Magnetically steered liquid crystal-nanotube switch

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A magnetically steered electric switch based on nematic liquid crystal-single-wall carbon nanotube dispersions is demonstrated. The device exploits the conductivity anisotropy of nanotubes in combination with the magnetic Freedericksz transition of a nematic liquid crystal. The performance is characterized with respect to the electric measuring field amplitude, frequency and sample cell gap. The dynamic behavior indicates a response time of approximately 4 s, and possible applications for magnetic field sensors are discussed. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2140069]

Liquid crystals (LCs) (Ref. 1) are spontaneously self-organized anisotropic fluids. They combine fluidity with the anisotropy of physical parameters and the elasticity observed for solids. The simplest of the LC phases is the nematic, which exhibits solely orientational order of the long molecular axes along a preferred direction called the director. LC displays (LCDs) based on nematics are by now a mature technology utilized in a wide range of applications from simple black and white pocket calculators to high-end full color television screens. All of these applications are based on the electric Freedericksz transition, a collective reorientation of the LC director along the direction of an applied electric field (for positive dielectric anisotropy). Carbon nanotubes[2] are also highly anisotropic materials. They exhibit a large elastic modulus and electric conductivity along the tube axis, while being flexible and nonconductive in the perpendicular direction. Proposed applications range from nanoelectronics[3] to biochemical sensors.[4] It lies at hand to combine these two modern materials to design novel nondisplay devices based on LC-nanotube dispersions.

It has recently been shown that the LC order through self-organization can be transferred onto dispersed carbon nanotubes,[5–7] resulting in well-aligned nanotubes with their tube axes in the direction of the LC director. It has further been demonstrated for two complementary geometries, that this direction can be selectively changed by application of an electric field.[6,7] Due to elastic interactions between the nanotubes and the LC, the tubes follow the reorientation of the LC, and *electrically* controlled OFF-ON and ON-OFF switches were realized on the basis of LC-nanotube dispersions. In the following, we demonstrate a *magnetically* controlled LC-nanotube device.

The basic principle is depicted in Fig. 1(a). A mixture of the commercially available nematic LC E7 (Merck) and a small amount of single-wall carbon nanotubes was sonicated at 40 kHz for 1 h to promote dispersion and detanglement. This dispersion was capillary filled into standard LC sandwich cells with indium tin oxide electrodes and a polyimide alignment layer for planar orientation. Cell gaps between 15–50 μm were employed. The ***magnetic*** Freedericksz transition[8] from planar to homeotropic orientation (director parallel to perpendicular to the electrode plane) was induced by use of an electromagnet with a maximum field strength of $B=1$ T. Simultaneously, the nanotube reorientation was monitored by conductance and capacitance measurements (Wayne Kerr Precision Component Analyzer) for increasing magnetic field strength. As the magnetic field reorients the LC from planar to homeotropic, elastic interactions cause a torque on the dispersed nanotubes, reorienting them from a nonconducting to a conducting state above the magnetic threshold field B_{th}. This is exemplary demonstrated by the

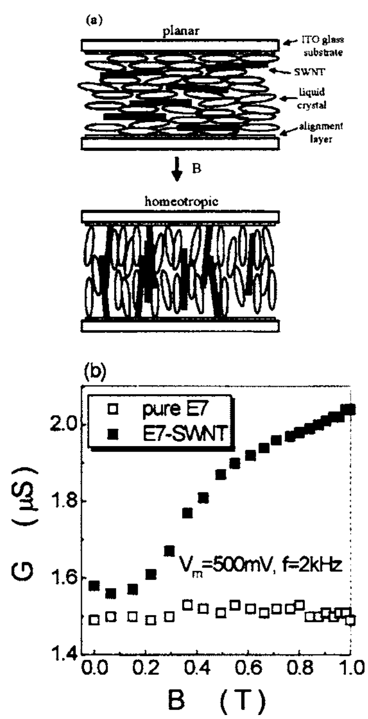

FIG. 1. (a) Schematic illustration of the working principle of the magnetically steered LC-single-wall nanotube dispersion device. (b) Experimental verification of the device, showing the conductance G of the pure LC (open squares) and the nanotube dispersed material (closed squares) as a function of applied magnetic field B for a probe voltage of $V_m=0.5$ V at frequency $f=2$ kHz.

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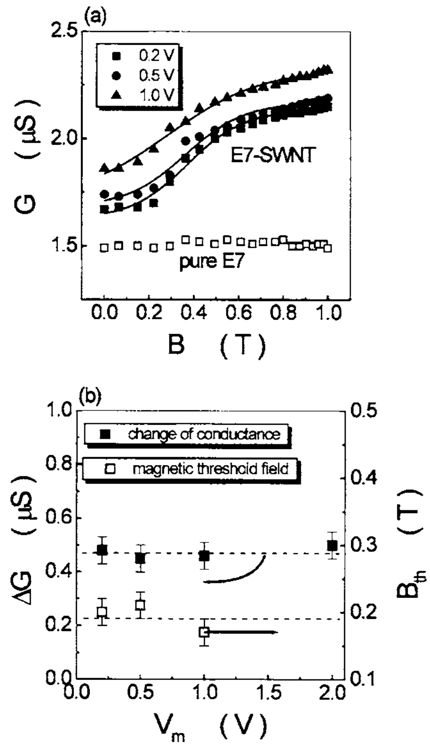

FIG. 2. (a) Device performance as a function of applied electric probe voltage V_m. (b) The change of conductance ΔG (closed squares) and the magnetic threshold field B_{th} (open squares) is independent of the probe voltage.

