New liquid crystal display with bistability and selective erasure using scattering in filled nematics

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We present a new bistable scattering effect in a filled nematic liquid crystal, and its application to a high resolution laser-addressed display. The filled nematic consists of a small fraction of inorganic particles of nm size in a nematic liquid crystal with positive dielectric anisotropy. The scattering ON state is reached by locally writing with a laser. The transparent OFF state can be obtained by combining a moderate voltage with selective application of the laser to the part to be erased. The key parameters controlling the processes and the possible physical mechanisms involved are discussed.

During the last years liquid crystal displays have become an increasingly important class of devices.[1] The large majority of these use polarizers, the effect of which is modulated by the display. In spite of all the virtues of liquid crystal displays this is still a significant drawback in terms of brightness. This is the main reason that interest in scattering displays has been revived. The best-known example is constituted by polymer dispersed liquid crystals (PDLCs),[2] formed by micron-sized randomly aligned droplets of (nematic) liquid crystals in a polymer matrix. In addition the nematic-to-cholesteric phase transition has been used to switch between a scattering and a nonscattering state.[3] Recently, a scattering type of display based on so-called filled nematics has been reported.[4,5] In this letter we present a novel variation on this principle that involves bistable switching between a scattering ON state (obtained by locally writing with a laser), and a transparent OFF state (obtained by combining a moderate voltage with selective application of the laser again). The key parameters controlling the processes and the possible physical mechanisms involved are discussed.

The filled nematic consists of a low portion of highly dispersed silica (typically 2–3 volume percent) in a nematic phase. Fumed silica[6] with primary particles form aggregates through $\equiv$Si—O—Si$\equiv$bonds, which in turn form larger agglomerates via hydrogen bonding (see Fig. 1). The BET surface is typically between 100 and 350 m^2/g. Investigations using scanning electron microscopy have shown that the nematic is divided into domains of typical dimensions in the range 50–100 nm. The material is placed between glass plates in a typical display configuration with transparent ITO electrodes and a cell thickness of about 10 μm. Such a cell has a milky appearance because of the large optical anisotropy of the nematic liquid crystal and the random orientation of the preferred direction (director) in the various domains. On application of a low frequency electric field to the display (positive dielectric anisotropy) a transparent homeotropic state can be reached.[4] This transparent state is retained if the field is switched off. The low content of the particles as well as the nature of the solid framework of agglomerates does not require any matching of the optical properties of the dispersed particles and the nematic phase, as is the case with PDLCs. Before discussing the reversal of this situation to a scattering state again, let us consider the possible mechanism.

The stabilization of the different states lies in the rebuildable agglomerates formed by the particles. If we assume strong anchoring of the nematic director at the surfaces of the particles forming the skeleton, not only the surfaces act elastically on the director, but the director also acts on the surfaces *and thus on the particles.* Reorientation of the director in an external field then can lead to a rearrangement of the particles. During this process hydrogen

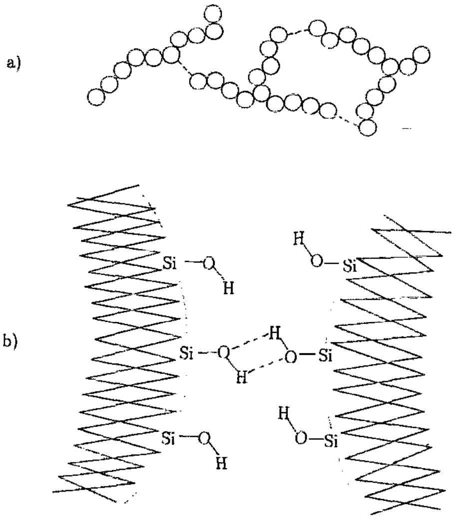

FIG. 1. Aggregates of primary particles forming agglomerates (a) via hydrogen bonding (b) after Ref. 6.

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bonds may be broken, and new ones formed with the surface orientations in agreement with the aligned director. The torque exerted by the director on a surface can be estimated as follows. The torque on unit surface in a Frederiks-transition process is given by[7]

$$\Gamma=(K/L)(\Theta_L-\Theta_0). \qquad (1)$$

Here $K\approx5\times10^{-7}$ dyne is a typical nematic elastic constant;[8] $L\approx50$ nm is half a typical domain size in the filled nematic, and Θ_L and Θ_0 are the angle between the director and the field in the middle of a domain and at the surface, respectively. Taking $\Theta_L-\Theta_0\approx1$ this leads to a torque per unit surface $\Gamma\approx0.1$ dyne/cm. Multiplying this value with a typical particle area we obtain the maximum torque per particle. For a half-sphere of an aerosil R812 primary particle[6] with a diameter of 7 nm, this area can be rounded to $100\ \text{nm}^2=10^{-12}\ \text{cm}^2$. This leads to: torque per particle: $\Gamma\approx10^{-13}$ dyne cm; energy involved: $U\approx\Gamma\times\Theta\approx10^{-13}$ erg (using again $\Theta\approx1$). The latter value can be compared to the energy of a couple of hydrogen bonds making the connection between particles. A hydrogen bond involved has typically $U\approx10\ \text{kJ/mol}=1.7\times10^{-13}$ erg/bond. We conclude that the orders of magnitude compare well. This is especially true if we realize that the hydrogen bonds not only are broken, but also will be formed again in a different direction. Hence the complete process does not require the full energy of the bonds to be supplied. These effects involve energies larger than k_BT at room temperature, so that we can expect that after reorientation of the aerosil particles the new configuration remains stable.

