied only on the top surfaces of the aircraft and the earthshine coating on the under side [29].

There are some theoretical considerations one can take to narrow down the material choices being investigated for infrared stealth. These can vary from material to material as the mechanism responsible for achieving IR stealth may differ in each case. The following sections list out the materials which have been investigated for their IR stealth properties along with their working mechanisms and performance characteristics.

3.2.1 Carbon Nanotubes (CNTs)

Carbon allotropes have been shown to exhibit some of the most extraordinary properties among materials, and CNTs are no exception to this trend. CNTs exhibit properties such as the strongest and stiffest material, thermal stability up to 750 °C, high thermal conductivity and electrical conductivity tunable from metallic to semiconductor-like. The above-listed properties make this material suitable for a wide range of applications ranging from lightweight fibers for aircraft to tips of atomic force microscopes. There is potential in the material as a stealth coating, given its stability regarding temperature as well as mechanical strength, qualities that are essential in the aerospace domain. The performance of CNTs as a RAM has already been noted [3] and can be explained by considering the proportional dependence of absorption coefficient and electrical conductivity. The problem with RAMs is that they convert the incoming EM waves into heat and on taking into account the natural heating of the aircraft body due to the engine and air friction, the IR signature becomes significant. This is where the excellent thermal conductivity of CNT helps as it can conductively transfer the internal heat to the outside air, thereby reducing the temperature of the material. The thermal conductivity of CNTs is different from normal materials as they exhibit ballistic conduction. It is the process of conduction where the mean free path of carriers is higher than the dimensions of the object, and hence resistance is provided only by colliding with the walls of the object. This leads to CNTs having very high thermal conductivity along the axial direction; this can be ten times as that of copper. The thermal conductivity is thus tunable owing to its ballistic conduction giving different conductivities for different lengths and diameters of the CNT [30]. CNTs also have the option of displaying different properties based on the type of doping and alignment of the nanotubes with respect to the polarization plane. The primary challenge with obtaining the thermal conductivity is to have an axially parallel distribution of nanotubes in the matrix and to avoid aggregation. The surface energy of CNTs being high makes it difficult to disperse them in a matrix, which can be solved partially by functionalizing them at the cost of decreasing the conductivity. There is an alternative approach to obtain infrared stealth using CNTs and perhaps a more widely used one which is to decrease the emissivity of the surface in the infrared band. This differs from the previous method where decreasing the surface temperature was the contributing factor for stealth. The lower emissivity-based CNT infrared stealth coating uses silver nanoparticles to increase the sheet conductivity and thereby decrease the emissivity.

3.2.2 Photonic Crystals

Photonic crystals (PC) are materials which act as selective filters to light waves, meaning that certain bands of light are not allowed to propagate within the crystal (Fig. 3). They rely on the periodic change in the dielectric material within the crystal causing light to reflect and refract at each boundary. When the reflected light waves of a particular wavelength reinforce each other from multiple layers, they form a standing wave with the incoming wave and lead to destructive interference and prevent further propagation of the wave. The other wavelengths have reflections out of phase and do not reinforce each other, resulting in less attenuation of the wave. This is very similar to the electronic bandgap observed in semiconductors. The alternating dielectrics cause the destructive interference of certain bands of wavelengths and leave the remaining wavelengths largely unhindered with low attenuation. The photonic bandgap can be controlled by various parameters such as the periodicity of the dielectrics, the diameter of holes, the thickness of individual layers, and the doping. The selective nature of photonic crystals allows them to have low emissivity in the atmospheric windows and high emissivity in the non-atmospheric windows. There have been investigations into photonic materials which would give the infrared emissivity needed for stealth applications and the recent developments in that direction have been discussed ahead. The first photonic crystal used for its thermal emission characteristics was the 3D PC made up of tungsten, which had a very detailed structure posing manufacturing challenges. Later a simple 1D PC was investigated which was primarily a metallodielectric material with either silver or tungsten as the metal

