Three-dimensional imaging of liquid crystal structures and defects by means of holographic manipulation of colloidal nanowires with faceted sidewalls

David Engström,[ab] Rahul P. Trivedi,[ac] Martin Persson,[ab] Mattias Goksör,[b] Kris A. Bertness[d] and Ivan I. Smalyukh*[ace]

Received 1st February 2011, Accepted 27th April 2011

to evaporate t e isopropano at ∼ °C on a otp ate e ﬁna ixture consistin of dye doped CLC and rods was stirred just before t e CLC ce preparation to i prove t e qua ity of dispersion FC M and po arizin icroscopy textures s ow t at t e GaN nanowire exerts tan entia surface boundary conditions on t e iquid crysta director a i ns para e to it and inor additiona oca director distortions appear on y at t e rod s ends Fi b and e w i e t e studied structures and defects re ain unperturbed

o pro ote appearance of dis ocations in c o esteric a e ae wed e CLC ce s wit a s a di edra an e α ° and p anar c o esteric structure were fabricated by use of t ic ass p ates e substrates were spin coated wit ∼ wt so ution of po y viny a co o A in deionized water at rp fo owed by ba in in an oven for at °C wo types of ce s were used for so e ce s t e A coated substrates were asse b ed wit no furt er treat ent w i e for t e ost ce s t e A coated substrates were unidirectiona y rubbed wit a ve vet c ot to force t e iquid crysta o ecu es to a i n para e to t e rubbin direction ed e s aped ce s were prepared by usin μ spacers on one ed e of t e ce and no spacers on t e opposite ed e e ce s were t en ﬁ ed wit a iquid crysta and sea ed wit epoxy e con ﬁne ent of t e CLC into t e wed e s aped ce s pro oted faci e appearance of defects suc as dis ocations and disc inations w ic we ave i a ed by eans of FC M and c assi ﬁed accordin to t e sc e e of K e an and Friede [16] In t e so ca ed λ disc inations t e ateria **n** director ﬁe d is non sin u ar because of **n** bein para e to t e defect ine in its core so t at t e sin u arity is observed on y in t e i a teria director ﬁe ds of CLC e ica axis **c** and τ ort o ona to bot **n** and **c** In t e τ disc inations t e τ ﬁe d is non sin u ar but **n** and **c** director ﬁe ds are sin u ar In χ disc inations t e sin u arities are found in **n** and τ director ﬁe ds but not in t e **c** ﬁe d

2.2. Integrated optical setup for imaging and manipulation

o anipu ate nanowires we ave uti ized o o rap ic optica tweezers H [15,25] In t e H setup Fi a co i ated bea fro a inear y po arized Ytterbiu doped ﬁber aser I G otonics $\lambda =$ n is resized by a te escope to s i t y over ﬁ t e active area of t e p ase on y spatia i t odu ator Bou der Non inear yste s e ave used aser trap powers of s a er t an t e CLC rea i n ent t res o d After bein re ected off t e LM t e bea is coup ed into t e back aperture of a × oi i ersion icroscope objective NA = ∼ trans ission at n by usin a second te escope e second te escope in t e so ca ed f arran e ent a so i a es t e p ase pro ﬁe encoded by t e LM to t e back foca p ane of t e icroscope objective e o o ra s disp ayed on t e LM create trap patterns in t e foca p ane of t e icroscope objective A dic roic irror C ro a re ects t e trappin aser bea into t e icroscope objective w i e trans its visib e i t used for

rod s aped or need e s aped nanopartic es a i nin wit t e director to en ance t e response to externa a netic e ds i i ar y e asticity ediated a i n ent of nanorods in CLCs wit optica y tunab e c o esteric pitc a owed for ac ievin rotation of co oida rods by eans of optica i u ination en dispersed in CLCs t e nanowires orient a on **n r** of t e equi ibriu e icoida structure Fi f As t e c o esteric pitc decreases fro in ﬁnity ne atic to t e used re ative y s ort pitc va ues of μ wit t e addition of t e c ira dopant ab e t e an u ar distribution of nanowire orientations broadens Fi a t ou t e widt of t e distribution re ains a fraction of de ree even for t e CLC wit $p =$ μ e reason for t e distribution broadenin is i e y t at t e transverse size of t e nanowire corresponds to a certain an u ar twist of t e equi ib riu e icoida structure of t e CLC $p \sim$ de rees for $p =$ μ is resu ts in a wea er e astic suppression of t e an u ar t er a uctuations of t e nanowire in t e CLC atrix as co pared to t e case of t e ne atic a t ou t e co oida nanowire sti a i ns para e to t e oca **n r** correspondin to t e center of t e nanowire

