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Anti-IgG-anchored liquid crystal microdroplets for label free detection of IgG†

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The orientational variation of 4-cyano-4'-pentyl biphenyl (5CB) molecules in LC microdroplets in response to IgG antigen (IgG) interactions has been utilized to develop a biosensor for rapid and label-free detection of IgG in biological fluids. In order to prepare a LC microdroplet-based biosensor, the anti-IgG (AlgG) anchored 4-cyano-4'-pentyl biphenyl LC microdroplets were prepared in the presence of sodium dodecylsulfate (SDS) as a mediator and amphiphilic poly(styrene-*b*-acrylic acid) (PS-*b*-PA) as a modifier of the LC/water interface. The AlgG-anchored LC microdroplets with a size variation from 20 to 30 μm have been used successfully for the detection of IgG within a concentration range of 20 to 1000 ng mL^{-1} , at a detection limit of as low as 16 ng mL^{-1} , and a response time of 30 min in PBS solution at room temperature. The LC microdroplets anchored with 5 $\mu\text{g mL}^{-1}$ of AlgG were found to be more sensitive for the detection of IgG in the concentration range from 20 to 800 ng mL^{-1} in PBS. The AlgG-anchored LC microdroplets have shown a delayed response of 90 minutes for IgG in a solution containing 10% FBS or 10% blood plasma in comparison to PBS solution. The LC microdroplets anchored with 5 $\mu\text{g mL}^{-1}$ (34 pmol) of AlgG have shown a recovery of 106% of IgG, a coefficient of variance of $\pm 4\%$ and a precision within a limit of 1–6% for a spiked sample of 25 ng mL^{-1} of IgG. The results indicated that orientational response of LC microdroplets is potentially useful to develop a biosensor for *in vivo* detection of proteins or pathogens in a biological fluid.

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1. Introduction

The protein level in blood serum provides a direct basis to assess the state of disease in a patient. Therefore, blood serum proteins are considered as attractive targets to develop sensors for the detection and diagnostic applications of diseases. The simple and sensitive immunoassaying of disease antigens under homogeneous liquid conditions using label-free techniques potentially eliminates the need for traditional cumbersome microscopic methods,¹ which require skilled personnel and sufficient time for preparation of samples for analysis. Therefore, there is a need to develop a rapid and cost-effective diagnostic method for the sensitive detection of disease-causing antigens in infected blood samples. The conventional enzyme-linked immunosorbent assaying (ELISA) method is time consuming for immunoassaying of proteins in the blood and feasible upon interaction of immunoreagents on contacting surfaces.² At present, owing to the high specificity and strong affinity of antibodies

for disease-causing antigens, immunoassaying using antibody-antigen interactions is the preferred tool for the detection of nanomolar amounts of antigen in the blood samples.³ The activity of gold nanoparticle (AuNP)-antibody conjugates in the detection of antigens has been shown to be dependent on the method of conjugation of the antibody.^{2,4} A number of immunoassaying methods, such as fluorescence polarization,⁵ fluorescence resonance energy transfer (FRET),³ bioluminescence resonance energy transfer,⁶ surface plasmon resonance,⁷ and light scattering,⁸ have been used for the detection of proteins in blood samples. However, most of these homogeneous protein assaying methods have been found to be less sensitive and expensive in comparison to other methods such as ELISA and dot-blot immune methods.⁹ Most antibody-anchored nanoparticle-based sensitive immunoassaying methods used for the detection of antigens, SKBR-3 breast cancer cells,^{10–15} and bacteria^{16,17} require the extraction of antigens from cells for the immunoassay to be performed. This introduces difficulties in assaying antigens precisely, as these methods involve several steps for immunoassaying of antigens in biological matrices. The enhanced fluorescence technique has also been used in immunoassaying *Escherichia coli* strain O157 using antigen-coated silica nanoparticles.¹⁸ Recently, aptamer-bacterial protein interactions have been exploited for the detection of bacteria utilizing aptamer-coated CdSe/ZnS quantum dots.¹⁹ Upconversion nanoparticles (UCNs)

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conjugated with an anti-HER2 antibody have been successfully utilized for the detection of the fluorescent HER2 receptors of SKBR-3 breast cancer cells.²⁰ The antibody-immobilized microchip of an electrochemical immunoassay system was found to be able to detect prostate-specific antigens in human serum with 75% accuracy.²¹ However, fluorescent green protein-nanoparticle conjugates were found to be able to simultaneously detect five serum proteins with 100% success in buffer, and 97% success in human serum.²² The long range orientation order of LC molecules has been used successfully to develop biosensors for the detection of the P53 mutation gene within the concentration range from 0.08–8 nM.²³ The conformational changes in oligonucleotides upon interactions with heavy metal ions have been used to develop a LC based biosensor for label free detection of Hg²⁺ ions with a lower limit of detection (LOD) of 0.1 nM.²⁴ To enhance the sensitivity in the detection of analytes, the signal enhanced LC DNA biosensor has been developed using the enzymatic silver deposition method.²⁵ These studies clearly indicate that antibody-conjugated LC based biosensors may be developed for the detection of disease causing proteins and cancer-specific antigens. The liquid crystal microdroplet based biosensor for the detection of antigens is not reported in the literature. However, LC microdroplet based sensors have been used in the detection of interfacial events involving interactions between chemicals^{26–31} and viruses.³² In some other studies, LC signal based systems have been used for the detection of proteins on solid surfaces^{33–36} and LC–water interfaces.^{37–39} Unlike AuNP-based immunoassaying of proteins, LC signal based detection systems do not require fluorescent labeling as the orientational response in LC molecules is utilized as the basis for detection of antibody–protein interactions at the interface. The LC-based sensing systems have been simplified by using LC molecules as small droplets, which found to be potentially more sensitive^{40–46} in comparison to LC molecules used for sensing on solid surfaces.^{33–36} The high sensitivity of LC microdroplets is attributed to their small size, mobility, and high surface area in comparison to solid-surface LC systems.^{47,48} The interfacial area of LC molecules in the form of microdroplets is comparatively more than the same amount of LC molecules placed on confined planar surfaces. The LC droplets have a well defined director with tunable optical properties.^{49–51} The interaction forces between LC microdroplets and species are sufficiently enough to produce a detectable optical signal in the presence of a small amount of species at the interface. The sensitivity of LC molecules on planar solid surfaces is limited as interaction forces are not sufficient to cause detectable optical transitions in LC molecules in the presence of a small amount of analytes at the interface. Recently, a microfluidic device-based LC system is developed for naked eye detection of antibodies with a lower limit of detection of 1 $\mu\text{g mL}^{-1}$,⁵² which supported the enhanced sensitivity of LC molecules as microdroplets. The response of LC microdroplets to interfacial forces is also found to vary with the type of polymer and surfactant used in their fabrication.^{42,47,53–56} Similar trends were observed in our recent studies on the LC microdroplet system used for the detection of KB cancer cells.⁵⁶ Considering the studies reported in

the literature, it has been hypothesized that the polystyrene segment of amphiphilic polymer has played a significant role in controlling the optical response in LC microdroplets upon interaction with antigens at the interface. Studies reported in the literature clearly indicate that the orientational response of LC microdroplets could be used^{40–46,52} for a sensitive and label-free detection of antigens in comparison to LC molecules on solid surfaces^{33–36,47,48} and antibody-conjugated AuNPs.^{2,4} Therefore, in the present study, we attempted to develop a LC microdroplet-based biosensor for label-free detection of IgG using AIGG-anchored LC microdroplets in PBS solution. The response of LC microdroplets for the detection of IgG was also determined in 10% FBS and 10% blood plasma. LC microdroplets developed with different amounts of AIGG were used for the detection of IgG in PBS and other media and to optimize the amount of AIGG to control the sensitivity of LC microdroplets.

