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Review article

From blackness to invisibility – Carbon nanotubes role in the attenuation of and shielding from radio waves for *stealth* technology

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ABSTRACT

Stealth technology combines numerous means and techniques to be 'invisible' for opponents in a battle field. Since metals are the key construction materials of military vehicles, weapon and equipment, they can be targeted and detected by RAdio Detection And Ranging (RADAR) systems. Radar-Absorbent Materials (RAMs) – as crucial components of passive countermeasures in the modern-day military tactics – are used for absorption of electromagnetic waves. In the same time, mainly due to high electric conductivity, RAMs – accompanied by designed geometry of the objects they are incorporated into – can yield programmable reflection, multiple internal reflection and scattering towards Electromagnetic Interference (EMI) shielding. Nowadays, the latest achievements of nanotechnology have transformed *stealth* technology into an even more powerful tool. And among many nanomaterials, carbon nanotubes (CNTs) have arisen as one of the most promising active component of RAMs and EMI shielding materials. The unique sp^2-derived macromolecular architecture equips CNTs with an exceptional combination of electromagnetic, mechanical and chemical properties. This review intends to summarize and critically evaluate the hitherto efforts in the production and applications of CNT nanocomposites/hybrid materials as key constructional civil and military elements, preferably as coatings, layers, films, textiles or panels, towards attenuation of the radio wave radiation.

Contents

1. Introduction

Stealth technology, also known as low observable technology, has recently emerged as a crucial passive countermeasure in military tactics. Use of various carbon forms, mostly as Radar Absorbing

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Materials (RAMs), is not a new idea – it dates back to 1936 in Netherlands. The first patent concerning RAM – realized in a constructional approach – was an absorber of a quarter-wave resonant type using carbon black (CB) as a lossy resistive material and TiO_2 for high permittivity (ε) to reduce the overall thickness [1]. In 1944 wings of a German bomber Horten Ho 229 (also called Gotha Go 229) were made from CB-impregnated plywood glued together with a mixture of charcoal and sawdust. In parallel, Germans used graphite particles dispersed in a rubber matrix, next to ordinary paper, in a three-layer material called *Sumpf* (Eng. 'swamp') and *Schornsteinfeger* (Eng. 'chimney-sweeper'). Application of this composite has allowed for reduction of reflectivity of radio waves in the submarine periscopes [2]. Autonomously, Americans have applied a similar solution but they replaced graphite with CB to obtain Halpern Anti-Radiation Paint (HARP) used in the aircrafts [3]. The dielectric matrix of HARP had elevated relative permittivity (150 F m^{-1}) due to loading with oriented disk-shaped aluminium flakes and CB for reflection losses – both suspended in a rubber matrix. Today after 80 years and after searching for 'carbon AND radar absorbing material', Google yields 205,000 while Espacenet® 246 hits, respectively.

In the 'battlefield' of *stealth* technology itself, development of RAMs accompanied a continuous advance in the construction of increasingly sophisticated radars as a natural counteraction. In principle, all radars constitute systems exploiting microwaves (MW) to detect, locate and determine velocity of the objects and can work in a high range of transmitted frequencies depending on the operational conditions. MW-transmitter emits focused waves of a length from 1 mm up to tens of meters and the corresponding frequency from 300 GHz to 50 MHz (Fig. 1).

The higher frequency of radar the more it is affected by weather conditions such as rain, fog, humidity or clouds. On the other hand, higher frequencies offer more precise accuracy of the analysis. Generally, once the EM radiation encounters in its path an object of dielectric or diamagnetic constant different from that of the medium in which it moves – the radiation is reflected, absorbed, dispersed or transmitted. This behaviour depends on radiation wavelength and a parameter called Radar Cross Section (RCS) which evaluates how detectable by radar an object is. The magnitude of RCS depends on the target itself (size, shape, surface smoothness and other material parameters it is made of, etc.) and the parameters of the radar beam (incident/reflected angle, wavelength, polarization, etc.) (Fig. 2).

