# Optical patterning of magnetic domains and defects in ferromagnetic liquid crystal colloids

A . H ,[1] , [1]a _a _ a [1,2,3a)]
[1]*D a P s cs, U s C ad , B d , C ad 80309, USA*
[2]*Ma a s Sc c a d E P a , D a E c ca , C a d E E ,*
*L d C s a Ma a s R s a c C , U s C ad , B d , C ad 80309, USA*
[3]*R ab a d S s a ab E I s , Na a R ab E Lab a a d U s*
*C ad , B d , C ad 80309, USA*

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A promi ing approach in de igning compo i e ma erial i h an n al ph ical beha ior combine olid nano r c re and orien a ionall ordered of ma er a he me o cale. S ch compo i e can no onl inheri proper ie of heir con i en b al o can e hibi emergen beha ior ch a ferromagne ic ordering of colloidal me al nanopar icle forming me o copic magne i a ion domain hen di per ed in a nema ic liq id cr al. Here, e demon ra e he op ical pa erning of domain r c re and opological defec in ch ferromagne ic liq id cr al colloid , hich allo for al ering heir re pon e o magne ic eld . O r nding re eal he na re of he defec in hi of ma er em hich i differen a compared o non-polar nema ic and ferromagne alike.  [h p://d .doi.org/10.1063/1.4928552]

Liq id cr al (LC) colloid a rac a con iderable amo n of cien i c in ere dri en b he richne of heir ill mina ion, 95 $\mu$l of pen lc anobiphen l (5CB, Cheng hi Yongh a Displa Ma erials Co. L d.) as mi ed i h 5 $\mu$l of a oben ene-con aining Beam 1205 LC (Beam Co.). Non-isomeri ing FLCCs (pro ocol 2) ili ed for s rface-enabled op ical defec pa erning ere based on sing 100 $\mu$l of p re 5CB as he hos medi m, b he prepara ion pro ocol as he same o her ise. Silane-PEG capped magne ic nanopla ele s dispersed in e hanol ere hen added o he LC hile follo -ing he dispersion proced res repor ed pre io sl .[5] 5 $\mu$l of e hanol as added o 15 $\mu$l of he LC mi re o bring i o he iso ropic phase, follo ed b adding 15 $\mu$l of 0.5 1 . % magne ic pla ele s dispersed in e hanol. The sample as kep a 90 °C for 3 h o f ll e apora e he e hanol, ielding an e cellen dispersion in he iso ropic phase a ero eld, and hen as rapidl cooled o he nema ic phase of he mi re hile igoro sl s irring. The ens ing FLCC as cen rif ged a 2000 rpm for 5 min o remo e resid al aggrega ions s o ha he nal composi e con ained onl ell-dispersed pla ele s . The nal frac ion of magne ic pla ele s in he LC as aried i hin 0.05 0.1 . %, as de ermined based on absorbance and magne i a ion al es . Nanopla ele s e hibi ed s pon ane-o s alignmen i h large-area faces or hogonal o **n**(**r**) and magne ic momen s along **n**(**r**), as con rmed b measring polari a ion-dependen absorbance[16] and probing respons e of heir dil e dispersions o magne ic elds . Dispersions of fer-romagne ic pla ele s in he LC mi re ere s able a all s ed elds ( p o 20 mT) e hibi ing a facile respons e alread a elds belo 1 mT. Homeo ropic glass cells i h pol domain FLCCs and **M** poin ing in one of he o an i-parallel direc-ions along he er ical far- eld direc or $\mathbf{n}_0$ ere prepared s ing 1- or 0.17-mm hick glass pla es rea ed i h an aq e-o s s ol ion of 0.1 . % N,N-dime h l-N-oc adec l-3-ami-noprop l- rime ho s il l chloride (DMOAP, Acros Organics ) ia dip-coa ing. The cell gap hickness of 30 $\mu$m or 60 $\mu$m as s e b in erspacing he glass pla es a heir edges i h UV-c rable op ical adhesi e (NOA-65, Norland Prod c s ) or epo con aining s ilica s pacers of correspondin g diame ers . Cell lling as done a room empera re s ing capillar ac ion. FLCC cells e hibi s pon aneo s forma ion of random magne ic domains of la eral dimensions picall compara-ble or s ome ha larger han he cell hickness and dependen on he ini iali a ion eld of 10 35 mT (Refs . 4 and 16) (Fig. 1

he orien a ion of **M**(**r**) ips o an opposi e in-plane orien a-ion, as depic ed in Fig. 3(b), al ho gh **n**(**r**) s a s con in o s (Fig. 3(a)) beca se half-in eger defec s are allo ed in he **n**(**r**) line eld b no in he **M**(**r**) ec or eld.

