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Radio-frequency linear absorption coefficient of carbon materials, its dependence on the thickness and its independence on the carbon structure

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A B S T R A C T

This work provides the first explicit report of the linear absorption coefficient α of materials in the radio frequency regime (0.1–1.5 GHz). The coefficient decreases with increasing carbon thickness. The highest α (940 mm^{-1}) is provided by the smallest carbon thickness (7 μm). The lowest α (38 mm^{-1}) is provided by the largest carbon thickness (460 μm). For carbon thicknesses that are much larger than the skin depth, α is essentially independent of the thickness. For any frequency, α depends negligibly on the carbon structure, as its values for carbon fiber, carbon nanofiber and flexible graphite fall on the same curve of α vs. carbon thickness. This is expected from the wavelength being long (30 cm at 1 GHz) compared to the carbon microstructural dimensions. At frequencies ≥0.3 GHz, the decrease of α with the carbon thickness is approximately exponential, with the exponent related to the inverse of the skin depth. At 0.1 GHz, α tends to be below the value based on the exponential function. An absorption edge (with α increasing with increasing frequency) occurs at 0.5–1.0 GHz, as shown for carbon fiber mat.

1. Introduction

The interaction of electromagnetic radiation with materials is central to numerous material applications, such as electromagnetic interference (EMI) shielding [1], radar, microwave processing, telecommunication, optical communication, optical data processing, optical data storage, optical interconnects, light detectors, solar cells, light-emitting diodes and solid-state lasers. The main mechanisms of this interaction are absorption and reflection. The absorption can involve electronic, vibrational, rotational and other excitations, depending on the photon energy associated with the radiation. This work focuses on the radio frequency regime, which is relevant to EMI shielding and other applications.

Due to absorption, the power of the radiation decays as it propagates in the material. This power decays exponentially with distance according to the equation

$$P_a = P_i e^{-\alpha x}, \tag{1}$$

where P_i is the incident power, P_a is the power after absorption by the path of distance x, and α is the linear absorption coefficient (also called the absorption coefficient, with unit mm^{-1}), which describes the tendency of a material to absorb electromagnetic radiation. Eq. (1) assumes that α is fixed as the radiation propagates in the material. In other words, it assumes that the probability of absorption in a slab of infinitesimal thickness in the specimen is independent of the depth x of the slab from the surface on which the radiation is incident.

The linear absorption coefficient α has not been previously explicitly reported for any carbon material in the radio frequency regime.

The loss in dB due to absorption is given by

$$\text{Absorption loss (dB)} = -10\log(P_a/P_i). \tag{2}$$

The absorption loss, which is not a material property, is commonly reported. For carbon materials, particularly of the types studied in this work, the absorption loss dominates over the reflection loss, so that absorption is the main mechanism of shielding in the radio frequency regime [2–4].

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The combination of Eqs. (1) and (2) gives

$$\text{Absorption loss (dB)} = -10 \log e^{-\alpha x} = (10/2.3)\alpha x = 4.35\alpha x. \quad (3)$$

Thus, the absorption loss (in dB) is proportional to x. As a result, the absorption loss per unit distance (in dB/mm) is a quantity that is sometimes reported [2–4]. According to Eq. (3), the absorption loss per unit distance is the same as α, except for a factor of 4.35.

In relation to carbon materials, it has been reported that the linear absorption coefficient at the ultraviolet wavelength of 1.5 μm is high, with the value 20,000 mm^{-1}, for single-walled carbon nanotubes [5]. It has also been reported that the absorption loss per unit material thickness decreases with increasing material thickness for carbon fiber mat and flexible graphite in the radio frequency regime [3,4]. However, the linear absorption coefficient has not been explicitly reported in the radio frequency regime for any material.

Various types of carbon in the graphite family exhibit structures that differ in the crystallinity, texture, specific surface area, defects, functional groups, etc. These carbons include carbon fibers, carbon nanofibers, graphite, graphene, etc. Table 1 of Ref. [2] shows the shielding effectiveness results that have been previously reported by various workers for a large variety of carbon materials. In spite of the large number of publications, carbons with various combinations of structure and thickness have been studied previously in a collective fashion that does not allow the unravelling of the effects of carbon structure and thickness on α [2–4]. The focus of this paper is on α rather than the absorption loss or shielding effectiveness.