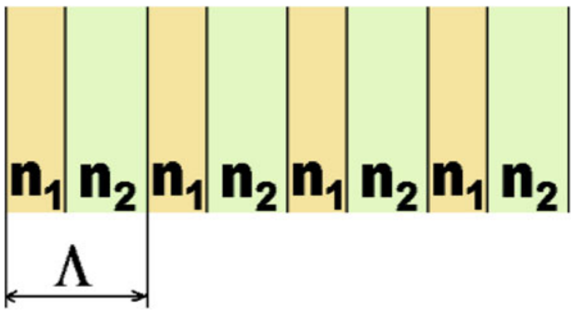

Fig. 3 Schematic of a simple 1D photonic crystal

and it was found to have an emissivity as low as 0.05 for a 10 nm film. These materials were being optimized for their low IR emissivity such that they could be applied in incandescent bulbs with low energy losses. This later expanded the search for similar materials which could be applied in stealth as well because of the similar requirement. One of the PCs investigated has the combination of Ge and ZnS as the two dielectrics. This composition has emissivities as low as 0.05 in the 3–5 μm range and 0.2 in the 8–14 μm range, while showing a good emissivity of 0.6 in the intermediate range. This is exactly the kind of emission characteristics required for stealth coatings as it allows radiative cooling while achieving IR stealth. This PC was prepared by using an optical coating machine where the Ge and ZnS layers were deposited one by one on a quartz substrate. The individual layer thicknesses were optimized to get the best absorption characteristics. In addition to this, there is the option of doping the crystal to obtain holes or valleys for further modification of the emissivity distribution [31].

3.2.3 Cerium(IV) Oxide Co-doped with Calcium and Yttrium

It is possible to relate the electrical conductivity of a material to its emissivity. This predicts that higher conductivity should lead to lower emissivity. This correlation was used to identify materials which can exhibit low infrared emissivities at high temperatures. The general nature of materials is that the conductivity decreases with temperature because there are more collisions. Semiconductors behave differently as they have a different mechanism which allows their conductivity to increase with temperature. One such semiconductor which was investigated for its high-temperature infrared properties is cerium oxide. When doped with lower valency materials oxygen vacancies are created which enhance the electric conductivity significantly. Cerium (IV) oxide was co-doped with calcium (Ca) and yttrium (Y) with varying degrees of concentration. The composites were measured for their electrical conductivities and their infrared emissivities. As objects reach higher temperatures, their emission spectrum peaks at shorter wavelengths and thus the 3–5 μm band is considered for performance measurements of the infrared stealth material. As predicted the particular composition which possessed the highest conductivity also exhibited the least emissivity of 0.241 at 600 °C. The oxygen vacancies which contribute to the high conductivity would benefit more from the Ca doping than the Y doping because of the higher difference in valency, yet co-doping is emphasized to counteract the unintended disadvantages. The perfect balance of the individual components was achieved for $Ce_{0.8}Y_{0.15}Ca_{0.05}O_{2-\delta}$ [32]. The higher yttrium content seems to contradict the valency-based prediction of higher vacancies with higher Ca content. The number of oxygen vacancies is not the only factor affecting the conductivity, considering the transport channel can explain this result. Lattice distortion inhibits the electron transport channels and decreases the conductivity; it is greater with Ca than Y because of the higher difference in size of the ions compared to the cerium ion. The composite is synthesized using a chemical process termed oxalate co-precipitation followed by dry heating the precipitate powder at a high temperature. This material can especially be used for the hot engine components and the exhaust nozzle area because of the high temperatures they maintain during flight.

