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A Nano-Rotor driven by the Electrorotation Effect acting on a cylindrical Bioparticle

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Abstract: - The present paper contributes to the field of nanoelectronics at a molecular size scale. Nanomachines carry out mechanical movements similar to their macroscopic counterparts, i. e. translation as well as rotation, although their driving forces are of different nature. While gravitational forces are typical only for macroscopic robots, on the nanoscale floating resistance and Brownian movement gain importance. The imposition of forces occurs mainly by external electric fields, electrical currents and other fields of any type, which interact with atoms, molecules and nanoparticles.

We present in this paper a study of the controlled rotational movement of a cylindrically shaped bioparticle by means of an alternating electric field, taking into account the geometrical shape of the nanoparticle as well as their dielectric properties within a suspending dielectric medium.

Key Words: - nano-rotor, bioparticle, dielectrics, electrorotation, nanorobotics, nanoelectronics

1 Introduction

One of the objectives of nanotechnology is the controlled manipulation of individual atoms and molecules [1,2]. Present research activities imply basic objectives, as e. g. the construction and characterization of artificial microstuctures, its mechanical and electrical properties, the chemical stability and the response to diverse stimuli. The nanotechnology universe is the mesoscopic scale, where classical physics looses its primacy and quantum effects take over. At this length scale, nanometric objects share characteristics, which are typical for macroscopic objects at the one hand, and for 'molecular' (quantum) objects at the other. In this hybride arrangement enter new phenomena to be considered: thermal noise, surface effects, quantum fluctuations, disorder and non lineality. Most of these effects are small at a macroscopic length scale and are thus treated as perturbations. At the mesoscopic length scale, these perturbations reach the importance of the main effect and their actions might be decisive.

2 Electrorotational force

Electrokinetic effects are caused by the interaction of induced dipoles with electric fields. A variety of movements is produced by changing the nature of the alternating electric field, including attraction, repulsion and rotation [3-5]. For a given external electric field $\vec{E}_0(\vec{r})$, the polarization within a dielectric body is given by

$$\vec{P}(\hat{r}) = \varepsilon_0(\varepsilon - 1)\vec{E}_i(\hat{r}) = \varepsilon_0(\varepsilon - 1)\alpha(\hat{r})\vec{E}_0(\hat{r}), \qquad (1)$$

where $\alpha(\hat{r})$ is a tensor, ε_0 is the vacuum permittivity, ε the permittivity of the particle, $\vec{E}_i$ the internal electric field, and $\hat{r}$ tho position vector pointing in the direction of the electric field. The depolarization factor $\alpha(\hat{r})$ relates the internal electric field to the external field

$$\vec{E}_i(\hat{r}) = \alpha(\hat{r}) \cdot \vec{E}_0(\hat{r}) \qquad (2)$$

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In the case of ellipsoidal dielectric bodies, this factor is easily obtained. For a sphere e. g. it is given by

$$\alpha = 3/(\varepsilon + 2), \tag{3}$$

for an oblate ellipsoide of radius *R* and length *L* *(R>L)*

$$\alpha = \{1 - (\varepsilon - 1) \cdot f(q)\}^{-1}, \tag{4}$$

with

$$f(q) = \left[(q^2 + 1)(q \cdot \arctan \frac{1}{q} - 1) \right], \tag{5}$$

and for a prolate ellipsoide of radius *R* and *L>R*, the function *f(q)* results in

$$f(q) = q^2 \left[1 + \frac{\sqrt{q^2+1}}{2} ln \frac{\sqrt{q^2+1} - 1}{\sqrt{q^2+1} + 1} \right] \tag{6}$$

In both cases is

$$q^2 = R^2 / \left| L^2 - R^2 \right| \tag{7}$$

3 Polarization of a short dielectric cylinder

Not so straight forward is the situation in the case of a short cylinder in a homogeneous electric field (see Fig. 1). We get

$$\oiint \frac{\vec{E}_0(\hat{r}_2) \cdot d\vec{F}_2}{\hat{r}_{12}^3} \frac{\vec{E}_0(\hat{r}_1) \cdot r_{12}}{\vec{E}_0^2(\hat{r}_1)} =$$

$$2 \int_0^R \frac{2\pi a da \cdot L}{(a^2 + L^2)^{3/2}} = \int_L^{(R^2+L^2)^{1/2}} \frac{rdr}{r^3} \cdot 4\pi L =$$

$$4\pi \left[1 - (1 + R^2 / L^2)^{-1/2} \right] ;$$

$$\vec{P}_1 = \frac{\varepsilon_0 (\varepsilon - 1) \vec{E}_0}{1 + (\varepsilon - 1)\left(1 - (1 + R^2 / L^2)^{-1/2} \right)} . \tag{8}$$

Such a homogeneous polarization is only the first approximation [6]. Due to the choice of the origin at z = 0, the by *P* generated field will be too weak in the transversal plane at z = 0, but along the z-axis at the limiting faces of the cylinder it is too strong.

