On a possibility of construction of a nonstationary waveguide channel based on extended nanoparticles

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For a microwave radiation within $\lambda = 1$–10 cm, a possibility was shown to construct a nonstationary multimode waveguide channel from conducting nanoparticles elongated along one direction based on the nanoparticle concentration in air (g/m^3). It is shown that if the particle length 10-12-fold exceeds the transverse dimensions, then the input radiation aperture is 13°–22° that is 4–7 times higher than for spherical nanoparticles. A sharp increase of polarizability of extended nanoparticles allows decreasing their volume concentration. At the hundred-fold extension of nanoparticles the wave field intensity can reach 10^4 V/cm, at which the mode of nanoparticles ignition is absent due to the field emission.

The waveguide channel in air based on the impurity of nanoparticles of spherical shape was considered in Ref. 1, where it was shown that if in a long air cylinder L of the radius ρ_0 in gaseous medium with the dielectric constant ε_1 (for air $\varepsilon_1 = 1$) nanoparticles of radius R at dielectric constant ε_2 are atomized, then the dielectric constant of the mixture ε_m will be found by the formula (Ref. 2, p. 69)

$$\varepsilon_m = \varepsilon_1 + c_1 \frac{3(\varepsilon_2 - \varepsilon_1)}{\varepsilon_2 + 2\varepsilon_1} \varepsilon_1, \tag{1}$$

where the nanoparticle concentration n is much less than the air molecule concentration; $c_1 = nv$, $v = (4\pi/3)R^3$ is the nanoparticle volume. If the nanoparticles are uncharged conductors, it is assumed in Eq. (1) that $\varepsilon_2 \to \infty$. In this case the dielectric constant of the mixture is

$$\varepsilon_m = \varepsilon_1 + 3c_1\varepsilon_1. \tag{2}$$

It was also shown in Ref. 1 that there is a possibility to construct the quasistationary waveguide channel, using a vortex and based on a stable volume formation of nanoparticles, as well as to estimate the life time of the vortex.

It is shown that the use of one-directionally extended nanoparticles allows a considerable increase the mixture dielectric constant at the same mass concentration as distinct from Eq. (2).

For the extended nanoparticles in accordance with (Ref. 2, p. 69) we obtain

$$\varepsilon_m = \varepsilon_1 + c_2 \frac{(\varepsilon_2 - \varepsilon_1)}{\varepsilon_1 + (\varepsilon_2 - \varepsilon_1)N_x} \varepsilon_1, \tag{3}$$

where $c_2 = n\tilde{v}$, $\tilde{v}$ is the volume of an extended nanoparticle; N_x is the depolarization coefficient of an extended nanoparticle along the axis OX (the field is considered to be directed along the axis OX). In the general case, the depolarization coefficients always satisfy the equality

$$N_x + N_y + N_z = 1.$$

For an elongated ellipsoid $a \gg b = c$ with the eccentricity $e = \sqrt{1 - 1/p^2}$, $p = a/b$, it will be (Ref. 2, p. 44)

$$N_x = \frac{1 - e^2}{e^3}(\mathrm{Arth}\, e - e). \tag{4}$$

At $p \gg 1$ the relationship (4) can be transformed to

$$N_x \approx \frac{1}{p^2}[\ln(2p) - 1], \tag{5}$$

where it was taken into account at deriving Eq. (5) that if at $p \gg 1$ $e = \tan\xi$, then $\xi = \ln(4p^2)$. From Eq. (5) at $p = 10$ we obtain $N_x \approx 0.02$ and at $p = 20$ we obtain $N_x \approx 0.0067$.