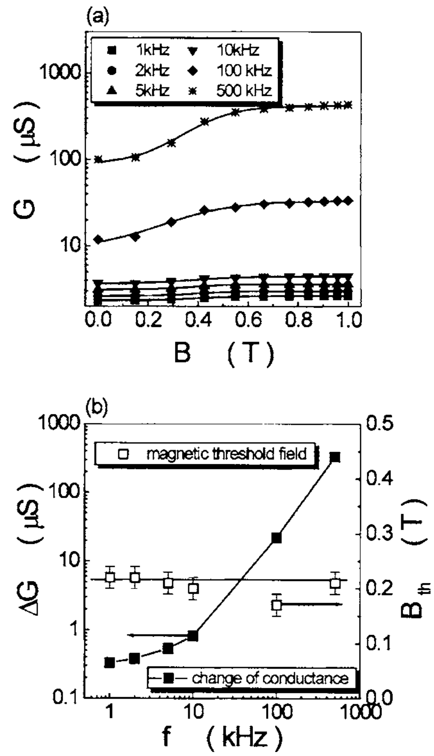

FIG. 3. (a) Device performance as a function of applied probe frequency f. (Note the logarithmic scales). (b) The change in conductance ΔG increases with applied frequency (closed squares), while the magnetic threshold field B_{th} is practically constant (open squares).

conductance measurements of Fig. 1(b) on a d=50 μm cell. For the pure LC (open symbols), the conductance is practically independent of the magnetic field, and the director reorientation can be verified from capacitance data. In contrast, the LC-single-wall nanotube dispersion (closed symbols) exhibits a clear increase in the conductance as the nanotubes reorient with their tube axes perpendicular to the electrodes. It is important to note that at all times it was assured that the applied electric ac measuring voltage was well *below* the threshold voltage for the ***electric*** Freedericksz transition.

Figure 2 summarizes the device performance for different measuring voltages $V_m \ll V_{th}$. The conductance is increased for increasing V_m, but the change of conductance ΔG between B=0 T and saturation obtained after reorientation at $B \approx 1$ T is practically constant. So is the threshold magnetic field, B_{th}=0.2 T, shown for cell gap d=50 μm [Fig. 2(b)]. For comparison the conductance of the pure LC E7 is additionally displayed as open squares at V_m=0.5 V. The dependence on measuring frequency is depicted in Fig. 3(a) in the range between f=1–500 kHz at V_m=0.2 V. The conductance increases with increasing frequency, as does ΔG, while the magnetic threshold field is again independent at B_{th} =0.2 T for the d=50 μm cell [Fig. 3(b)]. This implies that for best sensitivity the magnetically controlled LC-nanotube switch should be operated at small probing voltages and high frequencies.

In contrast to the *electric*-field induced Freedericksz transition, which occurs at constant voltage (independent of cell gap), the *magnetic* threshold B_{th} is inversely proportional to the cell gap d, or $B_{th}d$=constant.[1] From measurements equivalent to the ones presented above, we obtain a threshold field of B_{th}=0.4 T for a d=25 μm cell and $B_{th} \approx 0.6$ T for a d=15 μm cell, consistent with the above relationship (Fig. 4). As the magnetic threshold is otherwise independent on probing voltage and frequency, this implies the possibility to use the demonstrated device as an electric sensor for magnetic fields by employing a suitable cell gap for the device geometry.

The dynamics of the magnetically controlled LC-nanotube switch was investigated at a measuring voltage of V_m=0.2 V at a frequency f=2 kHz on a d=50 μm cell with a time resolution of 1 s. An illustrating curve of conductance versus time, reflecting the nanotube reorientation dynamics, is depicted in Fig. 5. The magnetic field is turned on at time t=0 s to B=1 T and the conductance steeply increases before reaching saturation. After the magnetic field is turned off at t=42 s, an exponential decay of the conductance is observed, reflecting the reorientation of the nanotubes back from the conducting homeotropic to the nonconducting planar orientation. This process is driven purely by the elastic interactions between the LC director field and the dispersed

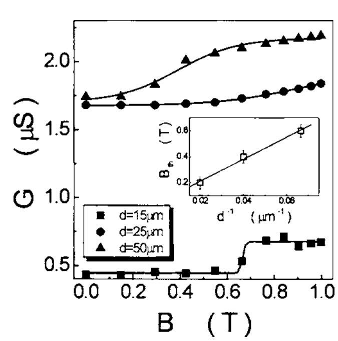

FIG. 4. Device performance for cells of different gaps between 15–50 μm. The inset demonstrates the linear dependence of the magnetic threshold B_{th} on reciprocal cell gap d^{-1}.

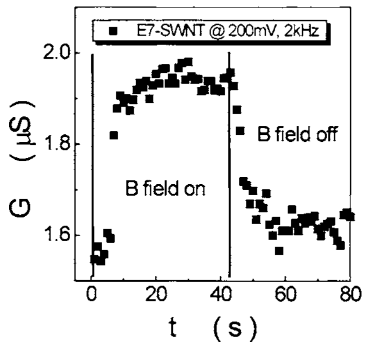

FIG. 5. Dynamic response of the magnetically steered LC-nanotube device. The characteristic decay time is found to be $\tau = (4.0 \pm 0.6)$ s.

nanotubes. Averaging the results of 12 individual dynamic conductance measurements, we obtain a characteristic time constant for the nanotube relaxation of $\tau = 4.0 \pm 0.6$ s at room temperature.

In conclusion, a magnetic field steered electric switch, based on LC-single-wall carbon nanotubes was demonstrated. The device has to be operated at low probing voltages, well below the LCs' electric threshold, and offers increasing resolution at high probing frequencies. At constant cell gap, the threshold magnetic field is independent of the probing parameters, but can be selected through variation of the cell gap.

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