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Photovoltaic Generator Based on Laser-Induced Reversible Aggregation of Magnetic Nanoparticles

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Abstract: A new principle of electromotive force generation is proposed, based on the intermittent laser-induced reversible cluster formation due to the aggregation of magnetic nanoparticles in a ferrofluid placed in the constant magnetic field. In such a configuration, according to Faraday law, in response to unsteady light-induced periodic motion of magnetized materials in an external magnetic field, an alternating current is induced in the coil wrapped around the ferrofluid tube.

Keywords: Cluster Formation; Faraday Law; Laser; Magnetic Nanoparticles; Photovoltaic Generator.

Colloids exhibit a rich and highly varied phase and structural behavior. Ferrofluid is a stable colloidal suspension of single-domain ferromagnetic particles with a dimension around 10 nm coated by a surfactant layer of 1–2 nm [1]. These magnetic nanoparticles have diverse application in many fields, e.g. laser-mediated magnetic drug targeting and release [2–4] and gene therapy [5, 6]. The thermal agitation randomizes the iron oxide particles so that the total magnetization of the ferrofluid is equal to zero when no magnetic field is applied. Ferrofluids are inexpensive, easily synthesized magneto-optic materials that offer attractive optical, magneto-optical, and environmental characteristics [7–12]. As has been experimentally observed under the illumination of the ferrofluid by laser in the presence of the external magnetic field, formation of large aggregates of magnetic nanoparticles occurs [13]. The key factor is that the combined action of both light and magnetic field is necessary. The action of any of these factors is not enough for cluster formation. Although the microscopic mechanism of this effect is not fully known, our aim in this study is to exploit it for the electromotive force (EMF) generation. Ferrofluid in an external homogeneous magnetic field has a non-zero magnetization. If a non-magnetic body crosses the ferrofluid, it leads to variation of magnetic flux, which induces an electromotive force, according to Lenz law. There are already two experimental realizations of this principle: Kubasov [14] used oscillation of glass rod in ferrofluid and Flament et al. [15] used bubbles of the gas crossing the cell containing ferrofluid. Vibratory and sloshing motion of ferrofluid, which changes the magnetic flux generated by the permanent magnet and creates a time-varying magnetic flux, which induces EMF in a coil, was also used for these purposes [16, 17]. There is also another theoretical design proposed by Zahn [18], where the waste heat is used to create a vapor bubble creating a time-varying flow that controllably rotates ferrofluid nanoparticles, as a possible device for micropowering of a nanoscience craft planned by NASA. In our approach, the mechanical movement of a non-magnetic body is replaced by the action of laser light, which leads to reversible formation of magnetic and non-magnetic domains in the ferrofluid container, so that there would be a time-varying magnetic flux through a coil that induces a current through a load.

The experimental setup is shown in Figure 1. For our experiments, we used light hydrocarbon oil-based ferrofluid EMG-911 (Ferrotec, Santa Clara, USA) with a volume concentration of 2 %. In a detailed structural study using 2D small-angle X-ray scattering, a rather broad distribution of magnetic nanoparticles with a maximum at particle diameter 10 nm and half-width of about 4 nm was found [19, 20]. The density of ferrofluid and saturation magnetization are 890 kg m^{-3} and 11 mT, respectively. This ferrofluid was already widely used in several studies, e.g. in [21] and [22]. For the illumination, we used 10 W of He–Ne laser ($\lambda = 633$ nm). The laser light was interrupted with a frequency of 0.5 Hz using an electromechanical shutter.

The EMF generated with intermittent illumination of ferrofluid is shown in Figure 2. Although the measured voltage is only in the millivolt range, and the signal is rather fluctuating, the periodic dependence on the laser

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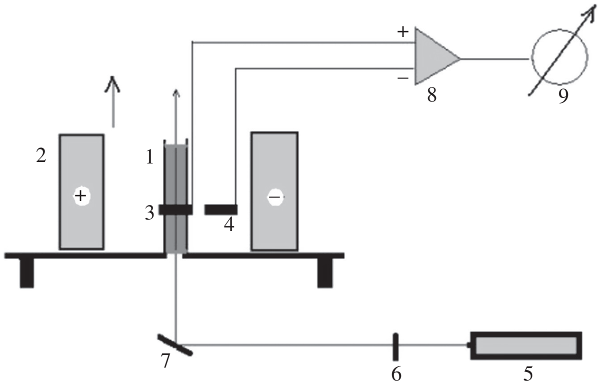

Figure 1: Experimental setup for the generation and measurement of laser-induced electromotive force: (1) glass tube filled with ferrofluid, (2) solenoid, (3) measuring coil, (4) compensative coil, (5) He–Ne laser, (6) electromechanical shutter, (7) mirror, (8) amplifier, (9) voltmeter.

source is clearly visible, and our results may serve as a proof of principle of a novel method of electromotive force generation.