In the case of $\varepsilon_2 \gg \varepsilon_1$ (for example, nanoparticle consists of the conducting material) the formula (3) can be written as

$$\varepsilon_m = \varepsilon_1 + 3c_2\varepsilon_1/N_x. \tag{6}$$

At $c_2 = 10^{-3}$ and $p = 10$ (this is equivalent to the fact that the averaged density of the graphite nanoparticles is equal to 1.7 kg/m^3) we obtain that the aperture of input into the waveguide channel of the electromagnetic radiation is $\alpha \approx \sqrt{c_2/N_x} = 12.8°$ and at $c_2 = 10^{-3}$, $p = 20$ the aperture is $\alpha = 22.1°$. At the same time, the aperture of input radiation in case of spherically symmetric nanoparticles[1] equals (in case of spherical particles $N_x = 1/3$) $\alpha \approx \sqrt{3c_1} = 3.1°$.

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Since at small α, the power input in the waveguide channel is proportional to the solid angle $\Omega = 4\pi\sin^2(\alpha/2) \approx \pi\alpha^2$, then at $10 \le p \le 20$ the input power will be increases by a factor of 17–51 as compared with spherically symmetric particles.

There exist single-mode and multimode regimes of radiation propagation in waveguides.[3] In the case of the single-mode regime, only the wave (mode) description of the radiation propagation process is possible. In the multimode case, the radiation propagation can be described both by the mode method and the geometric optics method. When using the mode method, the role of the aperture for the input radiation is played by the optical volume V (Refs. 1 or 3, p. 192):

$$V = k\rho_0\sqrt{n_{\rm co}^2 - n_{\rm cl}^2} = k\rho_0\sqrt{3c_2\varepsilon_1/N_x}, \qquad (7)$$

where $k = 2\pi/\lambda$, λ is the electromagnetic wavelength; $n_{\rm co}$, $n_{\rm cl}$ are the indices of refraction for the waveguide center and shell; ρ_0 is the waveguide center radius. Assuming $p = 10$, $\lambda = 3$ cm, $\varepsilon_1 = 1$, $c_2 = 10^{-3}$, $\rho_0 = 10$ cm, we obtain $V = 8.1$. This means that in such a waveguide the generation of modes up to HE_{41} and EH_{21} (see Refs. 1 or 3, p. 273) is possible. Similar results of calculations for $p = 20$, all other conditions being equal, lead to $V = 14.0$. It is seen that the optical volume is sensitive to p. In this case 1.7 kg of graphite nanoparticles, produced in the form of elongated ellipsoids, enables one to produce a waveguide channel of 19 m length.

Now evaluate the characteristic time, during which under the effect of external field a nanoparticle will be turned along the field. For this purpose, we must determine the period or, that is the same, the angular frequency of small oscillations of a particle. According to Ref. 2, p. 66, in the homogeneous electric field E_0 the torque K affecting the conducting ellipsoid at $p \gg 1$ equals

$$K = vE_0^2\sin 2\alpha/(8\pi N_x).$$

Taking into account the moment of inertia of the revolution ellipsoid $I \approx ma^2/5$ at $p \gg 1$, we obtain that the angular frequency of small oscillations is

$$\omega = \sqrt{\frac{E_0^2}{4\pi}\frac{5}{N_x\rho a^2}}.$$

At $E_2^0/(4\pi) = 10$ J/m^3; $N_x = 0.01$, $\rho = 2\cdot10^3$ kg/m^3 is density of nanoparticle matter; $a = 100$ nm $= 10^{-7}$ m, we obtain $\omega \approx 3\cdot10^6$ c^{-1}. This means that in the case of the wave of the centimeter length the field does not affect the change of orientation of the extended nanopaticles. Therefore, we believe that nanoparticles have an isotropic angular distribution.

Thus, the evaluations obtained in combination with the results of Ref.1 show a possibility to construct the waveguide channel using nanoparticles of graphite type. Therewith, the nanoparticles with elongated geometry along one direction can increase the optical volume that, in turn, results either in the decrease of mass concentration of nanoparticles at a fixed number of directed modes, or at constant mass concentration in the increase of the number of directed modes (increased aperture). In addition, the problem considered in this paper is of interest at radiation motion along the waveguide channel of an aircraft. In this case at the corresponding aperture the radiation capture and reflection from the aircraft are possible, which is located at a larger distance as compared with the object being under study.

References

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