3.2.4 Silver (Ag) and Germanium (Ge) Multi-layer Film

The goal for achieving infrared stealth is clear by now; it is to get low emissivities in the atmospheric windows and high emissivities in the non-atmospheric window for radiative cooling. These selective emission properties are attained by a thin multi-layer composite film made up of Ag and Ge. The multi-layer film contains four layers of alternating materials starting with a base Ag layer, next to a Ge layer, followed by an ultrathin Ag layer and a Ge layer on top. The ultrathin Ag layer is responsible for the high emissivity observed, but the layer on its own has a much broader bandwidth for the high emissivity and hence dielectric spacers are added above and below it. They utilize the impedance matching principle, according to this, on matching the wavelength-dependent impedance of a medium to the surrounding medium; in this case, air, by making the imaginary part zero and the real part close to one. The EM waves pass straight into the material and are not reflected [33]. The wavelength dependence of impedance allows for the manipulation of the bands that are allowed. The thicknesses of the dielectric Ge layers are optimized to give maximum transmittance in the 5–8 μm region to facilitate the radiative cooling from the ultrathin Ag layer and also to provide the particular nature by having low values for emissivity in the 3–5 and 8–14 μm bands [33]. The thermal performance measurements show lower temperatures for the coated substrates when compared to the uncoated substrate given equal heating rates. It is made using the thin film deposition process where the material is deposited on a substrate using chemical or physical processes to obtain properties such as corrosion resistance, and thermal resistivity. The process has widespread use in aerospace industry to make coatings that increase durability against atmospheric threats. The physical vapor deposition process used to fabricate the coating is the electron beam evaporation method, which as the name suggests, uses an electron beam to convert the metal atoms into a gas. This forms a thin coating over surfaces in the deposition chamber within its line of sight. There is potential for scalability due to the simplistic nature of the coating and the fabrication process compared to other materials in this field such as CNTs, PCs, and metasurfaces.

3.2.5 Metamaterial Absorber

Metamaterials find their application in infrared stealth as they did with microwaves. There have been multiple investigations of the metal–insulator–metal (MIM) type structures, with the metal layer having various geometries, like square patches, split ring resonators, and so on (Fig. 4). The flexibility of the properties attainable from metamaterials is what places them across the whole range of applications in electromagnetics. Among the combinations studied, one of them used silver as the metal

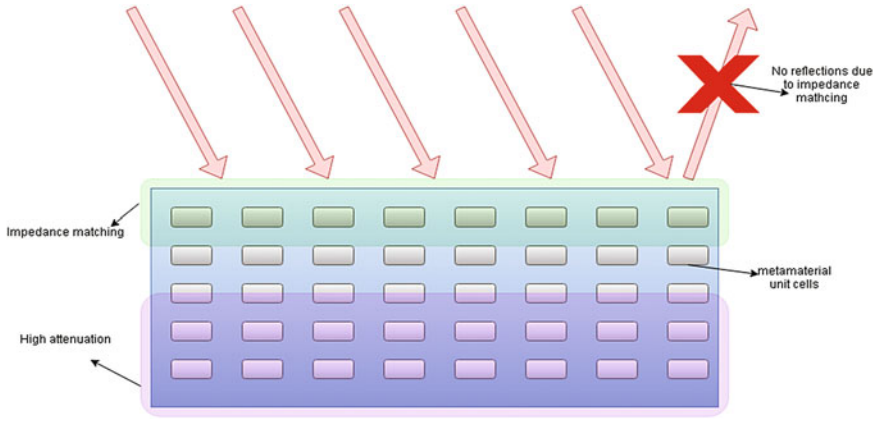

Fig. 4 Schematic of a metamaterial absorber

and polyimide, MgF_2 as the dielectric spacers with a total thickness less than 0.4 µm. This yielded an emissivity distribution having three peaks, all of them in the non-atmospheric windows and very low values in the middle and far atmospheric windows. The metallic pattern used was a simple square patch whose length was modified in each layer to obtain the best result. The intermediate peaks can be explained by magnetic resonances and coupling effects between the metal patches. The layer thickness and the square patch size were optimized using simulations and later experimentally verified. The absorber performs well for temperatures reaching up to 1000 K, making it suitable for the very hot surfaces of aircraft [34].

3.2.6 Aluminum Powder Embedded Resins

It is of utmost importance that both microwave and infrared stealth be achieved in a compatible manner. One of the approaches in this direction is to have the same material exhibit both the properties of high microwave absorptivity and low infrared emissivity. The other approach is to apply the coatings on top of each. The use of resins embedded with aluminum powder is one such example of IR stealth coatings that could be applied on top of RAM surface to achieve dual stealth. In this type of coating, the floating rate is an important factor affecting the emissivity. Given the same content, lower floating rate leads to higher porosity in the substrate which in turn increases absorptivity and emissivity of the material. The opposite is true for the high floating rate variants of the composite which have most of the metal particles aggregated on the surface, leading to low absorbance and thereby lower emissivity. Apart from this, the resin material also plays a role in deciding the emissivity of coating. It does not relate to the emissivity in an obvious manner, a resin with higher absorptivity can lead to lower emissivity when embedded with aluminum powder. This is related to the distribution of the metal powder inside the matrix which shows a uniform distribution of the particles in the resin with higher absorptivity. The IR emissivity of the polyurethane resin with 90% floating rate and 30% weight content was 0.2, lower than the coatings with lower absorptivity resins. This makes it clear that while selecting materials for the coating the individual components cannot be evaluated in isolation, and the combined performance needs to be considered. These coatings were tested for compatibility with metamaterial-based radar absorbers. The result was that the low IR emissivity is obtained without changing the radar stealth property, that is, the microwave absorptivity [35].

