Design of Carbon Nanotube-Based Broadband Radar Absorber for Ka-Band Frequency Range

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Abstract—The general principles of design and development of microwave absorbing materials are discussed and analysed in respect to 26–37 GHz frequency range (Ka-band). Dispersive composite materials based on carbon nanotubes in epoxy resin matrix are produced, and their electromagnetic responses are investigated in Ka-band. Both theoretical and experimental results demonstrate that presented composites may be used as compact effective absorbers in 26–37 GHz range.

1. INTRODUCTION

Design of a compact multifunctional strong absorber of microwave radiation is a very important goal for many practical applications. For development of 5G communication systems, it is necessary to solve many problems related to electromagnetic compatibility and develop materials effectively absorbing electromagnetic radiation at high frequencies. Many researchers worldwide concentrate on the design of absorbers for various frequency ranges [1–9].

A great number of investigations show that nanocarbon materials have excellent electromagnetic properties to be used for production of composite materials with controlled electromagnetic properties [10–14]. In the present paper, we use carbon nanotube-based composites to produce an effective broadband absorber for Ka-band region (26–37 GHz). In contrast to our recent work [7], here we consider electromagnetic properties of composites with concentration of inclusions above percolation threshold. So the materials under study are macroscopically conductive with a static conductivity of "several Siemens per meter" and have pronounced frequency dispersion of dielectric permittivity $\varepsilon \sim 1/\nu$, which is optimal for design of microwave absorbers [1].

2. BROADBAND ABSORBING COMPOSITE MODELLING

2.1. Maximum od Absorption

The equations below are given in the SI units, and we assume an $\exp[i(kz - \omega t)]$ dependence of the incident electric field. Let us consider the normal scattering of an incident plane wave on a plane-parallel layer of a composite material located on a metal plate. The first-principle equations describing the electromagnetic response of such a system in free space are well known [15, 16]. The amplitude of the reflected signal in the waveguide is defined as [7, 17]:

$$S_{11}(\lambda, \tau, \varepsilon) = -\frac{k_z(\exp[2i\tau k_{2z}] - 1) + k_{2z}(1 + \exp[2i\tau k_{2z}])}{k_z(1 - \exp[2i\tau k_{2z}]) + k_{2z}(1 + \exp[2i\tau k_{2z}])}, \tag{1}$$

with

$$k_z = \frac{\pi}{\lambda a} \sqrt{4a^2 - \lambda^2}, \quad k_{2z} = \frac{\pi}{\lambda a} \sqrt{4\varepsilon a^2 - \lambda^2}, \tag{2}$$

where τ is the thickness of the composite, a the width of the waveguide (set to 7.2 mm), $\lambda = c/\nu$ the wavelength, c the vacuum light velocity, ν the frequency, and $\varepsilon = \varepsilon' + i\varepsilon''$ the complex (relative) permittivity of the composite. Eq. (1) canm also be used in free space; in this case, wave vectors $k_z = 2\pi/\lambda$ and $k_{2z} = 2\pi\sqrt{\varepsilon}/\lambda$ should be used. From Eq. (1), it is easy to calculate the absorption coefficient as $A = 1 - |S_{11}|^2$.

In contrast to our recent work [7], here we consider radar absorbers design based on nonmagnetic materials. In this case, we will investigate the EM properties depending on complex dielectric permittivity components. By changing type of the filler and its quantity, it is also possible to change the dielectric permittivity to obtain the maximal absorption at fixed thickness and frequency. Fig. 1 shows a general view of the dependence of absorption coefficient $A = 1 - |S_{11}|^2$ on the real and imaginary parts of the dielectric permittivity, calculated using Eq. (1) for a 1.12 mm-thick composite attached to a metal plate at 30 GHz.
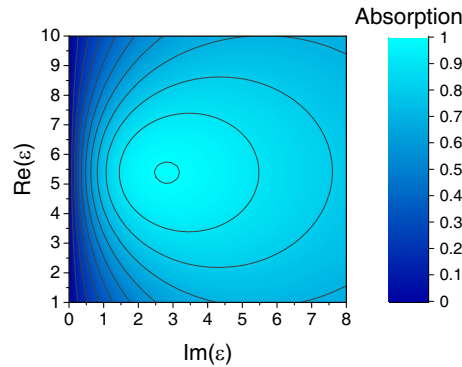

Figure 1. Dependence of the absorption coefficient A on real and imaginary parts of the dielectric permittivity of a 1.12 mm-thick composite located on a metal plate at 30 GHz in free space.