2. Experimental

2.1 Materials and methods

Poly(styrene-*b*-acrylic acid) (PS-*b*-PA) (M_w : 7246 g mol^{−1}), 4-cyano-4'-pentyl biphenyl liquid crystals in 98% nematic phase (5CB) (M_w : 249.15 g mol^{−1}, m.p.: 24 °C), sodium dodecylsulfate (SDS) (M_w : 288.38 g mol^{−1}), di-*tert*-butylpyrocarbonate, 1-ethyl-3-(3-dimethyl aminopropyl) carbodiimide hydrochloride (EDC) (M_w : 312.38 g mol^{−1}), *N*-hydroxysuccinimide (NHS) (M_w : 115.09 g mol^{−1}), and fluorescein isothiocyanate (FITC) were purchased from Sigma-Aldrich Chemical Company, USA, and used as received. Phosphate-buffered saline solution (PBS) of pH 7.4 was used for washing and dispersion of LC microdroplets. The >95% pure reagent grade (SDS-PAGE) salt-free lyophilized white powder of rabbit antigen (IgG) (150 kDa) was purchased from Sigma-Aldrich Company, USA, and stored at <8 °C before using as a reference antigen for immunoassaying of pathogens (viruses and bacteria) by LC microdroplets. Unconjugated rabbit anti-IgG (AIGG) (M_w : 150 kDa, lyophilized white powder) was purchased from Sigma-Aldrich Company, USA. This AIGG is specific to rabbit IgG and does not react with human immunoglobulin-G (IgG). All measurements were carried out in PBS solution. Ultrapure water was prepared using the Milli-Q system and used in all experiments. UV spectra were recorded using the double beam spectrophotometer and the UV-vis spectrophotometer, Jasco-650, USA. The size distribution of LC microdroplets was determined using the optical microscope (Nikon Eclipse TS100, Japan) and the particle size analyzer (Beckman coulter, N/LS-1332, USA). Optical and polarized optical microscopy images of LC microdroplets were recorded using the Olympus IX 71 inverted fluorescence microscope in both cross-polarization and transmission modes. The upright fluorescence microscope (Olympus BX61, Olympus America Inc., USA) with a fluorescent filter tube above objective lenses, coupled with a digital camera, was used for detection of FITC (λ_{EX} = 519 nm). The AIGG- and FITC-AIGG-conjugates were synthesized by anchoring AIGG and FITC-AIGG to LC microdroplets.

2.2 Preparation of LC microdroplets

In order to prepare LC microdroplets, 10 mg (1.4 μmol) of block copolymers (PS-*b*-PA) were added to a 100 mL round bottom flask containing 10 mL PBS solution and 10 mg (35 μmol) of sodium dodecylsulfate (SDS). The mixture was magnetically stirred for about 30 min at 800 rpm for thorough mixing of SDS with the amphiphilic block copolymer (PS-*b*-PA) to obtain a homogeneous mixture of PS-*b*-PA with SDS. Next, the LC microdroplets were prepared by dropwise addition of 10 mL PBS solution containing 50 mg (200 μmol) of 4-cyano-4'-pentyl biphenyl (5CB) liquid crystal (98% nematic phase) to the homogeneous solution of PS-*b*-PA and SDS. The resulting mixture was stirred continuously at 11 000 rpm for 1 min for homogeneous dispersion of LC microdroplets. The emulsion consisting of dispersed LC microdroplets was centrifuged at 800 rpm in PBS solution (pH 7.4) to separate LC microdroplets from unused 5CB, SDS, and PS-*b*-PA. After removing supernatant containing small-sized microdroplets, the centrifuged LC microdroplets were dispersed in PBS solution and centrifuged again to collect the size-selected samples of LC microdroplets. These LC microdroplets were preserved in PBS solution for anchoring with AIGG in order to study their interactions with IgG in PBS and other media such as 10% FBS and 10% blood plasma. The size distribution of LC microdroplets was determined using the optical microscope (Nikon Eclipse TS100, Japan) and the particle size analyzer (Beckman coulter, N/LS-1332, USA). The orientational state of 5CB molecules in LC microdroplets was determined by recording optical and polarized optical microscope images using the Olympus IX 71 inverted fluorescence microscope operating in both cross-polarization and transmission modes. The bipolar and radial configuration of LC microdroplets was confirmed on the basis of their optical texture visible in optical micrographs recorded using the Olympus IX 71 inverted fluorescence microscope. The optical images of LC microdroplets after interactions with IgG have shown two points of defects (boojums) indicating orientational transition from radial to bipolar. The bright field images of LC microdroplets after interaction with IgG have shown a bright spherical dot with dark dimples, confirming the transition from radial to bipolar. The orientation of 5CB molecules in LC microdroplets was found to be opposite to that reported by other workers.^{45,46,57} The application of a small amount of SDS (51 μmol) in the fabrication of LC microdroplets has produced microdroplets with bipolar orientation⁴² in comparison to SDS (17.3 μmol) used in our studies which stabilized the LC molecules in a radial configuration.

2.3 Conjugation of anti-IgG to LC microdroplets

The AIGG-anchored LC microdroplets were prepared by conjugating AIGG with the activated carboxylic group of amphiphilic block copolymers in LC microdroplets. In order to activate the carboxylic group of amphiphilic block copolymers in LC microdroplets, 1.0 mL of concentrate (9×10^3 microdroplets per mL) of LC microdroplets was added to a round bottom flask containing 10 mL of PBS. To this solution, 100 mg (320 μmol) of NHS and 100 mg (870 μmol) of EDC were added

and the solution was incubated for 1 h at room temperature in the dark. Next, 5 μg (34 pmol) of AIGG was added and after 12 h, the mixture was dialyzed using regenerated cellulose nitrate membranes to remove unused EDC, NHS, and other impurities. Finally, AIGG-anchored LC microdroplets were washed with PBS solution to remove unused AIGG. The amount of AIGG anchored on LC microdroplets was determined by the Bradford method by using the calibration curve drawn at $\lambda_{\text{max}} = 278$ nm for different amounts of AIGG in PBS solution. The configuration of 5CB in LC microdroplets, before and after conjugation of AIGG, was determined by polarized optical microscopic examination of 1.0 mL of PBS solution of AIGG-anchored LC microdroplets in a 1.0 cm diameter dish. The LC microdroplets were also prepared by varying the amounts of AIGG from 10 to 100 μg^{-1} 10 mL (6.8–68 pmol) in PBS solution containing 9×10^3 LC microdroplets to optimize the amount of AIGG for sensitive LC microdroplets for the detection of IgG.