The physical mechanism behind the effect is Faraday law because the electromotive force is induced in response to the unsteady light-induced motion of magnetized materials in an external magnetic field. The induced EMF can be obtained by the Faraday law as [23]

$$\mathrm{EMF} = -N\frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{1}$$

$$\Phi = \int (\mathbf{B}.\mathbf{n})\mathrm{d}A \tag{2}$$

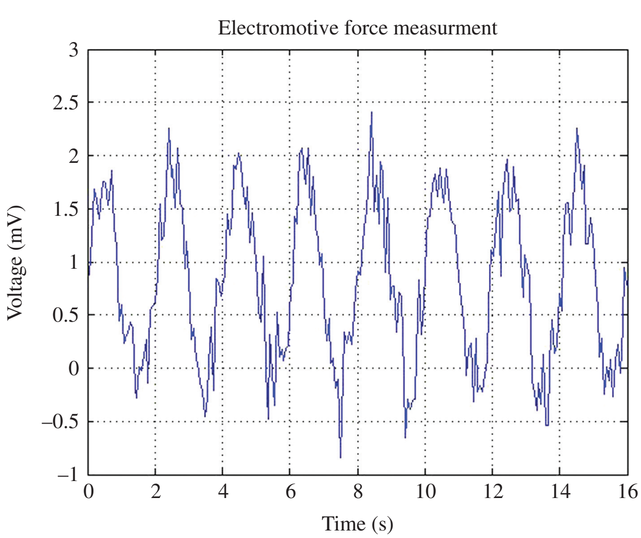

Figure 2: Instantaneous values of EMF generated with intermittent illumination of ferrofluid (periods of light-on for 1 s and light-off for 1 s) are shown after 6 s, when transient events disappear.

where N, Φ, and t stand, respectively, for the number of identical turns of the induction coil, the magnetic flux, and the time, and $\mathbf{n}$ and A represent a unit normal vector and the area. The magnetic induction field $\mathbf{B}$ can be further expressed by $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$; where μ_0, $\mathbf{H}$, and $\mathbf{M}$ are the permeability of vacuum, the magnetic field strength, and the magnetization of ferrofluid, respectively. It is apparent that both the temporal variations of the magnetic-induced field and the effective area, which is perpendicular to the magnetic flux, are capable of generating the EMF. Devices for measuring the concentration and dispersion quality of magnetic particles by the induced EMF were also suggested [24].

A tentative microscopic explanation for these fully reversible cluster and structure formation phenomena was proposed in [25] and [26]. At higher laser powers of the order of 1 mW occurs a reversible photobleaching caused by the Soret effect-driven migration of the magnetic colloids out of the laser beam [27]. Another possible explanation is offered for the low laser powers, namely, in the existence of the photonic "glue" effect [25] due to the increased average population of excited electronic states with higher electric polarizability than the ground state, the estimated number of absorption events per colloid is of the order of $10^6\ \mathrm{s}^{-1}$. An increased polarizability enhances the van der Waals interaction, which might then be able to overcome the steric repulsion of the surfactant layer. Once the light is turned off, the van der Waals forces are switched back to their normal value, and the aggregates dissolve.

Despite the fact that the attained EMF is rather small compared to the traditional electromagnetic energy generators, the proposed principle has some unique advantages because a moving solid permanent magnet is not used. For practical applications, the method should be further improved in several possible ways, e.g. using ferrofluid with higher magnetization, the electromagnet can be replaced by a strong annular permanent magnet and also different, possibly more efficient, lasers should be used to influence kinetics and form emerging clusters of magnetic nanoparticles.

The conversion of energy from one form to another [28], or the production of useful work, has long been an important element of engineering and scientific research [29]. The present method provides proof of the principle of a new method on how to exploit the light energy for electricity production using nanotechnology tools.

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