The maximum considered in Fig. 1 is equivalent to the maximum considered in terms of complex refractive index in [7]. The position of the absorption maximum strongly depends on thickness and frequency, but the general view (Fig. 1) is the same both in free space and inside the waveguide. In Fig. 1, only the first absorption maximum related to minimal values of $\mathrm{Re}(\varepsilon)$ was presented as it is most important for practical applications. As shown in Fig. 1, the absorption maximum may reach up to 100% near the point $\varepsilon = 5.39 + i2.80$. The corresponding absorption maximum in the waveguide has a different position $\varepsilon = 5.67 + i2.03$ due to the difference in wavevectors inside the waveguide and in free space.

In our recent work [7], we considered positions of maximum absorption in terms of real and imaginary parts of refractive index $n = \sqrt{\varepsilon}$. In that case, we estimated that variation of thickness and frequency affected generally only $\mathrm{Re}(n)$-coordinate of absorption maximum in free space. In the present communication, contrarily, we will show below that the coordinates $(\varepsilon', \varepsilon'')$ of absorption maximum position are strongly dependent on both thickness and frequency. The dependence of the position of absorption maximum on thickness and frequency inside the waveguide is shown in Fig. 2(a). In this figure, these two parameters are varied in the range 0.8–1.3 mm and 26–37 GHz, respectively, and the positions of corresponding absorption maxima are estimated. The dependence of the absorption maximum on the thickness at a constant frequency in the waveguide is presented in Fig. 2(a) with green solid lines. One can see that an increase of thickness leads to a monotonic shift of the maximum position to lower values of $\mathrm{Re}(\varepsilon)$ and $\mathrm{Im}(\varepsilon)$. The dependence of the position of the absorption maximum on the frequency at constant thickness in the waveguide is presented in Fig. 2(a) with dashed red lines. It can be seen that by increasing the frequency the absorption peak is shifted to lower values of $\mathrm{Re}(\varepsilon)$, and simultaneously its $\mathrm{Im}(\varepsilon)$-coordinate changes nonmonotonically. So we can conclude that if the investigated material has dielectric permittivity located inside the gridded region in Fig. 2(a), this material has good absorption ability for applications inside a waveguide.
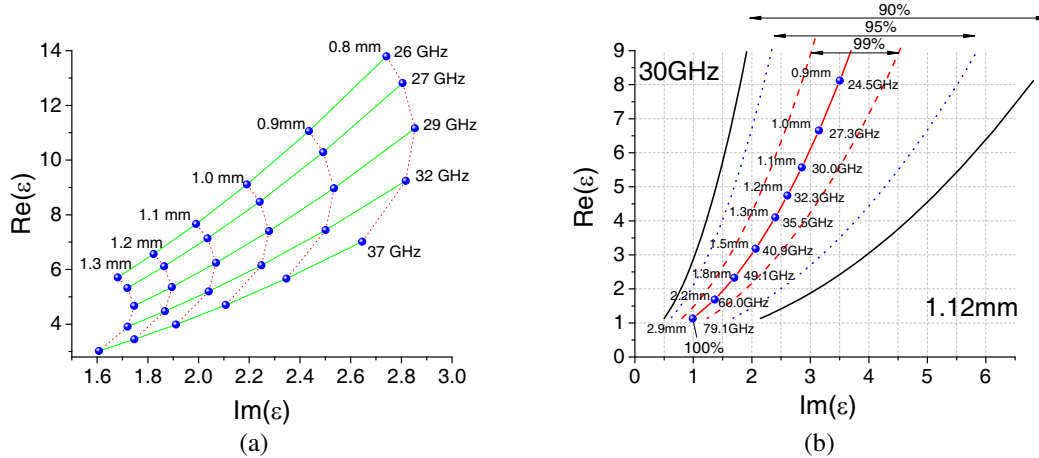
Figure 2. Dependence of the position of absorption maximum on thickness and frequency of composite located on a metal plate in (a) the waveguide and in (b) free space.