2.4 Synthesis of FITC- and anti-IgG-anchored LC microdroplets

In order to confirm the presence of anti-IgG (AIGG) in LC microdroplets, AIGG was firstly conjugated with FITC and used to anchor to LC microdroplets. For conjugation of FITC with AIGG, 5 μg (34 pmol) of AIGG was added to a 10 mL solution of PBS containing 100 mg each of EDC and NHS. The solution was kept for 1 h at 5 $^{\circ}\text{C}$ to activate the carboxylic group of the antibody. A freshly prepared 10 mL volume of DMSO solution containing 50 μg of FITC was added gently to this solution and left for 8 h in the dark at 5 $^{\circ}\text{C}$. The reaction mixture was dialyzed using regenerated cellulose acetate membranes and FITC-conjugated AIGG was washed with PBS solution and lyophilized to obtain a powdery white solid. To anchor the FITC-conjugated AIGG on the LC microdroplet, 10 mL of PBS solution containing 25 μg FITC-conjugated AIGG was added to a 100 mL round bottom flask containing 1.0 mL of LC microdroplets (9×10^3 microdroplets per mL), activating agents (EDC and NHS, 100 mg each), and 10 mL PBS solution. The mixture of FITC-conjugated AIGG and LC microdroplets was incubated for 8 h at 5 $^{\circ}\text{C}$. Then solution was dialyzed in PBS solution using the regenerated cellulose membrane. Finally, LC microdroplets were preserved after washing with PBS solution to remove unused FITC-conjugated AIGG. In order to confirm the conjugation of FITC with AIGG, the UV spectra of FITC, AIGG, and FITC-conjugated AIGG were recorded using the UV-vis spectrophotometer. The upright fluorescence microscope (Olympus BX61, Olympus America Inc., USA) with a fluorescent filter tube above the objective lenses, coupled with a digital camera, was used to record the micrographs ($\lambda_{\text{EX}} = 519$ nm) of FITC- and AIGG antibody-conjugated LC microdroplets. The optical and polarized optical microscopy images of LC microdroplets with and without FITC-coupled AIGG were recorded using the Olympus IX 71 inverted fluorescence microscope, operating in both cross-polarization and transmission modes, to confirm the anchoring effect of AIGG and FITC-AIGG conjugates on the orientational state of 5CB molecules in LC microdroplets. The micrographs were recorded using 1.0 mL solution of LC microdroplets

(9×10^3 microdroplets per mL) with and without FITC-conjugated AIGG in a optical dish of 1.0 cm diameter in PBS solution, to enable the microdroplets to move freely and prevent overlapping in the optical path during recording of micrographs. All experiments were performed in triplicates, and optical and polarized optical images were recorded at three different locations of the optical dish containing LC microdroplets.

2.5 Detection of rabbit-IgG using anti-IgG-anchored LC microdroplets

In order to measure the orientational variation of 5CB molecules in anti-IgG (AIGG)-anchored LC microdroplets for the detection of IgG, fixed amounts of pristine and AIGG-anchored LC microdroplets were incubated by varying the amount of IgG from 0 to 1000 ng mL⁻¹ in PBS and in other media such as 10% FBS and 10% blood plasma. In order to determine the response time of AIGG-conjugated LC microdroplets, the AIGG-conjugated LC microdroplets were incubated for different time-periods ranging from 30 to 90 min in PBS solution containing a known amount of IgG. After incubation, polarized optical microscopy images were recorded to visualize the effect of IgG interactions on the orientational state of 5CB molecules in LC microdroplets. The orientational variation in 5CB molecules in LC microdroplets was used to evaluate the response time. The sensitivity, lower detection limit and reproducibility of the optical response of LC microdroplets in the detection of IgG were determined by carrying out experiments in triplicates. The orientational response of LC microdroplets with different amounts of AIGG is evaluated to fabricate the LC microdroplets with high sensitivity and lower limit of detection of IgG in the solution. In a different set of experiments, the orientational response of LC microdroplets was recorded in the presence of 10% blood plasma to analyze the effects of other proteins such as blood human globulins (IgG, IgA, IgM, *etc.*) in the detection of IgG by AIGG-anchored LC microdroplets.

3. Results and discussion

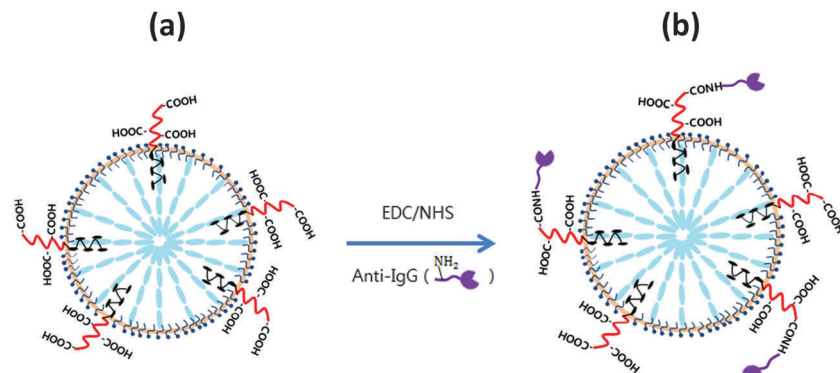
The development of a rapid and reliable method for the detection of antibodies and antigens in human blood serum is expected to be useful in diagnosis of diseases using infected blood samples.⁵⁸ Detection of an antibody and its assaying is found to be redundant in differentiating the past and present infections or in assessing the efficacy of treatments. This problem may be circumvented by detecting antigens and the assaying method.⁵⁹ Several studies have indicated that immunoassaying of antigens is more useful for diagnosis of diseases than assaying the antibodies.^{60,61} Various diagnostic approaches based on fluorescence immunoassaying using nanoparticles or quantum dots anchored with dye-labeled antibodies have been reported for the detection of antigens and tumor cells.^{21,22} In these studies it has been demonstrated that NP-based imaging probes emit a strong fluorescence signal, thus providing improved detection sensitivity for clinical applications. In order to achieve antigen-specific targeting and emission of strong

fluorescence for clinical applications, the fluorescent nanoparticles must be modified with high affinity targeting moieties. The surface of fluorescent nanoparticles needs to be modified appropriately in order to increase the stability and half-life of NPs in blood circulation. In view of these limitations of immunofluorescent-NPs, the AIGG-anchored LC microdroplets were prepared for sensitive and rapid detection of IgG in blood serum by recording optical signals of 5CB molecules in AIGG-anchored LC microdroplets. The goat AIGG is a secondary antibody with strong affinity for binding the heavy chains of rabbit IgG. In order to enhance the sensitivity of 5CB in the detection of interfacial interactions, 5CB was used in the form of LC microdroplets^{40–46} to enable the achievement of an optically detectable response in the presence of virus and bacteria. The small-sized 5CB droplets provided more surface area and sensitivity, similar to the nanoparticle-based assaying methods.^{62,63} The force of interfacial interactions in the presence of minimal amounts of IgG (<20 ng mL⁻¹) was sufficient to produce detectable optical signals by 5CB in LC microdroplets; however, 5CB on the solid planar surface produces optically detectable signals in the presence of microgram amounts of analytes.^{34,35,64} This indicated that 5CB in the form of microdroplets is more sensitive to interfacial events and interactions than 5CB on solid planar surfaces. The LC microdroplets and AIGG-anchored LC microdroplets showed a radial configuration (Scheme 1) but AIGG-anchored LC microdroplets were only successful in showing orientational variation upon interaction with IgG (Scheme 2). As pristine LC microdroplets were not able to interact strongly with IgG, orientational variation from radial to bipolar was visible in AIGG-anchored LC microdroplets in PBS (pH 7.4) solution and other media (Scheme 2). The change in configurational transition in LC microdroplets on interaction with IgG provides the basis for real-time and sensitive detection of IgG in biological fluids.