Al ho gh, in principle, sim l aneo s pa erning of bo h **M**(**r**) and **n**(**r**) can be achie ed b combining he o approaches described abo e, i is in eres ing o no e he e ol - ion of domain s r c res in **M**(**r**) hen onl he direc or is pa erned (Fig. 4). The **M**(**r**) i hin magne ic domains in he pa erned region follo s he s pa iall ar ing **n**(**r**) i hin he magne ic domains and beha es discon in o s l ( ipping o opposi e domains ) a he in er-domain alls. A applied magne ic elds, he pol domain na re of he FLCC in erpla s i h he opologicall req ired all connec ing he half-in eger defec lines in **n**(**r**), ca sing a comple pa ern of domains and all defec s in er spacing hem, hich s lo l e ol e i h ime and s rongl depend on bo h he direc ion and s reng h of **B**. In eres ingl , he id h of all defec s i hin he regions of dis or ed **n**(**r**) is of en larger han ha in regions of niform direc or (Fig. 4). To nco er he na re of magne ic in er-domain alls in he FLCCs, e s ed dark eld microscop obser a ions ha re eal bo h loca ions and orien-a ions of indi id al nanopla ele s ( pplemen ar ideo S1)[22] a ero eld and hen **B** a differen orien a ions s elec i el s i ches he domains of opposi e **M**. Unlike in con en ional magne ic s s ems, here magne ic domains are picall

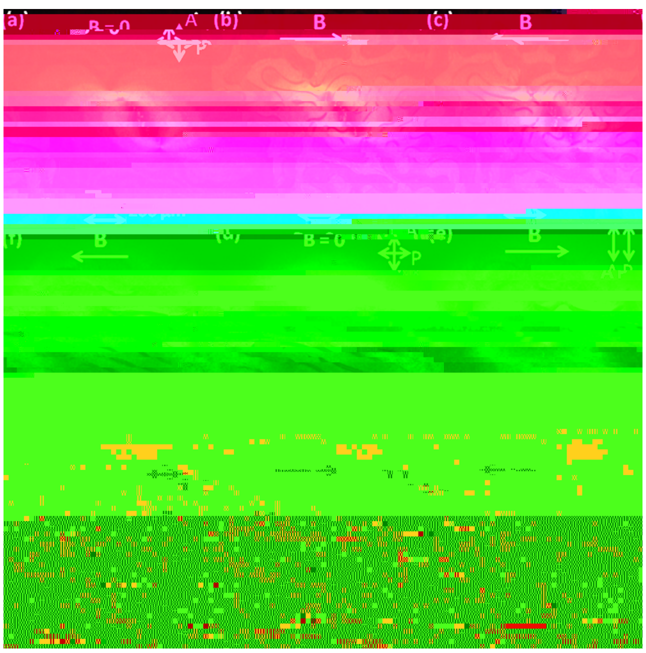


FIG. 4. POM images of FLCCs i h pho o-pa erned defec s. (a) A micrograph of he s r c re corresponding o **n**(**r**) s ho n in Fig. 3, i h he all in **M**(**r**) isible as a brigh jiggling line. An in-plane **B** along opposi e direc-ions marked in (b) and (c) s i ches complemen ar domains i h an i-parallel non- niform **M**(**r**). (d) (i) POM images of he FLCC cell i h a dis-clina ion pair. The in er-discl ina ion and o her **M**- all defec s separa ing magne ic domains are clearl isible. Polari ing micrographs (a) (d) and (g) ere aken i h crossed polari er **P** and anal er **A**, as sho n sing hi e do ble arro s. The ob ained i h parallel **P** and **A**, as sho n sing hi e do ble arro s. The red-ligh ill mina ion s ed o ob ain POM micrographs sho n in (a) (f) and ello -ligh ill mina ion s ed in (g) (i) pre en nin ended changes of s r-face bo ndar condi ions hro gh pho oalignmen d ring imaging. The compari son of micrographs (d f) and (g i), hich ere aken ≈10 min af er (d f), demons ra es slo e ol ion of domains i h ime.