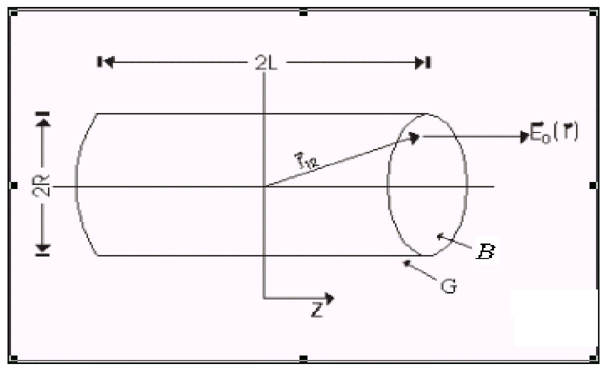

Fig.1 Dielectric cylinder of length *2L* and diameter *2R*. At B and G polarization charges accumulate.

The dipole moment in a second approximation is produced by

$$\vec{P} = \varepsilon_0 (\varepsilon_p^* - \varepsilon_m^*) \vec{E}_0 \cdot \alpha = \varepsilon_0 \cdot K(\omega) \cdot \vec{E}_0$$

with

$$\alpha = \left\{ \varepsilon_m^* + (\varepsilon_p^* - \varepsilon_m^*)\left[1-(1+R^2/L^2)^{-1/2}\right]\right\}^{-1} *$$
$$\left\{ 1 + \frac{\frac{1}{2} - \left(1+\frac{R^2}{L^2}\right)^{-\frac{1}{2}} - \frac{1}{2}\left(1+\frac{8L^2}{R^2}\right)^{-1}}{(\varepsilon_p^* - \varepsilon_m^*)^{-1} + 1 - \frac{7}{16}\left(1+\frac{11R^2}{56L^2}\right)} + \frac{\frac{1}{2L}\left(R^2+2L^2\right)\cdot\left(R^2+4L^2\right)^{-\frac{1}{2}} - \frac{1}{2L}R}{(\varepsilon_p^* - \varepsilon_m^*)^{-1} + 1 - \frac{7}{16}\left(1+\frac{11R^2}{56L^2}\right)} \right\}. \qquad (9)$$

Here *K(ω)* is the Clausius-Mossotti factor. We have taken into account, that the dielectric cylinder of length *2L* and radius *R* displays a complex dielectric constant ε_p^* and is situated within a suspending medium of a complex dielectric constant ε_m^*.

4 The Clausius-Mossotti factor (CMF)

The CMF is a measure of the effective polarizability of the dielectric particle under consideration, and depends on the depolarization factor *α*, i. e. very sensitively on the geometrical shape of the particle. The complex permittivity is given by

$$\varepsilon^* = \varepsilon - j(\sigma / \varepsilon_0 \omega) \qquad (10)$$

where *j* is the imaginary unit $(-1)^{1/2}$, and *σ* is the electrical conductivity of a dielectric medium.

Given that in the case of a finite cylinder considered here its length will be several times exceed the radius, we apply *f(q)* as given in equ. (6), and arrive at a CMF

$$K(\omega) = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_m^* + (\varepsilon_p^* - \varepsilon_m^*)\cdot f(q)} \qquad (11)$$

In consequence, this factor depends among other things on the frequency of the applied alectric field. If only frequency dependencies are the objetive of the study, it is sufficient to consider *K(ω)* and its dependence on particle properties and external field properties.

5 Electrorotation of a tiny short cylinder (nano-rotor)

A circularly polarized rotating electric field induces a rotating dipole moment in a dielectric object. The time-averaged rotational torque in such conditions is given by the vector product of induced dipole moment and conjugate field

$$\langle \vec{\Gamma}(\omega) \rangle = \frac{1}{2} \cdot V \cdot Im[\vec{P} x \vec{E}^*] \qquad (12)$$

The induced dipole moment $\vec{p} = V \cdot \vec{P}$ is proportional to the external field $\vec{E}$, the permittivity of the suspending medium ε_m^* and the volume *V* of the object.

The friction, experienced by the dielectric particle in the suspension medium affects the mobility in both electrorotation and dielectroforesis. Dismissing the Brownian movement and floating forces, the equation of movement can be written by

$$\vec{p}\,\frac{du}{dt} = \vec{F}_{EK} - \vec{F}_{drag} \qquad (13)$$

where $\vec{F}_{EK}$ is the electrorotation force.

The momentary velocity *u* is proportional to the instantaneous electrokinetic force

$$u = \vec{F}_{EK} / \vec{F}_f \quad , \qquad (14)$$

and substituting $\vec{F}_{EK}$ one gets

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$$\vec{u} = \frac{V \cdot \varepsilon_0 \overset{*}{\varepsilon}_m Im[K(\omega)] \vec{E}_0^2}{2\vec{F}_f}, \qquad (15)$$

with the friction force

$$\vec{F}_f = K\eta\vec{u}, \qquad (16)$$

(η- viscosity of the medium, K- friction coefficient).

6 Electrorotation spectra

We will consider the Tobacco Mosaic Virus (TMV) as specific bioparticle with properties as treated in the foregoing sections (Table 1),

L	$2R$	ε_p	ε_m	σ_p	σ_m
25nm	18nm	55	78.5	0.085	σ_{m1} a σ_{m5}

Table 1: Properties of the considered bioparticle (TMV), and the aqueous solution (subindex *m*).