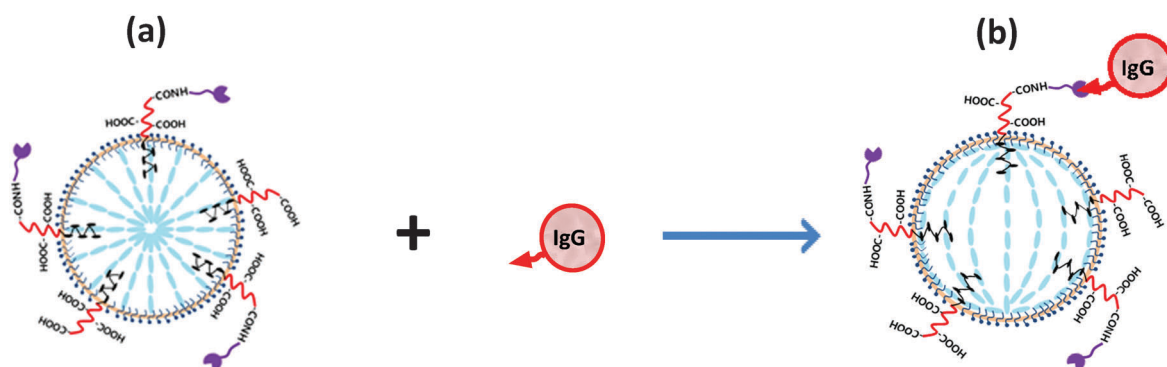
3.1 Synthesis of FITC- and anti-IgG-anchored LC microdroplets

In order to confer target-specific binding affinity to LC microdroplets, the AIGG-anchored LC microdroplets were prepared using the amphiphilic block copolymer (PS-*b*-PA) and 5CB in the presence of the SDS surfactant by the method reported in our earlier communication.⁵⁶ The anchoring of AIGG is carried out using a fraction of LC microdroplets of sizes varying from 20 to 30 μ m. The absorbance ($\lambda_{\text{max}} = 278$ nm) of the mixture of the filtrate and LC microdroplet washings was determined by the Bradford method (Fig. 1) to find out the amount of AIGG anchored on LC microdroplets.

The AIGG-anchored LC microdroplets within the size range of 20–30 μ m have produced naked eye-visible signals in polar micrographs upon interaction with IgG. These were not observed for the AIGG-anchored LC microdroplets whose size was lower than 10 μ m. However, the configurational state of 5CB in LC microdroplets was similar to that in the LC microdroplets of size 20–30 μ m. The configuration of 5CB in LC microdroplets was confirmed by recording polar micrographs using polarized optical microscopy. These results indicate that 5CB molecules are



Scheme 1 Orientational state of 5CB in LC microdroplets before (a) and after (b) anchoring AlGg.



Scheme 2 Orientational state of 5CB in AlGg-anchored LC microdroplets before (a) and after (b) interactions with IgG.

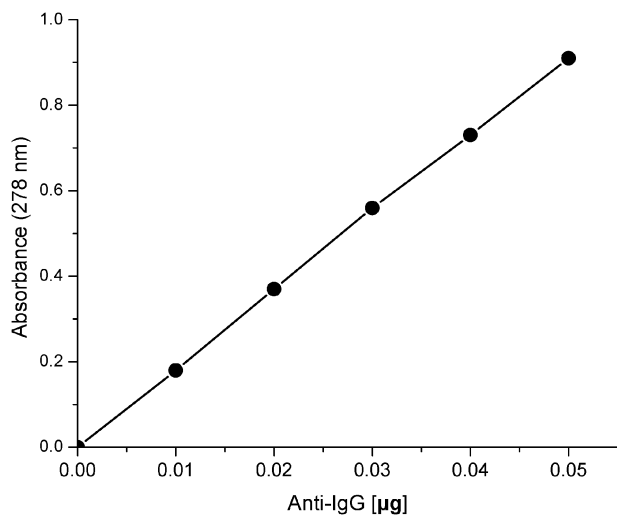


Fig. 1 Calibration curve for quantitation of AlGg.

stabilized in a radial configuration in the LC microdroplets, due to the dynamic nanostructure of the amphiphilic block copolymer and the SDS surfactant at the interface and in the core of the microdroplets. The styrenic benzene of the amphiphilic block copolymer was found to control the orientation of 5CB molecules in the core of LC microdroplets, while polar and hydrophobic alkyl parts of SDS controlled the interactions of

5CB at the interface and within the bulk of the LC microdroplets. The 1:5 weight ratio of SDS and the amphiphilic block copolymer employed was able to stabilize 5CB in a radial configuration in LC microdroplets ranging from 10 to 30 μ m in size in PBS (pH 7.4) solution.

The presence of an absorption band at 495 nm in the UV spectrum of FITC-conjugated AlGg (Fig. 2b) confirmed the conjugation of FITC (Fig. 2a) with AlGg (Fig. 2c). The UV spectrum of pure FITC showed a characteristic band⁶⁵ at 500 nm (Fig. 2a). Pure AlGg did not show an absorption band at around 500 nm (Fig. 2c). The fabricated FITC-conjugated AlGg was subsequently used to anchor to LC microdroplets using activating agents EDC and NHS (100 mg each) in PBS solution at 5 °C. In order to confirm the presence of AlGg on LC microdroplets, fluorescence images of LC microdroplets anchored with the FITC-AlGg conjugate were recorded using fluorescence microscopy. The presence of green fluorescence of LC microdroplets confirmed the anchoring of AlGg to LC microdroplets (Fig. 3).