This work is aimed at (i) determining the linear absorption coefficient α of carbon materials in the radio frequency regime, (ii) investigating the effect of the carbon thickness on α, thereby testing the validity of Eq. (1), and (iii) comparing various carbon materials (with different structures) in terms of α and its thickness dependence.

2. Experimental methods

2.1. Materials

The carbon materials investigated in this work are (i) carbon fiber mats of non-woven PAN-based carbon fiber diameter 7 μm, solid content 4.4 vol% and thicknesses 0.15, 0.25, 0.42, 0.84, 1.26 and 1.68 mm, as prepared by wet papermaking and provided by Technical Fibre Products (Newburgh, NY, U.S.A.), (ii) carbon nanofiber (originally known as carbon filament) mat of nanofiber diameter 0.16 μm, solid content 10 vol% and thickness 4.63 mm, with the amorphous nanofiber provided by Applied Sciences, Inc. (Cedarville, OH, U.S.A.) and the mat prepared by wet papermaking [2], and (iii) flexible graphite (Grade GTB) of solid content 49 vol% and thicknesses 0.127, 0.254 and 0.381 mm. Refer to Ref. [3] for the details on these materials.

2.2. Testing method

The EMI shielding effectiveness is measured by an HP-8752C Network Analyzer using the coaxial cable method. The specimen is in the form of an annular ring of outer diameter 98 mm and inner diameter 29 mm. The specimen is held by an Elgal SET 19A (Israel) shielding effectiveness tester, which, due to its dimensions, theoretically allows testing at frequencies up to 1.5 GHz. The frequency used in this investigation is ranges from 0.1 to 1.5 GHz. The maximum frequency of 1.5 GHz is limited by the dimensions of the testing fixture. Refer to Ref. [3] for the details on the testing method.

The power loss in dB in electromagnetic radiation propagation is defined as

$$\text{Loss (dB)} = -10 \log(P/P_i), \quad (4)$$

where P is the output power and P_i is the power input. The shielding effectiveness SE_T (total) is given by

$$SE_T = -10 \log(P_t/P_i), \quad (5)$$

where P_t is the transmitted power.

The shielding involves absorption and reflection of the radiation. The part of the shielding due to reflection loss (SE_R) is given by

$$SE_R = -10 \log(1 - R), \quad (6)$$

where R is the fraction of the incident power that is reflected. The part of the shielding due to absorption loss (SE_A) is given by

$$SE_A = -10 \log[T/(1 - R)], \quad (7)$$

where T is the fraction of the incident power that is transmitted. The quantities R and T are measured. Note that

$$SE_T = SE_A + SE_R. \quad (8)$$

The absorption loss in dB (i.e., SE_A) is proportional to the linear absorption coefficient α in accordance with Eq. (3).

Eqs. (7) and (8) neglect the contribution of multiple reflections (successive reflections from the back and front surfaces of the specimen) to the shielding effectiveness. This is because the

Table 1
Linear absorption coefficient of carbon for various types of carbon at 1.0 GHz. The entries are listed in the order of increasing carbon thickness. CF = carbon fiber mat. CNF = carbon nanofiber mat. FG = flexible graphite.

Carbon type	Specimen thickness (mm)	Carbon thickness (μm)[a]	Absorption loss (dB)[b]	Linear absorption coefficient of carbon (mm^{-1})[c]
CF	0.150 ± 0.001	6.6 ± 0.5	27 ± 1	941 ± 77
CF	0.250 ± 0.001	11.0 ± 0.4	32 ± 1	669 ± 31
CF	0.421 ± 0.001	18.52 ± 0.04	43 ± 2	534 ± 25
CF	0.842 ± 0.001	37.05 ± 0.08	51 ± 2	317 ± 13
CF	1.263 ± 0.001	55.57 ± 0.13	57 ± 4	236 ± 17
FG	0.127 ± 0.001	60.96 ± 0.02	64 ± 4	241 ± 15
CF	1.684 ± 0.001	74.10 ± 0.17	62 ± 4	192 ± 12
FG	0.254 ± 0.001	121.92 ± 0.03	82 ± 5	155 ± 10
FG	0.381 ± 0.001	182.88 ± 0.04	101 ± 10	127 ± 13
CNF	4.634 ± 0.005	463.4 ± 0.5	63 ± 5	31 ± 2

[a] Obtained by multiplying the specimen thickness by the solid volume fraction.
[b] From Ref. [3].
[c] Obtained by dividing the absorption loss by the carbon thickness and further dividing by 4.35.