Illumination of the homeotropically aligned filled nematic display with a focused laser beam locally switches the display back to the scattering state.[5] This method has great advantages over the original proposal using a nematic liquid crystal that changes the sign of its dielectric anisotropy with frequency in combination with a two frequency addressing scheme.[4] To investigate the laser writing process we used a setup typically used to produce computer generated holograms.[5] This setup was designed to use an argon-ion-laser ($\lambda=514$ nm) delivering 3 mW onto the display with a spot diameter of 5 μm. Appropriate dyes (for examples 0.5% P 105 (Merck), $\lambda_{\max}=456$ nm), converting electromagnetic radiation into heat, were dissolved in the liquid crystal to reduce laser intensity needed for thermally addressed laser writing. As the contrast depends on laser energy the intensity of the laser was modulated by an acousto-optic modulator. Figure 2 shows a high information content image with 16 grey-levels in a filled nematic display. The image consists of 4096×4096 points having a diameter of about 5 μm.

To demonstrate applications, for example, as graphic output for computer aided design (CAD), we have rebuilt a setup of a conventional slide projector. A diode laser as a reliable commercial product was used as laser source delivering 17 mW ($\lambda=780$ nm) onto the display. A pair of galvanometer mirrors scans the laser beam (focused by a lens) via a dichroic mirror over the display while the image is on line projected onto a screen. The diameter of the laser focus is 40 μm and the maximum scanning speed about 0.7 m/s. Grey levels can be realized by direct modulation of the diode laser. In Table I the characteristics of the system are summarized.

FIG. 2. Photograph of a filled nematic display. 64 images, each consisting of 512×512 points, were written on an area of 2 cm^2.

The mechanism of laser writing to obtain scattering again is evidently thermal in nature. It should be realized that no heating to above the nematic-isotropic phase transition is involved. This distinguishes the display in an important way from older scattering displays that exploit the smectic-nematic phase transition, and thus require thermostatization.[9] In agreement with the above discussed mechanism we assume that the laser beam causes a thermal shock that breaks locally the aerosil network, and subsequently gives a random structure again. This in turn leads to a locally random director orientation in the domains involved, and thus to local scattering.

In the original proposal electrical erasing was obtained via switching to a homeotropic situation by applying a relatively high voltage (of the order of 100 V RMS)[4] to the display. Of course, this method can still be used for global

TABLE I. Summarizing of display properties.

Mechanism	Thermal
Thickness d	2–20 μm (typ. 10 μm)
Sensitivity	<1 nJ/μm^2
Contrast ratio	$>30:1$
Resolution	>500 lines/mm
Grey-levels	Yes
Linearity	Good
Global erase	$\geqslant70$ V @500 Hz
Selective erase	≈25 V @500 Hz
Liquid crystals	ZLI 1132 (Merck), E48 (BDH)
Dye	SC 1515 (BASF)
Aerosil (Degussa)	R812/R709 (1:1), R974

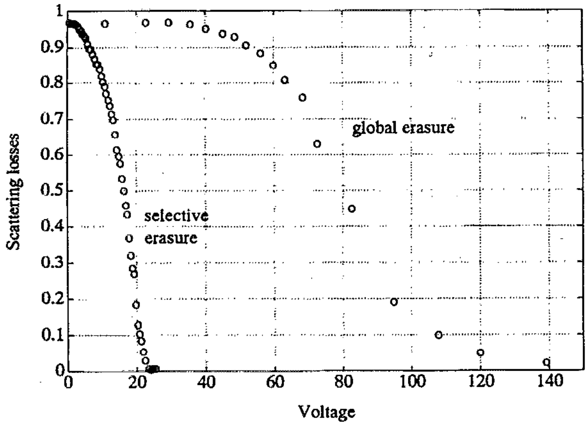

FIG. 3. Selective and global erasure as function of applied voltage in a dispersion of 3% vol Aerosil R974 in ZLI 1132.

erasure. However, the thermal shock writing mechanism suggest an alternative if combined with an electric field. A much lower voltage (about 20 V RMS) can be applied that has an effect only when combined with overwriting the information to be erased with the laser beam. Evidently the thermal shock causes the aerosil network to break up, which gives either a random scattering structure if left by itself (as during the writing process) or a homeotropically aligned transparent structure (erasing the information) if combined with a moderate electric field. To break up the network by an electric field alone a much higher voltage is required. In this way selective erasure can be achieved in a simple and elegant way (see Fig. 3).

In conclusion we have obtained a scattering liquid crystal display of excellent contrast and brightness using a filled nematic liquid crystal. Writing can be done with high resolution using a semiconductor laser, while selective erasure can be reached by repeating the writing process in combination with a moderate electric field. Grey scales can be obtained by modulation of the writing power. The display has considerable potential for applications in projection displays (for example displaying computer output) and for optical data storage.

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[9] F. J. Kahn, Physics Today **35**, 66 (1982).