The fluorescence images of LC microdroplets anchored with the FITC-AlGg conjugate also confirmed the average size variation of LC microdroplets (10–30 μ m) in the samples (Fig. 3). The anchoring of AlGg to LC microdroplets (Scheme 2) did not elicit a change in the configurational state of 5CB in the microdroplets. In order to confirm the configurational state of 5CB in LC microdroplets, the polarized optical micrograph of LC microdroplets without AlGg (Fig. 4a) was compared with the polarized

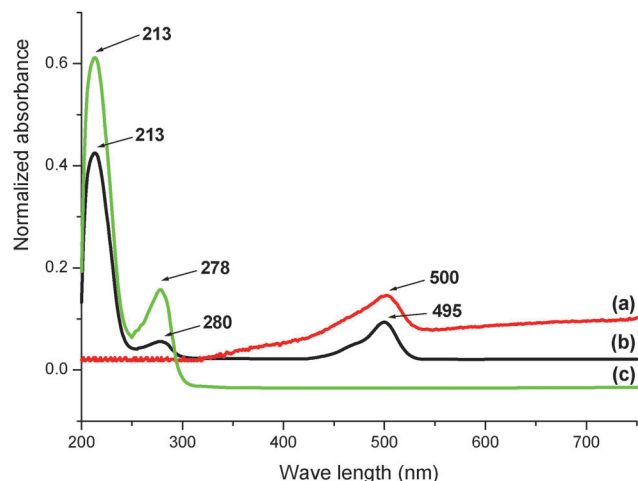


Fig. 2 UV-spectra of FITC (a), FITC-conjugated AlGg (b), and AlGg (c).

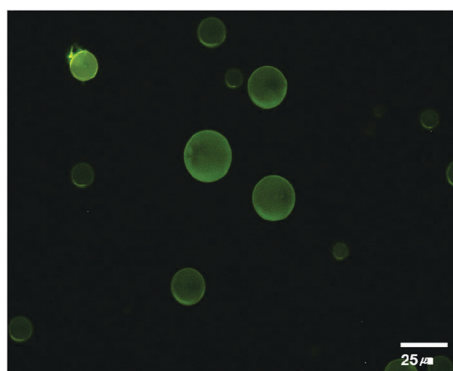


Fig. 3 Fluorescence image of FITC-AlGg-anchored LC microdroplets.

optical micrograph showing LC microdroplets anchored with AlGg (Fig. 4b). The comparison between polarized optical micrographs of LC microdroplets with and without AlGg (Fig. 4) clearly indicates that LC microdroplets with and without AlGg both showed 5CB in the radial state. This suggested that the anchoring of AlGg on LC microdroplets did not influence the interactions of SDS and the amphiphilic block copolymer with 5CB molecules in the core of LC microdroplets, which may be due to the presence of weak interaction forces between AlGg and LC microdroplets.

The anchoring of AlGg to LC microdroplets produces symmetrical and weak interaction forces around the 5CB molecules, which were not sufficient to polarize the orientation of these molecules in the LC microdroplets. Therefore, no configurational transition in 5CB molecules was observed to occur in LC microdroplets upon anchoring of AlGg. This further indicates that AlGg anchors symmetrically to LC microdroplets without creating any local field to polarize the 5CB molecules. LC microdroplets with fixed surface density of AlGg were obtained by optimizing the amount of AlGg. To this end, different amounts of AlGg were used with a fixed density of LC microdroplets (9×10^3 microdroplets per mL) at a sufficient amount of IgG (1000 ng mL^{-1}) and the optical signals were recorded. The response of LC microdroplets has shown variation on varying the anchoring amount of AlGg from $1\text{--}10 \text{ } \mu\text{g mL}^{-1}$ ($6.8\text{--}68 \text{ pmol}$) on 9×10^3 LC microdroplets per mL. Each LC microdroplet conjugated with $3.33 \times 10^{-3} \text{ pmol}$ of AlGg has shown high sensitivity than conjugated with a low ($< 3.33 \times 10^{-3} \text{ pmol}$) or high ($> 3.33 \times 10^{-3} \text{ pmol}$) amount of AlGg. These results indicated that $5 \text{ } \mu\text{g mL}^{-1}$ (34 pmol) of AlGg was sufficient to form an IgG sensitive monolayer ($3.33 \times 10^{-3} \text{ pmol}$ of AlGg) around each microdroplets on conjugating with 9×10^3 LC microdroplets per mL. At a low amount of AlGg ($1 \text{ } \mu\text{g mL}^{-1}$, 6.8 pmol), the IgG sensitive layer of AlGg formed a small fraction of LC microdroplet to transmit the interfacial forces to the core of LC microdroplets to induce configurational transition in 5CB molecules, whereas upon taking more amount of AlGg ($10 \text{ } \mu\text{g mL}^{-1}$, 68 pmol), a thick layer of coiled chains of AlGg is formed, which was less sensitive to interact with IgG and interaction force was insufficient to induce configurational transition in all LC microdroplets. The fraction of LC microdroplets with a sensitive monolayer of AlGg ($3.33 \times 10^{-3} \text{ pmol}$ per LC microdroplet) was reduced on conjugating with a high amount of AlGg ($10 \text{ } \mu\text{g mL}^{-1}$, 68 pmol) in comparison to LC microdroplets obtained at $5 \text{ } \mu\text{g mL}^{-1}$ (34 pmol) of AlGg. However, the fraction of LC microdroplets with a sensitive layer of AlGg ($3.33 \times 10^{-3} \text{ pmol}$ per microdroplet) was high in comparison to LC microdroplets conjugated with $1 \text{ } \mu\text{g mL}^{-1}$ (6.8 pmol) of AlGg. The LC microdroplets anchored with $5 \text{ } \mu\text{g mL}^{-1}$ of AlGg have shown configurational transition in 5CB molecules in a large fraction of LC microdroplets (9×10^3 microdroplets per mL) in the presence of 1000 ng mL^{-1} concentration

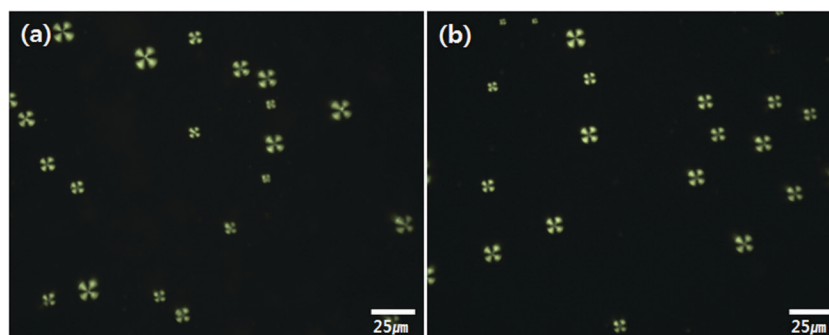


Fig. 4 Polarized optical microscopy images of LC microdroplets before anchoring of AlGg (a) and after anchoring of AlGg/FITC-AlGg conjugates (b).

of IgG, indicating that $5 \mu\text{g mL}^{-1}$ of AIGG was adequate to form a uniform sensitive layer on a large fraction of LC microdroplets, as examined using the polarized optical microscope. This is confirmed from the polarized optical micrograph recorded on incubating LC microdroplets anchored with $5 \mu\text{g mL}^{-1}$ of AIGG in PBS solution containing 1000 ng mL^{-1} of IgG (Fig. S1b, ESI†) and from LC microdroplets with a low amount of AIGG ($<5 \mu\text{g mL}^{-1}$) recorded with 50 ng mL^{-1} of IgG (Fig. 7a and b).