The bioparticle is exposed to an aqueous solution of different values σ (electrical conductivity), which are shown in Table 2.

σ_{m1}	σ_{m2}	σ_{m3}	σ_{m4}	σ_{m5}
0.001 S/m	0.005 S/m	0.01 S/m	0.05 S/m	0.1 S/m

Table 2: Considered values of the electrical conductivity of the suspending medium

Electrorotation spectra are displayed in Fig. 2, where the imaginary part of the CMF in dependence on the circular frequency ω of the electric field is shown. Each almost bell-shaped curve corresponds to a certain value of length L of the TMV. The maximum torque value occurs at frequencies around 10^6 rad/s, and is the larger the longer the TMV is chosen.

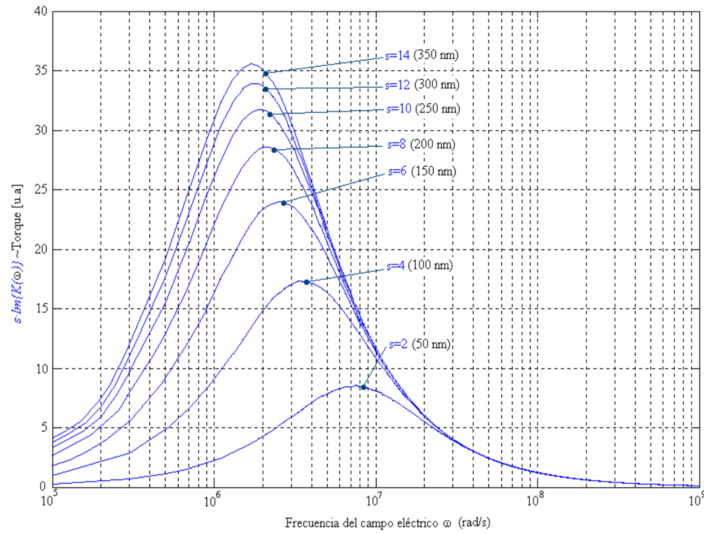

Fig. 2 Electrorotation spectra for different lengths of the TMV. *s* represents a multiplication factor (s = 1, 2, 3, ...) of the minimum length of 50 nm chosen. The electrical conductivity of the medium is σ_m= 0.001 S/m.

From equ.(15) one arrives at a value for the velocity of the bioparticle of

$$\vec{u} = \left[\frac{V\varepsilon_0\varepsilon_m \operatorname{Im}\{K(\omega)\}\vec{E}_0^2}{12\pi R\eta} \right]^{1/2} \qquad (17)$$

and the rotation frequency W

$$W = \frac{\vec{u}}{L/2} \qquad (18)$$

for a vertical axis of the cylindrical particle of length L.

By changing the intensity of the acting electric field E_0, the value of u can be controlled. Considering a 4-electrode arrangement with a distance of 10 µm between opposite electrodes, and applying a voltage of 0…20 Volts, it results the variation of the electric field $E_0=0\ldots10^6$ *V/m.*

The rotation frequency W vs. the electric field intensity of two different TMV of length L = 50 nm and L = 300 nm, respectively, is shown in Fig. 3.

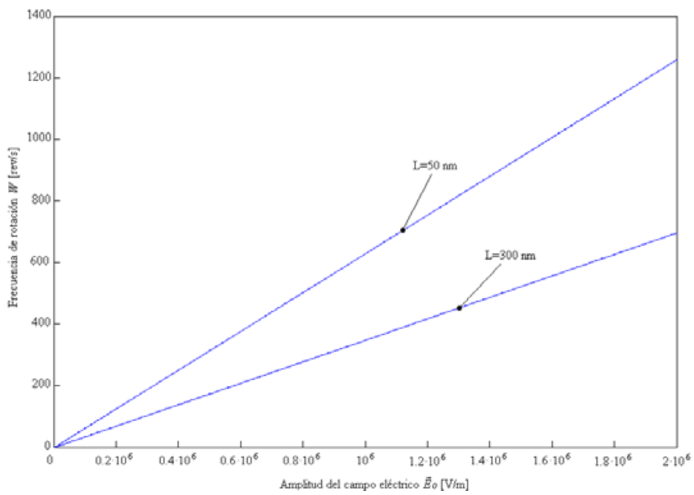

Fig. 3 Rotation frequency W vs. electric field intensity E_0 for two different TMV lengths, L = 50 nm and L = 300 nm. The conductivity of the suspending medium is $\sigma_m = 0.001$ S/m.

As displayed in Fig. 3, quite high rotation frequencies can be reached.

7 Conclusions

The presented results prove that the electrorotation technique, applied to molecular nanosystems, is suitable for the generation and the control of rotational movements of a 'nano-rotor', formed e. g. by cylindrically shaped TMV bioparticles of different lengths. Realistic properties of the participating components provide for a controlled rotative movement of the bioparticle. Forthcoming work has to take into account the effects of friction and Brownian movement in order to study their influence on the obtained rotation frequency and stability.

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