3.2.7 Metal-dielectric Nanostructures

Metal dielectric nanostructure uses a combination of metallic nanowires and nanoparticles to act as scattering and absorbing centers which attenuate the IR waves as they propagate. The nanowires are made with diameter and length randomly varying within a limit which causes most of the incoming waves to scatter and interfere with each other while the nanoparticles act as strong absorption centers that convert EM waves into heat. The dielectric matrix is fully transmitting such that it only serves to hold the composite nanostructures in place. One of the metal–dielectric nanostructures showing good performance for IR stealth consisted of silicon nanowires and silver nanoparticles embedded in a polyimide substrate. The silicon nanowires offer almost zero reflectance because of impedance matching, whereas the silver nanoparticles increase the imaginary part of the refractive index leading to attenuation of EM waves. The effectiveness of the composite varies with the dimensions of the nanowires. The transmissivity decreases with increase in the length of the nanowires but also leads to higher reflections as they are more prone to breaking. The optimum length achieved a transmissivity of 0.02 for the 3–5 and 8–14 μm regions. The absorbed heat is proposed to be dissipated away using cooling air channels which can be incorporated in the sheet [36].

3.3 Visible Spectrum

The visible spectrum of light is what we humans can perceive with our naked eyes. The wavelengths range from 300 to 700 nm. The idea of stealth originated from trying to deceive the visual perception of humans by techniques such as camouflage and flash grenades. The challenge with achieving stealth in the visible spectrum is that our vision works similar to the bistatic radar, as the light that makes an object visible is a diffused source which hits the object from multiple angles and the light scattered is perceived by our eyes. If one attempts at taking a route similar to the ones before, which is to absorb all the light hitting the object, there will be a black spot in the backdrop of the surroundings which will make the location known even though its exact surface details remain hidden. The most promising technique in this aspect is also one of the most ambitious technologies termed the invisibility cloak.

The name might sound familiar as it had been thought of in the fictional realm a long time ago perhaps even inspiring the modern cloak. There have also been proposals of dynamically controlling a screen to match the background and simpler models such as color changing surfaces based on temperature.

3.3.1 Invisibility Cloaking and Metamaterials

Invisibility cloaking in its true form can be considered to be at the epitome of stealth. The concept is to make light bend around the object and pass through to the other side as if there was nothing in the path; similar to how river water diverts around a stone leaving no trail in the downstream. It relies on transformation optics to translate geometrical transformations into material properties based on the form invariance of Maxwell's equations. The geometrical transformation involves mapping the region enclosed by an object onto the annular region outside of it to make all light flow in that same annular region. This transformation is used to derive material properties which would make light follow the mapped space. The two properties which dictate light's interaction with the material are the permittivity and permeability. Generally thought of as scalars, they can be tensors of the second order exhibiting the anisotropy required for cloaking. The properties derived from transformation optics are these permittivity and permeability tensors which on being reproduced in the real world would achieve invisibility. The challenge arises when one tries to look for materials which exhibit the extreme values of anisotropic properties; natural materials do not exhibit these properties. There were two approaches to solve this with the first one being the development of artificial materials called metamaterials whose properties could be tailored at will. The second approach relies on reducing the complexity of the cloak by keeping some variables fixed such that performance is traded off with practical feasibility. The metamaterials approach requires the cell size to be smaller than the wavelength of the EM wave under consideration. This poses a problem in the visible spectrum as the cell size required would be few nanometers long, and such small structures would be tough to manufacture. The cloak also needs 3D structures and corresponding 3D metamaterial cells which require non-conventional fabrication methods such as 3D printing. The current work done with respect to invisibility cloaking using metamaterials is aimed at the microwave frequencies as the cell size required would be in the order of millimeters and is easy to fabricate. The actual materials that the metamaterials are made up of are of two types, one is the conductive material and the other is the dielectric spacer. The materials which would be easy to fabricate while satisfying the conductivities required for behaving as metamaterials need to be investigated such as conductive printing filaments.