3.2 Sensitivity evaluation of anti-IgG-anchored LC microdroplets in detection of IgG

In order to avoid interference from FITC in the detection of IgG using configurational variation in 5CB molecules in LC microdroplets, the AIGG-anchored LC microdroplets were used for immunoassaying of IgG in PBS and other media such as 10% FBS, and 10% blood plasma. A calculated volume of AIGG-anchored LC microdroplet concentrate was added to an optical dish (1.0 cm diameter) to achieve a constant density of LC microdroplets (9×10^3 microdroplets per mL) for recording the configuration variation in LC microdroplets in the presence of IgG. The response of LC microdroplets to the presence of IgG was studied by varying the concentration of IgG from 20 to 1000 ng mL^{-1} . The diffusional and dilution effect on interactions of IgG with AIGG-anchored LC microdroplets was avoided by maintaining the final volume of LC microdroplets and IgG at 1.0 mL. In order to avoid the effect of temperature on the interactions between IgG and LC microdroplets, the incubation dishes containing AIGG-anchored LC microdroplets and IgG were maintained at room temperature and allowed to shake horizontally to provide enhanced opportunity for interaction between IgG and AIGG-anchored LC microdroplets. After incubation for 30 min, the configurational state of 5CB in AIGG-anchored LC microdroplets was examined by recording polarized optical micrographs at 3 or 4 different locations of the optical dish in order to obtain an average view of the orientational variation of 5CB in LC microdroplets. All experiments were recorded in triplicates to ensure reproducibility. The polarized optical images of LC microdroplets incubated for 30 min in PBS solution (pH 7.4) indicated that LC microdroplets incubated with 10 ng mL^{-1} of IgG, like the original

LC microdroplets, showed a radial configuration (Fig. 4 and 5a). The LC microdroplets incubated with 20 ng mL^{-1} of IgG showed clear configurational variation from radial to bipolar (Fig. 5b). It was observed that, upon further increasing the amount of IgG to more than 20 ng mL^{-1} , the fraction of LC microdroplets showing a bipolar configuration increased significantly at 50 ng mL^{-1} concentration of IgG.

The increase in the number of LC microdroplets with a bipolar configuration has continued till 800 ng mL^{-1} amount of IgG in test solution. This increasing trend was attributable to the increased rate of diffusion of IgG from the bulk phase of the test solution to the surface of LC microdroplets, where it was able to bind with AIGG anchored to the LC microdroplets. The fraction of LC microdroplets with a bipolar configuration has continued to increase upon increasing the amount of IgG till 800 ng mL^{-1} while keeping other variables constant. The LC microdroplets have shown high sensitivity in transforming LC microdroplets from radial to bipolar (2.5 LC microdroplets per ng of IgG) within the concentration range of IgG from $20\text{--}800 \text{ ng mL}^{-1}$ (Table 1). Upon further increasing the amount of IgG ($>800 \text{ ng mL}^{-1}$), the LC microdroplets have shown a decreasing trend in their sensitivity (<2.5 LC microdroplets per ng of IgG), which might be due to the increase in viscosity of the medium (Fig. S1a, ESI†). Upon incubating LC microdroplets loaded with $5 \mu\text{g mL}^{-1}$ of AIGG in a solution with $\geq 1000 \text{ ng mL}^{-1}$ IgG, the sensitivity of LC microdroplets has decreased as a significant fraction of LC microdroplets remained with bipolar orientation (Fig. S1b, ESI†). This has supported that prepared LC microdroplets were useful for the detection of IgG within the concentration range from $20\text{--}800 \text{ ng mL}^{-1}$. No variation in the orientational state of 5CB in LC microdroplets was observed upon further increasing the amount of IgG beyond 1000 ng mL^{-1} , which might be due to significant reduction in interactions of IgG with AIGG anchored-LC microdroplets. This result demonstrates a correlation between the fraction of LC microdroplets showing configurational transition and the amount of IgG used to interact with AIGG-anchored LC microdroplets upto a maximum amount of 1000 ng mL^{-1} of IgG in test solution. This correlation has been found to be useful for determining the lower limit of detection of IgG by LC microdroplets. The lower

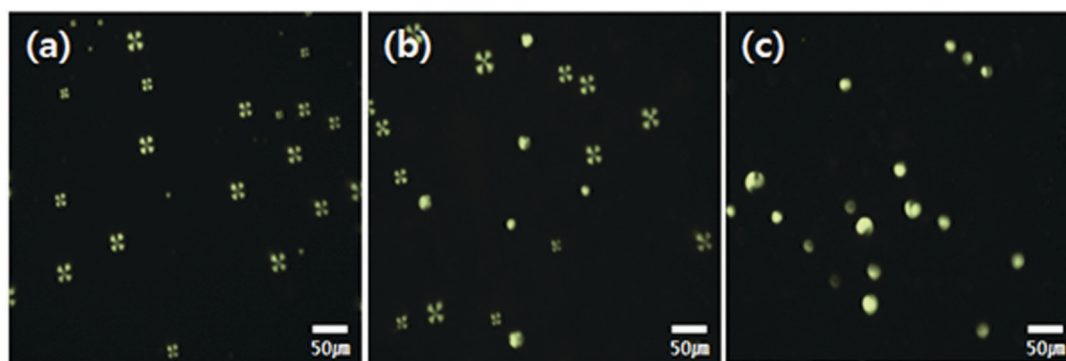


Fig. 5 Polarized optical microscopy images of AIGG-anchored LC microdroplets incubated in PBS (pH 7.4) having different concentrations of IgG at a constant density of LC microdroplets (9×10^3 microdroplets per mL) anchored with $5 \mu\text{g mL}^{-1}$ of AIGG. Contact time: 30 min. Temp. = room temperature, [IgG] = (a) 10 ng mL^{-1} , (b) 20 ng mL^{-1} , and (c) 50 ng mL^{-1} .

Table 1 Performance of AIGG-anchored LC microdroplets in detection of IgG

AIGG ($\mu\text{g mL}^{-1}$)	Sensitivity for IgG (LCdroplets per ng)	Working range (ng mL ⁻¹ of IgG)	LOD (ng mL ⁻¹)	Reproducibility (%)
1.0	0.8	80–560	60	3–8
5.0	2.5	20–800	16	1–6
10.0	1.8	20–940	16	2–10

limit of detection of LC microdroplets anchored with $5 \mu\text{g mL}^{-1}$ (34 pmol) of AIGG was found to be 16 ng mL^{-1} of IgG for a concentration range of IgG from 20 to 800 ng mL^{-1} in PBS (pH 7.4). The LC microdroplets anchored with $10 \mu\text{g mL}^{-1}$ (68 pmol) of AIGG have shown low sensitivity (<2.0 LC microdroplets per ng of IgG) but an upper detection limit was enhanced to 940 ng mL^{-1} and a lower limit of detection of IgG was found to be the same as with LC microdroplets anchored with $5 \mu\text{g mL}^{-1}$ (34 pmol) of AIGG (Table 1). The LC microdroplets anchored with $1 \mu\text{g mL}^{-1}$ (6.8 pmol) of AIGG were found to be less sensitive (0.8 LC microdroplets per ng of IgG) in transforming LC microdroplets with a radial configuration to a bipolar configuration on interaction of IgG in test solution. The working range for detection of IgG was found to be $80\text{--}560 \text{ ng mL}^{-1}$ and a lower limit of detection for IgG was $>60 \text{ ng mL}^{-1}$ (Table 1).

