Smart Materials Vis-à-vis Metamaterials

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Abstract. Smart materials are custom-designed materials that have certain properties that can undergo significant changes as guided by external influence such as electric or magnetic fields. One of the most amazing developments in the smart materials is that of metamaterials. The origin of Meta stems from Greek meaning “beyond”. Metamaterials have rare properties not found in natural occurring materials such that their properties are based on their structure rather than material of their composition. These materials find applications in many fields like public safety, sensors, battlefield communication, ultrasonic devices, solar power equipments, and remote aerospace applications. A synthetic composite material with a structure such that it possesses properties being unusual in natural materials especially a negative refractive index-these materials scatter electromagnetic wave unlike any known material. Thus the shape of the wave emerging from the metamaterials is entirely different from a conventional wave. Besides having a myriad of applications, these materials have the remarkable ability to bend light which can make airplanes, tanks and submarines invisible resulting in the epitome of stealth capability. Metamaterials now find recognition as an enabling technology being the most exciting research area at the crossroads between photonics and nanoscience. Without any exaggeration, the present era is the century of metamaterials. This paper, inter alia, highlights the significance of metamaterials in general and its stealth capabilities for defence sector in particular.

1. Introduction
Smart materials [1] are custom-designed materials possessing certain properties that can undergo significant changes as guided by external influence such as electric or magnetic fields- one of the most amazing developments in the smart materials is that of metamaterials. The Meta [2] stems from Greek meaning “beyond”, metamaterials have rare properties not found in natural occurring materials such that their properties are based on their structure rather than material of their ingredients. These materials find applications [3, 4, 5] in many fields like public safety, battlefield communication, ultrasonic devices, solar power equipment, and remote aerospace applications besides stealth capability i.e. a type of military camouflage to make personnel, aircraft, ships, submarines etc. less visible(ideally invisible) to radar and other detection methods. A synthetic composite material with a structure such that it possesses properties being unusual in natural materials especially a negative refractive index – these materials scatter electromagnetic wave unlike any known material. Thus the shape of the wave emerging from the metamaterials is entirely different from a conventional wave.

2. Smart vis-à-vis Metamaterials-Concepts
Smart materials are [6] intelligent in the sense that these respond to their environment. Emerging concepts of smart materials pertain to piezoceramics, self – repairing airplane etc. besides active
suppression of submarine noise. Due to the capacity of these materials to reconfigure to match the environment – these are called smart rather active materials. In contrast, metamaterials are man-made materials designed to possess properties not occurring in nature. Composite materials such as metals and plastics are assembled in layers to create these materials. Each layer has different shape, geometry, size and orientation of atoms to produce unusual electromagnetic properties such as negative index of refraction. The material with a negative angle of refraction changes the angle of refraction of incident light causing its propagation direction to change to absorb electromagnetic waves thus producing a weaker radar signal. This results in cloaking technology that fully bends all light incident to the targeted area ultimately becoming undetectable to the radar. Thus metamaterials could make radar obsolete to make the airplane invisible.

3. Piezoelectric Ceramics
The piezo- in Greek means to ‘press’ or ‘squeeze’. Piezoelectric sources are versatile devices that measure various processes. Lead zirconate and lead titanate are the basic ingredients of these materials. Their main advantage is that their properties can be adjusted to suit specific applications by using the appropriate zirconate-titanate ratio. These are hard, chemically inert and thoroughly insensitive to environmental conditions. Their mechanical properties resemble ceramic insulators and are synthesized almost by the same processes. Piezoelectrics are ideal for all kinds of electro mechanical transducers. These materials are marketed under the trade name PZT (Lead Zirconate Titanate) Major applications include generators, sonic and ultrasonic transducers, sensors and actuators. [7] Piezoelectric effect was discovered by Pierre Curie in 1880 but it was only in 1950 that manufacture of sensors started using the piezoelectric effect as sensing applications. These materials have very high modulus of elasticity comparable to that of metals and goes up to 106N/m2. Some sensors have working range up to 1000ºC. Piezoelectric sensors are used to monitor combustion in IC engines. A major application of piezoelectric transductions is in the defence industry. They are used in the nose fuze of rocket propelled grenade (RPG)-an antitank weapon wherein these transducers produce very high voltage to initiate the base fuze of RPG. [8] When an RPG hits a target, the nose fuze equipped with piezoceramic is crushed and consequently very high voltage is generated and transmitted for the ignition of the base fuze of the rocket to detonate the main high explosive charge which in consequence produces a hyper velocity metallic jet to defeat the armour or any other target fired upon Fig. 1.