Radiation is reflected particularly strongly by materials of high electrical conductivity. If the wavelength is much shorter than the object, a mirror image is obtained. In turn, if the wavelength is much longer, the reflection is so weak that the object is 'imperceptible' by the radar. One can be hence claimed that 'detectability' of the object results from the resonance associated with a comparable wavelength and size of the object. This phenomenon allows for registering the object by radar. Furthermore, a use of dual linear polarization (vertical and horizontal) allows for a significant improvement in the identification accuracy of the reflecting surface. More sophisticated approaches such as application of circular polarization enable to eliminate the influence of rain droplets and other weather conditions, e.g. the backscatter from small spheres increases as the fourth power of the radar frequency increases. Circular polarization, coming with a help here, can be right-handed

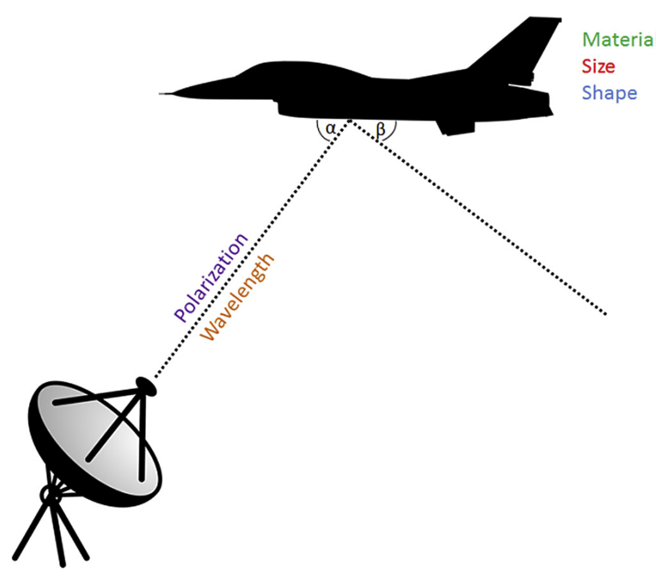

Fig. 2. A simplified selection of the most important parameters influencing RCS of a given object. (A colour version of this figure can be viewed online.)

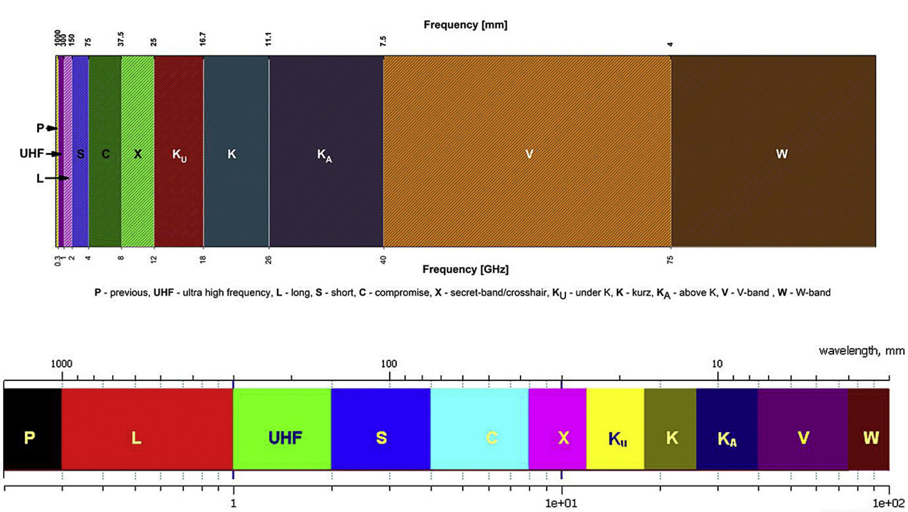

Fig. 1. Radar frequency bands with their origins of abbreviation (UHF – ballistic missile early warning, L – air traffic control, S – weather radar, C – transponder, X – marine and airport radar, K_u – satellite transponders, K – weather and photo radar, K_a – photo radar): in linear (*above*) and logarithmic (*below*) scales; **the colours from the linear scale** will be consequently applied throughout the paper in order to **identify EM-wavelengths** at glance. (A colour version of this figure can be viewed online.)