For the case of absorption in free space, the coordinates of the absorption maximum can be obtained as roots of the transcendental equation $\tan(2\pi\nu\tau\sqrt{\varepsilon}/c) = i\sqrt{\varepsilon}$. As discussed recently [7], this equation depends only on the product of thickness τ and frequency ν. So the variations of both parameters in free space are equivalent. In contrast to Fig. 2(a), all roots are located on one curve presented in Fig. 2(b) with solid red line. In this figure, we fix the frequency at 30 GHz and vary the thickness (labels left of the red curve) to find the corresponding absorption peak positions (blue dots), and then vice-versa we fix the thickness at 1.12 mm and estimate the frequency at the same peak positions (labels right of the red curve). Additionally, for further practical use, we estimate regions near the red curve, where absorption is $> 99.9\%$, $> 95\%$ and $> 90\%$. Fig. 2(b) is very useful for practical design of absorbers based on nonmagnetic materials. Analysis of Fig. 2(b) shows that an increase in the frequency and thickness leads to a similar monotonic shift of the maximum absorption peak to lower values of $\mathrm{Re}(\varepsilon)$ and $\mathrm{Im}(\varepsilon)$.

Due to the frequency dependence of absorption maximum position it is impossible to develop a broadband absorber using non-dispersive materials. For example, in [7] we experimentally showed that using non-dispersive composites it is possible to obtain an absorber with absorption coefficient varying from 65% to 100% within full Ka-band range. This result may be improved by using dispersive materials.

2.2. The Advantage of Using Dispersive Materials

The simplest way to obtain dispersive materials is to use the conductive inclusions inside the composite [17–19]. Typically, composites with conductive filler above percolation threshold have pronounced $\varepsilon \sim 1/\omega$ dispersion in microwave frequency range. In the present communication, we try to use this type of dispersion to develop effective absorbing material for Ka-band range.

The comparison of dependence of S_{11} on frequency for nondispersive ($\varepsilon = \varepsilon_{opt} = 5.39 + 2.80i$) and dispersive ($\varepsilon(\nu) = \varepsilon_{opt}(\nu_0/\nu)$) materials of thickness 1.12 mm ($\nu_0 = 30$ GHz) located on metal plate in free space is presented in Fig. 3. This value of ε is used here because it is the closest to dielectric permittivity of composites presented below in Section 4. Fig. 3 shows how exactly frequency dispersion of composite affects the absorption peak in Ka-band. We see that for wide range of electromagnetic absorption applications in Ka-band $\varepsilon \sim 1/\nu$ of dispersion is sufficient.

From this figure we see that dispersion leads to significant widening of absorption $A = 1 - S_{11}^2$ peak. Analysis of Fig. 3 shows that using $\varepsilon \sim 1/\nu$ dispersive non-magnetic materials it is theoretically possible to achieve absorption of up to 97–100% within full Ka-band range.
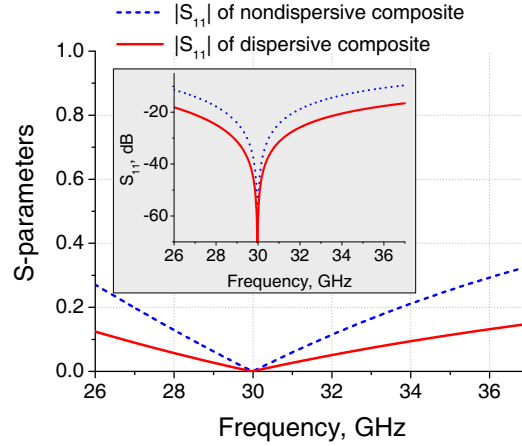
Figure 3. Dependence of the S_{11} on frequency for nondispersive ($\varepsilon = \varepsilon_{opt} = 5.39 + 2.80i$) and dispersive ($\varepsilon(\nu) = \varepsilon_{opt}(\nu_0/\nu)$) materials of thickness 1.12 mm ($\nu_0 = 30$ GHz) in free space (inset: the same in logarithmic scale).

3. EXPERIMENTAL

3.1. Used Materials

For preparation of composites, we used commercially available epoxy resin ED-22 with triethylenetetramine hardener (TETA). Multiwalled carbon nanotubes (MWCNTs)[20] produced using CVD technology [21] were used as conductive filler in the composites. The SEM-image of MWCNTs is presented in Fig. 4. The average diameter of used nanotubes is about 30–40 nm, and their length is up to 100 μm.
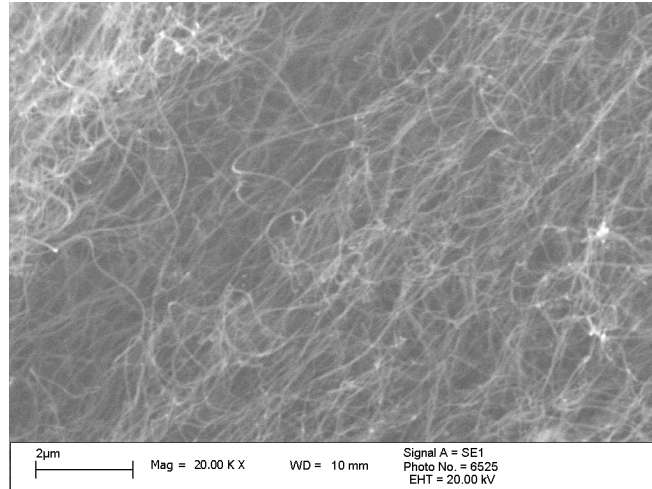

Figure 4. SEM-image of multiwalled carbon nanotubes.