e contro and probe D nanowire orientations and positions in t e CLC by use of a co bination of o o rap ic optica tweezers wor in at $\lambda =$ n optica trans ission icros copy and a stepper otor contro in t e sa p e s vertica position re ative to t e foca p ane of an objective wit n precision For optica anipu ation one or two aser traps are positioned at t e ends of a nanowire and t en used to rotate and ove it in D In CLCs nanowire orientation and position a on t e e ica axis are coup ed to eac ot er trans ation across t e c o esteric ayers is possib e on y *v a* rotation fo owin t e e icoida **n r** Fi f and ideo e andedness of t e e ix and t e rotation direction deter ine w et er t e nanowire oves upward or downward its trans ation away fro t e icroscope objective is typica y easier t an toward it due to t e scatterin forces ori inatin fro t e ar e nanowire CLC refractive index is atc e easured vertica position nw of a nanowire a on t e e ix is a inear function of its in p ane orientation an e ϕ_{nw} Fi f consistent wit t e **n r** of t e equi ibriu e icoida structure **n** = cos π sin π

Fro t e inear ﬁt of t e experi enta data s own in Fi f by nw $= \phi_{\text{nw}}\, p$ π t e easured effective pitc is $p =$ μ atc in t at obtained fro t e FC M cross section in t e sa e ocation top ef t inset of Fi

In order to app y our tec nique to i a in of co p ex D director structures and defects we ave constructed wed e c o esteric ce s wit a di edra an e about and stron surface anc orin t at eeps near surface c o esteric ayers para e to substrates E e entary ed e dis ocations perpendicu ar to t e direction of t e t ic ness radient introduce additiona c o e steric a e ae in accord wit increasin t ic ness of t e wed e Fi ese dis ocations ave t eir cores sp it into disc ination pairs and are often acco panied by ot er c o esteric defects for in co p ex D conﬁ urations of **n r**

A t ou t e non destructive D i a in of **n r** around defects can be ac ieved by eans of o o rap ica y anipu ated nanowires a one we use FC M i a in for t e co parative ana ysis of nanowire positions and orientations re ative to **n r** In t e vertica FC M cross sections t e nanowires oriented ort o ona y to t e confoca i a e ive rise to a dar trian u ar wed e spreadin upward fro t e position of t e rod Fi a w ic is due to t e scatterin of t e FC M excitation i t by t e i index GaN nanowire $n_{\text{GaN}} =$ uc ar er t an t e effective CLC indices wit in ptica trans ation of a nanowire serves as a sin e partic e probe of **n r** a owin one

not on y to easure t e equi ibriu pitc but a so to ap c an es in its effective va ue due to defects yie din resu ts t at are in a ree ent wit FC M i a in Fi e confoca vertica cross sections in Fi s ow sequentia trans ation of t e nanowire a on a Bur ers circuit wit t e trans ation across t e c o esteric ayers i p e ented by rotatin t e nanowire e atte pted optica trans ation of a nanowire across t e dis oca tion discontinuity in a ayered CLC structure resu ts in stretc in of t e dis ocation resisted by its ine tension for exa p e w en ovin t e nanowire fro point in Fi c to t e ri t we observe t at as t e dis ocation eventua y oves to t e ri t and stretc es w en t e nanowire approac es t e defect core A co bination of rotationa and trans ationa otion upward or downward in accord wit t e disp ace ent of t e ayers to preserve its orientation para e to t e oca **n r**

nonsin u ar disc inations in its core sp it into t e λ f $^{-}$
pair en t e nanowire is p aced on t e λ disc ination side o $_{f}$

Supplementary Information

Three-dimensional imaging of liquid crystal structures and defects by means of holographic manipulation of colloidal nanowires with faceted sidewalls

David Engstršm,[a,b] Rahul P. Trivedi,[a,c] Martin Persson,[a,b] Mattias Goksšr,[b] Kris A. Bertness,[d] and Ivan I. Smalyukh[a,c,e*]

[a]Department of Physics, University of Colorado, Boulder, Colorado 80309, USA

[b]Department of Physics, University of Gothenburg, 412 96 Gšteborg, Sweden

[c]