4 Conclusion

The advancements in stealth materials have come a long way since the primitive technologies of the past century. The challenge of achieving dual stealth with respect to radars and IR has been addressed with the help of RAMs such as CNT composites with their high thermal conductivity, metamaterials with flexible properties, and IR coatings that can be applied on top of existing RAMs. The limit of narrow bandwidths is overcome by using metamaterials that are tunable to frequencies or by adding thin graphene layers on top of them. Some of the materials like the cerium multi-layer composite have shown high thermal stability, and the carbon composites like the FSFCs can stand up to the structural standards that aircraft require. The advancements in radars such as the bistatic radar can be countered by upcoming technologies like invisibility cloak. The future direction of research for stealth materials needs to take into account the requirement of broadband performance across the entire spectrum. The materials also need to be tested for other application-specific requirements, such as thermal stability, atmospheric durability, and aerodynamic compatibility.

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References

1. Katz D (2017) The ‘Magic’ behind radar-absorbing materials for stealthy aircraft, part 3, special topic state of stealth, e-book series. Aviation Week & Space Technology
2. Sidiki K (Maj, HAF), Skondras A (2nd Lt, HAF), Tokas C (2nd Lt, HAF) (2014) Low observable principles, stealth aircraft and anti-stealth technologies. J Comput Model 4(1):129–165 (2014). ISSN: 1792-7625 (print), 1792-8850 (online) (Scienpress Ltd)
3. Fang Z, Fang C (2010) Novel radar absorbing materials with broad absorbing band: carbon foams. Appl Mech Mater 26–28:246–249
4. Bhattacharya P, Sahoo S, Das CK (2013) Microwave absorption behavior of MWCNT based nanocomposites in X-band region. eXPRESS Polym Lett 7:212–223
5. Ye W, Sun Q, Zhang GY (2018) Effect of heat treatment conditions on properties of carbon-fiber based electromagnetic-wave-absorbing composites. Ceram Int
6. da Silva VA, Rezende MC (2018) Effect of the morphology and structure on the microwave absorbing properties of multiwalled carbon nanotube filled epoxy resin nanocomposites. Mater Res
7. en.wikipedia.org
8. Panwar R, Puthucheri S, Singh D, Agarwala V (2015) Design of ferrite–graphene-based thin broadband radar wave absorber for stealth application. IEEE Trans Magn 51(11)
9. Chen H, Lu W-B, Liu Z-G, Zhang J, Zhang A-Q, Wu B (2018) Experimental demonstration of microwave absorber using large-area multilayer graphene-based frequency selective surface. IEEE Trans Microw Theory Tech 66(8)
10. Zhou JH, Huo LX, Li WW, You BQ, Li YL, Li HX (2013) A magnetic-controlled detection system for radar absorbing coatings. Adv Mater Res