4. Active Coatings for Signature Suppression
Even modern submarines have acoustic signatures produced by the propulsion system, internal rotating machinery/pumps and the flow of water over/around the hull. The localized excitation of the acoustic modes of the hull effectively mix with the surrounding water and are readily detectable at long range. The role of smart materials here is an active coating; it is possible to measure the amplitude and frequency of an acoustic mode in the hull. If acoustic actuators are then built into the coating, it becomes possible to create 180° out-of-phase acoustic signals of an amplitude and
frequency that match that of the acoustic mode. The outcome results in destructive interference and a greatly reduced signal radiated into the surrounding. This ‘active stealth’ approach promises to greatly reduce acoustic signatures by 60 dB.[8] Besides this, R&D is being conducted for the development of advanced materials and coatings through the fabrication of Nano-and ultrafine materials. Nickel aluminum bronze (NAB) thus developed is employed widely in a variety of sea water systems due to its high corrosion resistance [9].

5. Metamaterials: A Novel Approach

A Metamaterial is designed to have a property not found in naturally occurring materials. These are made from layers of several ingredients like metals and plastics and are arranged in repeating sequence being smaller than the wavelength of the phenomena they affect. Their properties depend upon their new structures rather than the ingredients from which they are synthesized. Their precise shape, geometry, size, orientation and arrangement determine their smart unique properties for manipulating electromagnetic waves by blocking, absorbing, enhancing, or bending waves to achieve rare benefits not found in conventional materials.

Metamaterials by directing and controlling the propagation and transmission of specified parts of the light spectrum demonstrate to render an object seemingly invisible. Metamaterial cloaking, based on transformation optics, explains the shielding of an object from view by controlling electromagnetic radiation. Despite the presence of objects in defined locations, the incident waves are guided such that these are not affected by the objects.

Working of conventional lens, Fig. 2 owes to its specific shape. The light converges due to material property of glass having variable thickness. The light ray slows down in the middle of the lens and travels faster near the edges due to less thickness as depicted in Fig. 3. This convergence results into focusing of image. The lens shape must be well-controlled and precise Fig. 4. Lens with a simpler shape can perform the required task with more flexibility in material property such that the light waves can be controlled by controlling material properties which is the basic idea of metamaterials [10].

More material property at the centre and less at the corners can reproduce the similar results of controlling the light wave. The wavelength and amplitude are important characteristics of waves. Creating an array/grid of metamaterial structure with different material in each square having size comparable to or smaller than the wavelength produces a completely arbitrary complex wave front instead of a converging wave shape produced from a conventional lens, Fig. 5. Thus, by creating a powerful and complex wave processing, the stealth capability is achievable.
6. Century of Metamaterials

It was nigh improbable to predict towards the end of 20th century that the well-established field of electromagnetism would be jolted beyond imagination. This happened in the year 2000 at the start of the new century in the form of a revolution echoed by one word – metamaterials. Ever since the advancement in research, metamaterials have now grown as a full-established discipline termed as the “The century of metamaterials”. [11] Accordingly, these metamaterials are artificial materials not natural. [12] The field is a synergic research outcome achieved by the top talent from microwave and optical sciences, solid state physics, material science, acoustics, mechanics, nanotechnology and high performance computing domains.

7. Conclusion

Needless to emphasize that metamaterials have become an extremely exciting research domain. Multiple disciplines are involved in the R&D in this area due to the unique electromagnetic properties provided by metamaterials. Consequently, this will herald the merging of knowledge and expertise across host of areas, in the fantastic advance of metamaterials research. Many amazing and novel concepts and devices such a negative refraction, superlens and invisible cloak have already been witnessed.

Metamaterials now find recognition as an enabling technology and are of the most exciting research area at the crossroads between photonics and nanoscience. Besides having a myriad of exciting applications, the stealth capability is an achievement par excellence with complete flexibility to control the material properties. What could be done next: The sky is the limit! [13]

8. References

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