The lower detection limit of LC microdroplets anchored with an optimized amount of AIGG ($5 \mu\text{g mL}^{-1}$) for the detection of the antigen found to be within the limit reported by other methods. The conventional ELISA is time consuming and able to show a LOD of 8 ng mL^{-1} for the detection of antigens whereas electrochemical ELISA⁶⁶ shown a LOD of 0.3 ng mL^{-1} . The electrochemical ELISA needs sufficient time in sample preparation and to generate a detectable signal in comparison to the LC molecule based biosensor. The fluorescence immunoassaying of malarial antigens in infected human blood by the AuNP based system⁴ has shown a LOD of $2.4 \mu\text{g mL}^{-1}$, which is quite high in comparison to the LOD of IgG (16 ng mL^{-1}) found in present investigation. The LC microdroplet detection of IgG has also been found better in comparison to recent studies based on the microfluidic LC based system for the detection of antigens ($1 \mu\text{g mL}^{-1}$).⁵² The results indicate that the application

of 5CB as LC microdroplets provides the advantage of sensitive detection of IgG in the nano-range in comparison to 5CB on the solid surface^{64,65} and other detection systems.^{67,68} The high sensitivity of the LC microdroplets developed in the present study is attributable to their small size ($20\text{--}30 \mu\text{m}$) in comparison to larger-sized LC microdroplets ($60\text{--}85 \mu\text{m}$) used for the detection of proteins.⁶⁵ In order to analyze the effect of proteins on orientational variation in 5CB in LC microdroplets, the response of AIGG-anchored LC microdroplets containing $5 \mu\text{g}$ of AIGG was studied in other media such as 10% FBS and 10% blood plasma, for fixed amounts of IgG (20 ng mL^{-1}).

The polarized optical micrographs of LC microdroplets incubated with 20 ng mL^{-1} concentration of IgG in 10% FBS at contact times of 30 min and 60 min were found to be similar to those of the AIGG anchored LC microdroplets without IgG (Fig. 6a and b). However, upon further increasing the contact time to 90 min, the polarized optical micrographs showed sufficient LC microdroplets with a bipolar configuration (Fig. 6c). The AIGG anchored LC microdroplets were also used in 10% blood plasma for the detection of IgG. The corresponding micrographs were recorded (Fig. 7) at different time intervals, as with 10% FBS. The AIGG anchored LC microdroplets, which were in contact with IgG for 30 and 60 min in 10% blood plasma, showed a radial configuration of 5CB molecules (Fig. 7a and b). The configuration of LC microdroplets was the same as observed for the original LC microdroplets in the absence of IgG; however, upon further increasing the contact time to 90 min, the 5CB molecules in LC microdroplets showed a substantial number of LC microdroplets with a bipolar configuration of 5CB (Fig. 7c).

The results of IgG interactions with AIGG anchored LC microdroplets in 10% FBS and 10% blood plasma indicate that AIGG-anchored microdroplets may be used for the detection of IgG in 10% FBS and 10% blood plasma. However, in order to obtain the same configurational variation in 5CB as in LC microdroplets obtained from PBS medium, the LC microdroplets in 10% FBS and 10% blood plasma must be allowed a contact time of 90 min. The presence of non-specific protein molecules in 10% FBS and 10% blood plasma has slowed down the rate of diffusion of IgG molecules to LC microdroplets and

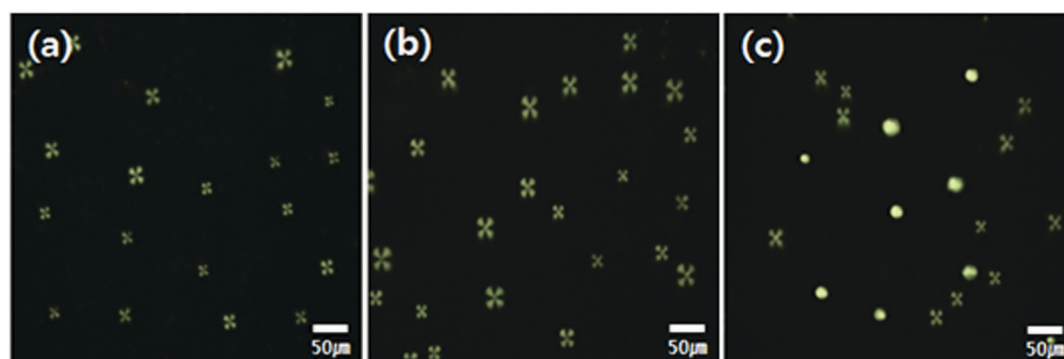


Fig. 6 Polarized optical microscopy images of LC microdroplets for the detection of IgG in 10% FBS, recorded at different contact times, at constant density of LC microdroplets (9×10^3 microdroplets per mL) using 20 ng mL^{-1} concentration of IgG test solution at room temperature. Contact time: 30 min (a), 60 min (b), and 90 min (c).

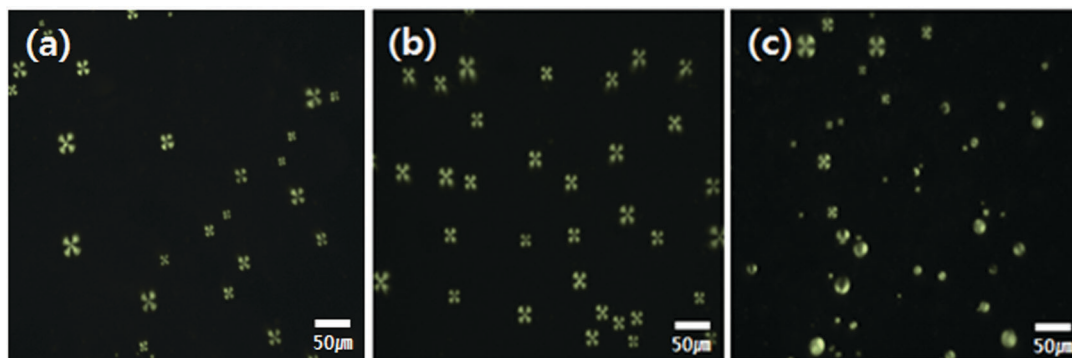


Fig. 7 Polarized optical microscopy images of LC microdroplets for the detection of IgG in 10% blood plasma, recorded at different contact times, at constant density of LC microdroplets (9×10^3 microdroplets per mL) using 20 ng mL^{-1} concentration of IgG in test solution at room temperature. Contact time: 30 min (a), 60 min (b), and 90 min (c).

able to generate an optimal signal at 90 minutes for detection of IgG (Fig. S2, ESI†).