separa ed b he s o-called Bloch or Néel alls[8] i h con in o s albei locali ed s oli onic deforma ions of **M**(**r**), magne i a ion a he in er-domain alls of he FLCCs is no de ned, so ha he are s ing lar in na re. This is beca se **M**(**r**) and **n**(**r**) are s rongl co pled, so ha he s oli onic deforma ions of **M**(**r**) be een he domains o ld be cos l in erms of he corresponding elas ic deforma ions of **n**(**r**). Ins ead, he do-main alls in he FLCC ha e niform direc or b nde ned **M**(**r**), so ha here is no associa ed elas ic free energ cos d e o s ch alls. A applied elds, he in er-domain alls can be par iall depri ed of nanopar icles ( pplemen ar ideo S1) and ranging in id h from he a erage s pacing be een indi id al nanopar icles o ∼1 μm, as de ermined b colloidal in erac ions be een nanopla ele s i h differen l orien ed dipole momen s of he neighboring domains of oppo-si e **M**‖**n**$_0$. When **n**(**r**) ‖**M**(**r**) i hin he domains is dis or ed, his in erpla is f r her al ered b he energe ic cos of elas ic dis or ions (Fig. 4). Al ho gh he domain all defec s in he FLCCs are s ing lar in **M**(**r**), differen from he s oli onic Bloch or Néel alls commonl obser ed in magne ic s s-ems,[8] one-, o-, and hree-dimensional is ed s oli ons can also form in he chiral co n erpar s of he FLCCs, in hich is ed **n**(**r**) ‖**M**(**r**) s r c res are promo ed b he chiral na-re of he LC hos id.[16]

Unlike con en ional LCs, hich e hibi a response o magne ic elds ha is m ch less facile han he response o elec ric elds, he FLCCs are s i ched a ≈1 mT elds and e hibi polar response. Al ho gh ei her onl magne icall ni-form or random pol domain FLCC samples ere s died pre-io s l ,[4,7,16] o r ork demons ra es ha he magne ic domains can be pa erned on mesoscopic leng h scales in man differen a s, h s allo ing for engineering he mac-roscopic response of s ch ma erials o magne ic elds. Since his pa erning is achie ed in a re-con g rable fashion, s ing lo -in ensi ies of ligh , o r ndings ma enable designs and implemen a ions of mesos r c red s of ma er composi es i h n s al proper ies and facile pre-de ned responses o eak e ernal s im li. Be ond he po en ial prac ical s es, he e perimen al frame ork e ha e de eloped ma allo one o s d ho he polar na re of ordering in s of ma er gi es rise o ne pes of opological defec s and s oli ons. In addi-ion o s mall-molec le liq id cr s alline hos s of magne ic nanopar icles, he FLCC ordering can po en iall be pa erned in pol meric, elas omeric, and o her s of ma er s s ems.

To concl de, e ha e demons ra ed he op ical pa erning of magne ic domains and defec s in he FLCCs. Beca se of he facile magne ic s i ching i h eas il con g rable domain po-lari and elas ic dis or ion pa erning, o r e perimen al frame-ork ma lead o reali ing s r c res and composi es ell be ond he ones presen ed in his le er. The in rod c ion of chirali and par icle-like e ci a ions can enable magne ic con-rol of comple op ical phenomena, s ch as nema icon forma-ion and de ec ion,[17] s elec i e re ec ion ning,[18,19] non-con ac manip la ion of defec s,[20,21] e c. Moreo er, pol mer or elas omer ne orks in he FLCCs ma ield no el mechanical beha ior of he ens ing s of s olids, s ch as programmable s rain biases and s elec i e mechanical ac a ion.[12,14]

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