11. Smitha P, Singh I, Nazism M, Panwar R, Singh D, Agarwala V, das Varma G (2016) Development of thin broadband radar absorbing materials using nanostructured spinel ferrites. J Mater Sci: Mater Electron 27:7731–7737
12. Verma A, Mendiratta RG, Goel TC, Dube DC (2002) Microwave studies on strontium ferrite based absorbers. J Electroceramics 8:203–208
13. Meshrama MR, Agrawala NK, Sinhaa B, Misrab PS (2004) Characterization of M-type barium hexagonal ferrite-based wide band microwave absorber. J Magn Magn Mater 271:207–214
14. Liu C, Yu D, Kirk DW, Xu Y (2017) Electromagnetic wave absorption of silicon carbide-based materials. J R Soc Chem RSC Adv
15. Wu R, Zhou K, Yue CY, Wei J, Pan Y (2015) Recent progress in synthesis, properties and potential applications of SiC nanomaterials. Prog Mater Sci 72:1–60
16. Liang C, Guo Y, Wu L, Zhou J, Kang Z, Shen B, Wang Z (2016) Nature of electromagnetic-transparent SiO_2 shell in hybrid nanostructure enhancing electromagnetic attenuation. J Phys Chem C 120:12967–12973
17. nano.materials.drexel.edu
18. Han M, Yin X, Wu H, Hou Z, Song C, Li X, Zhang L, Cheng L (2016) Ti_3C_2 MXenes with modified surface for high-performance electromagnetic absorption and shielding in the X-band. ACS Appl Mater Interfaces 8:21011–21019
19. Wakatsuchi H, Greedy S, Christopoulos C, Paul J (2010) Customized broadband metamaterial absorbers for arbitrary polarization. Opt Express 18(21):22187–22198
20. Grant J, Ma Y, Saha S, Khalid A, Cumming DRS (2011) Polarization insensitive, broadband terahertz metamaterial absorber. Opt Lett 36(17):3476–3478
21. Liu Y, Gun S, Luo C, Zhao X (2012) Ultra-thin broadband metamaterial absorber. Appl Phys A 108(1):19–24
22. Yuan W, Cheng Y (2014) Low-frequency and broadband metamaterial absorber based on lumped elements: design, characterization and experiment. Appl Phys A 117(4):1915–1921
23. Saville P (2005) Review of radar absorbing materials, Defence R&D Canada, Technical Memorandum DRDC Atlantic TM 2005-003, Jan 2005
24. Truong V-V, Turner BD, Muscat RF, Sarina Russo M (1997) Conducting-polymer-based radar-absorbing materials. In: Proceedings of the SPIE 3241, smart materials, structures, and integrated systems, 14 Nov 1997
25. Huber T, Saville P, Edwards D (2003) Investigations into the polyaniline and polypyrrole families of conducting polymers for application as radar absorbing materials, Defence R&D Canada, Technical Memorandum DRDC Atlantic TM 2003-005, Jan 2003
26. Zhang Y-Y, Pei Q-X, Liu H-Y, Wei N (2017) Thermal conductivity of a h-BCN monolayer. R Soc Chem Phys Chem Chem Phys 19:27326–27331. https://doi.org/10.1039/c7cp04982j
27. Zhang T, Zhang J, Wen G, Zhong B, Xia L, Huang X, Zhao H, Wang H, Qin L () “Ultra-light h-BCN architectures derived from new organic monomer with tunable electromagnetic wave absorption. Carbon 13127
28. Mahulikar SP, Rao GA, Kale PS (2006) Infrared signatures of low-flying aircraft and their rear fuselage skin’s emissivity optimization. J Aircr 43(1)
29. Mahulikar SP, Sonawane HR, Arvind Rao G (2007) Infrared signature studies of aerospace vehicles. Prog Aerosp Sci 43(7–8):218–245
30. Kolanowska A, Janas D, Herman AP, Jędrysiak RG, Giżewski T, Boncel S (2018) From blackness to invisibility—carbon nanotubes role in the attenuation of and shielding from radio waves for stealth technology. Carbon N Y 126:31–52
31. Zhang W, Xu G, Zhang J, Wang H, Hou H (2014) Infrared spectrally selective low emissivity from Ge/ZnS one-dimensional heterostructure photonic crystal. Opt Mater (Amst) 37(C):343–346
32. Zhao X (2018) The effects of Ca^{2+} and Y^{3+} ions co-doping on reducing infrared emissivity of ceria at high temperature. Infrared Phys Technol 92:454–458
33. Peng L, Liu D, Cheng H, Zhou S, Zu M (2018) A multilayer film based selective thermal emitter for infrared stealth technology. Adv Opt Mater 1801006:1–8

34. Li Chen X, Hui Tian C, Xin Che Z, Ping Chen T (2018) Selective metamaterial perfect absorber for infrared and 1.54 μm laser compatible stealth technology. Optik (Stuttg) 172:840–846
35. Shi M (2018) Achieving good infrared-radar compatible stealth property on metamaterial-based absorber by controlling the floating rate of Al type infrared coating. J Alloys Compd 764:314–322
36. Moghimi MJ, Lin G, Jiang H (2018) Broadband and ultrathin infrared stealth sheets. Adv Eng Mater 20(11):1–6