3.2. Preparation of Composites

To obtain good absorption properties of composite, the inclusions of high aspect ratio should be used, or concentration of filler should be above percolation threshold. In the latter case, the composite is electrically conductive because inclusions form joined electronic system in the composite material which defines the EM response.

The MWCNT/epoxy-based composites were prepared by the technology described in details in [11, 22]. The samples were produced at different filler concentrations of MWCNTs: 0%, 1.5% and 2%wt. First, the resin was degassed under vacuum (13 mbar) for 12/14 h and heated in an oven at 65°C. Next, MWCNTs were dispersed in ethanol using an ultrasonic tip (Fig. 5(a)) for 30 min. Then, the solution was mixed with the resin and sonicated for 60 min with the ultrasonic tip at the temperature of near 80°C. After this step, the dispersion was completed, and the alcohol has been evaporated. The curing agent (TETA) was added to the mixture of resin and MWCNTs by shear mixing during several minutes. The mixture was then poured into a mold (Fig. 5(b)) for a 20 h curing and 2 h in an oven at 80°C.
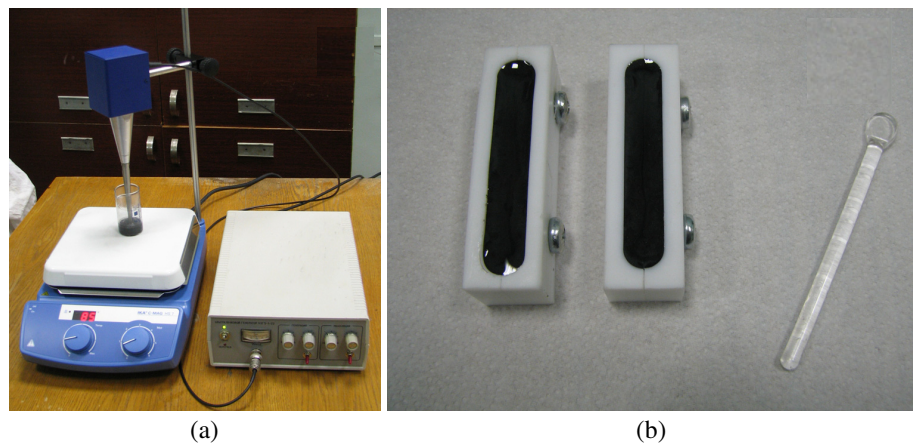

(a)   (b)

Figure 5. (a) Ultrasound device used for composites preparation, (b) molds for final polymerisation.

3.3. Microwave Measurements

Microwave measurements were carried out using a scalar network analyser ELMIKA R2-408R described in our recent work [7]. All measurements were performed in a 7.2×3.4 mm waveguide system. We considered only H_{10}-mode propagating in the waveguide. In a typical experiment, the plane-parallel layer of the composite was placed normally to the wave vector of the incident radiation. The scattering coefficients S_{11} and S_{21} of the sample were obtained as the ratio of the reflected and transmitted amplitude signal to the input one. The electromagnetic response was not dependent on power of initial radiation (in our experimental setup the power of initial radiation was varied in range 0.1–2 mW), and the plane wave approximation discussed above in Section 2 gives excellent correspondence between experiment and modeling. To analyse the electromagnetic properties of the investigated samples, the standard procedure was used to convert S-parameters to dielectric permittivity spectrum [23, 24].

Additionally, for absorption properties investigations, the short end was located behind the sample (i.e., the mirror with the reflection coefficient of 100%), and corresponding S_{11}-parameters were measured.

4. RESULTS AND DISCUSSION

The dielectric permittivity spectra of the obtained composites are presented in Fig. 6. It is worth to note that presented in Fig. 6(b) imaginary part of dielectric permittivity is positive due to using mentioned in Section 2.1 $\exp[i(kz - \omega t)]$ notation for plane waves.