3.3 Sensitivity evaluation of LC microdroplets fabricated with different amounts of anti-IgG

In order to evaluate the minimum amount of AIGG required for fabrication of the 5CB-based LC microdroplet sensor for the detection of IgG, 1.0 mL of LC microdroplets of constant density (9×10^3 microdroplets per mL) was used to anchor different amounts of AIGG in the presence of activating agents (EDC and NHS, 100 mg each). The LC microdroplets fabricated with different amounts of AIGG were used to evaluate configurational response to a fix amount of IgG (50 ng mL^{-1}) in PBS for a contact time of 30 min at 30°C . The amounts of AIGG used to anchor to a 9×10^3 microdroplets per mL concentration of LC microdroplets varied from 1.0 – $10 \text{ }\mu\text{g mL}^{-1}$ (6.8 – 68 pmol). The resulting mixture was incubated with IgG (50 ng mL^{-1}) for a contact time of 30 min in PBS solution. After incubation, the configurational state of 5CB in LC microdroplets was examined by recording polarized optical micrographs in an optical dish of 1.0 cm diameter (Fig. 8). The polarized optical micrograph of LC microdroplets anchored with $1.0 \text{ }\mu\text{g mL}^{-1}$ (6.8 pmol) amount of AIGG indicated a radial configuration of 5CB without any change in orientation from radial to bipolar in any of the LC microdroplets (Fig. 8a).

However, a substantial fraction of the LC microdroplets anchored with $5 \text{ }\mu\text{g mL}^{-1}$ (34 pmol) of AIGG showed bipolar orientation (Fig. 8b).

The number of LC microdroplets with a bipolar configuration increased further for LC microdroplets anchored with more amounts of AIGG ($> 5 \text{ }\mu\text{g mL}^{-1}$). The LC microdroplets anchored with $10 \text{ }\mu\text{g mL}^{-1}$ (68 pmol) of AIGG showed maximum configurational transition from radial to bipolar (Fig. 8c). The force of interactions between IgG and LC microdroplets anchored with $5.0 \text{ }\mu\text{g mL}^{-1}$ (34 pmol) of AIGG was sufficient to induce detectable orientational variation in LC microdroplets with optimal surface density of AIGG ($3.33 \times 10^{-3} \text{ pmol per microdroplet}$). Upon further increasing the amount of AIGG ($> 5.0 \text{ }\mu\text{g mL}^{-1}$), the number of LC microdroplets with the optimal amount of AIGG increased but overall sensitivity was found to decrease due to the presence of a sufficient number of LC microdroplets possessing a thick layer of AIGG (Table 1). Accordingly, the fraction of LC microdroplets with a bipolar configuration increased significantly upon anchoring LC microdroplets with $10 \text{ }\mu\text{g mL}^{-1}$ (68 pmol) of AIGG (Fig. 7c) but these LC microdroplets shown less sensitivity for IgG as shown in Table 1. The orientational variation of LC microdroplets with different amounts of AIGG was also recorded in 10% FBS and 10% blood plasma in the presence of 50 ng mL^{-1} concentration of IgG. The trends in

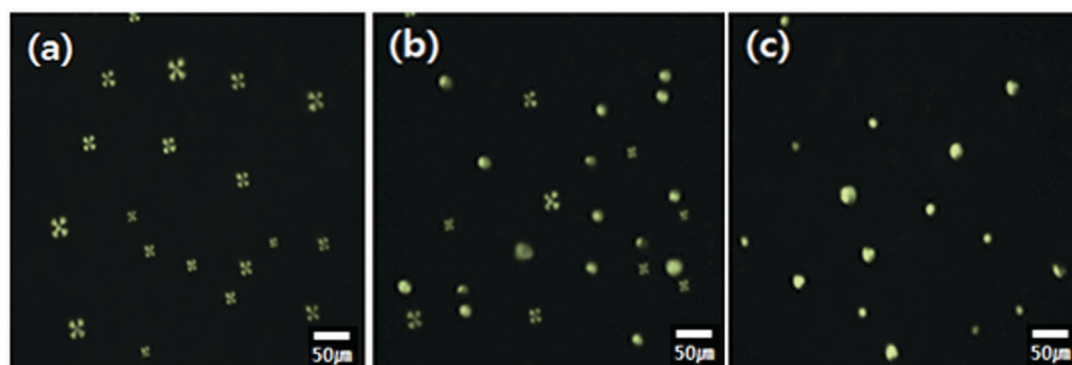


Fig. 8 Polarized optical microscopy images of LC microdroplets fabricated with different amounts of AIGG. The configurational variation in AIGG-anchored LC in PBS (pH = 7.4) at 50 ng mL^{-1} of IgG. Temp. = room temperature, contact time: 30 min. [AIGG] = $1.0 \text{ }\mu\text{g mL}^{-1}$ (a), $5.0 \text{ }\mu\text{g mL}^{-1}$ (b) and $10.0 \text{ }\mu\text{g mL}^{-1}$ (c).

variation in the orientational configuration for LC microdroplets fabricated with different concentrations of AIGG at 50 ng mL⁻¹ concentration of IgG in 10% FBS and 10% blood plasma were similar to those of PBS solution. However, the fraction of LC microdroplets with a bipolar configuration was found to be slightly lower in comparison to LC microdroplets in PBS solution. These findings clearly demonstrate that LC microdroplets anchored with 5.0 µg mL⁻¹ (6.8 pmol) of AIGG were having high sensitivity (2.5 ± 0.01 LC microdroplets per ng of IgG) for the detection of IgG in PBS and other media such as 10% FBS and 10% blood plasma within a concentration range of 20–1000 ng mL⁻¹ of IgG with a response time of 30 min at room temperature. The sensitivity and working range for detection of IgG has shown significant variation upon varying the amount of AIGG anchored on LC microdroplets (Table 1).

3.4 Validation of IgG detection by AIGG anchored LC microdroplets

To authenticate the accuracy in the detection of IgG by AIGG anchored LC microdroplets, IgG was detected in rabbit serum and the percentage recovery of IgG was recorded from the spiked sample containing 25 ng mL⁻¹ of IgG. The calibration curve drawn between numbers of LC microdroplets vs. concentration of IgG was used to determine the amount of IgG in rabbit serum and percent recovery of IgG in the spiked sample. The detection of IgG was carried out in triplicates to validate the accuracy and precision of IgG detection by LC microdroplets in PBS. The amount of IgG in rabbit serum was found to be 68 ng mL⁻¹ (±4%), which is almost comparable within the range of IgG found in rabbit serum. The percent recovery and coefficient of variance for the spiked sample were found to be 106% and ±6% respectively for a spiked amount of 25 ng mL⁻¹ of IgG in the test sample.

4. Conclusions

In the present study, we successfully demonstrated that the orientational response of liquid crystal molecules might be utilized for developing a sensitive and label-free biosensor for the detection of pathogenic proteins in biological fluids. Our results also indicate that the sensitivity of LC microdroplets for the detection of proteins may be improved further by controlling the size of the LC microdroplets and controlling the surface density of antibodies on these microdroplets. The LC microdroplets prepared were stable in PBS solution at pH 7.4 and were able to detect IgG with great precision and accuracy. We are attempting to extend these findings to the development of a dual detection system to confirm the selectivity and sensitivity of LC microdroplets for the detection of proteins. To this end, we aim to utilize the immunofluorescence and orientational variation of 5CB in LC microdroplets upon interaction with nano-amounts of proteins in solution. The technique should enable non-invasive detection of cancer-specific biomarkers in biological fluids such as blood and urine, with great sensitivity.

Conflicts of interest

The authors declare no competing financial interest.

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