Analysis of both Fig. 2 and Fig. 6 shows that composites with MWCNTs content 1.5%wt. are most promising for absorption applications.

The experimentally measured S_{11}-parameters of the 1.12 mm-thick composite with 1.5%wt. MWCNTs located on a metal plate inside the waveguide is presented in Fig. 7 by black squares.

We see from this figure that the composites with 1.5% MWCNTs inside the waveguide have absorption coefficient within whole Ka-band in the range from 84 up 100%. Additionally, the expected
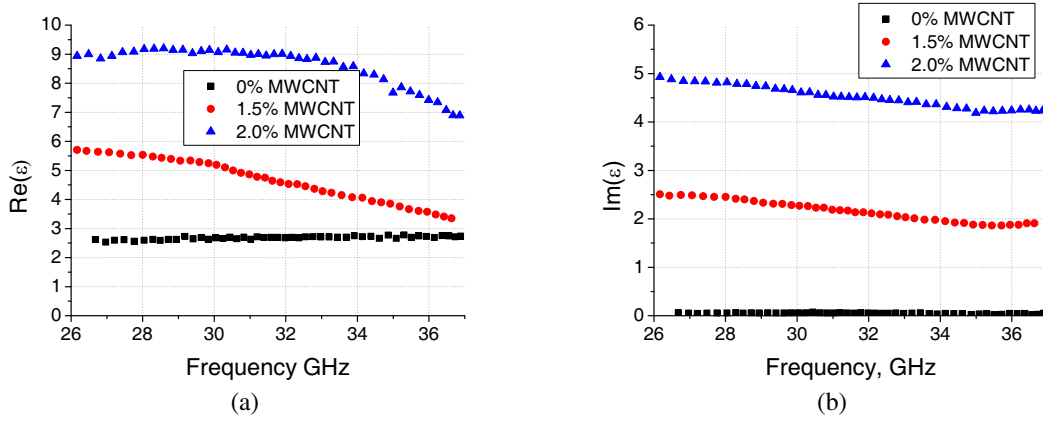
(a)   (b)

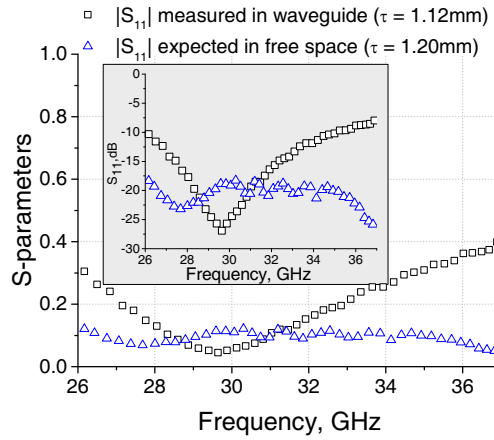**Figure 6.** Dielectric permittivity spectra of composites with various MWCNTs content.

Figure 7. Measured S_{11}-parameters for 1.12 mm-thick composite with 1.5%wt. MWCNTs inside the waveguide and expected S_{11}-parameters for 1.20 mm-thick composite in free space (inset: the same in logarithmic scale).

absorption coefficient in free space obtained by using Eq. (1) (using thickness $\tau = 1.20$ mm and ε from Fig. 6) is also presented in Fig. 7 by blue triangles. These results show that the composites with 1.5% MWCNTs may be potentially used as effective absorbers within 26–37 GHz range.

5. CONCLUSION

To summarize, for absorption applications in Ka-band dispersive materials should be used. The $\varepsilon \sim 1/\nu$ dispersion was effectively realized in polymer composite materials with a concentration of MWCNTs above percolation threshold. The general absorption mechanism in the investigated composites is Ohmic losses in the conductive matter. In the case of Ka-band region, this mechanism allows the achievement of significant attenuation of electromagnetic radiation.

As mentioned in our recent work [7], using nondispersive materials allows reaching absorption within whole Ka-band in the range from 65 to 100%. The results presented above show that using dispersive materials may significantly improve absorption properties of composites. In fact, for composites with 1.5% MWCNTs, the absorption coefficient within the whole Ka-band in the range from 84 up 100% inside the waveguide was experimentally observed. The predicted absorption properties of the investigated composites in free space are close to the theoretical maximum of 97–100% for whole Ka-band. So even simple $\varepsilon \sim 1/\nu$ dispersion may significantly improve the absorption properties of composites within Ka-band and potentially used for design of effective compact absorbers in 26–37 GHz range.

ACKNOWLEDGMENT

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