

Evanescent Wave Based System for Observation of Injected Charge and Field Induced Electrophoresis

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Abstract

A system using interaction of evanescent light wave with particles in a liquid (such as ink) allows one to observe accumulation and stability of such particles at and in the vicinity of a surface. Particles can be moved either by electric field between electrodes, or by charge injected into the liquid by charge generator. Observation is sensitive only to particles within less than 1 micron of the interface, so observation can be made with an arbitrary thickness of fluid sample. This kind of system is ideal for investigating device life limiting interaction between colorants and substrates in displays. We show that adhesion to electrodes can dominate motion of pigments in display applications.

Introduction

Electrophoretic motion of pigment (toner) particles due to electric fields is utilized in printing [1,2] and in displays [3,4]. Interactions between pigment particles and bounding surfaces are very important to lifetimes and performance of the devices. Understanding surface-particle interactions is critical to improving products based on electrophoresis. Until now it was not possible to distinguish between particles in the bulk of the liquid and those in the vicinity of a surface, either because of absorption of light in the bulk, or because thickness of films under observation is comparable to depth of focus of imaging equipment which is typically very expensive and of very limited field of view. For purposes of investigations fluid containing the pigment particles is typically held between electrodes making it not possible to distinguish between effects of electric field and electrode injected charge. Methods and equipment presented in this article provide for simple and inexpensive equipment that solves these issues.

A new laser-based optical absorption method was developed to observe particles within a narrow region adjacent to a substrate. The light beam is coupled into the liquid through a prism at an angle above the total internal reflection angle. This results in a particle-light interaction region within the evanescent wave penetration depth, which extends much less than a micrometer into the liquid. Changes in particle concentration in that region are observed as changes in reflected light intensity due to absorption or scattering.

Since the light beam sees particles only in close proximity to the liquid-electrode interface, it is possible to observe effects in a thin film of liquid with a free surface. This in turn permits one to inject charge into the system from an external device. Either positive or negative charge can be injected with controlled current magnitude. Migration and adhesion of particles to electrode surfaces can be observed by evanescent wave absorption in liquid layers as thin as a few micrometers.

System optics

A simplified diagram of the optical system is shown in Figure 1. A laser beam is coupled into a sample at high angle of incidence by a prism. In order to achieve total internal reflection at the sample-substrate interface, refractive indices of the prism and substrate need to be larger than that of the sample carrier fluid. Laser light wavelength should be selected based on the sample under study. If the solute absorbs light, then one may want to select the wavelength to match the absorption peak. Alternatively one may want to stay away from the absorption band and rely on scattering only as sensing method. The latter may be applicable when multiple species are mixed as solute and one wants to study averaged behaviour; the former if one wants to select one species over another or to maximize sensitivity for a single species. The substrate is typically coated with a transparent conductor such as indium tin oxide (ITO) to be able to apply electrical fields on the sample fluid while simultaneously monitoring the intensity of the reflected light beam.

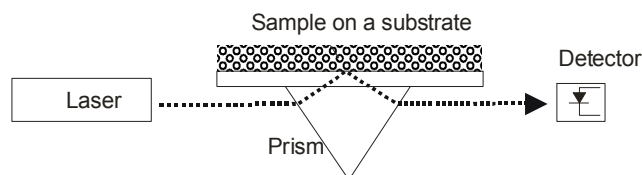


Figure 1. Optical system diagram.

Figure 2 shows details of the beam geometry at total internal reflection (TIR) condition. If TIR is achieved, light penetrates into the low index of refraction liquid as an evanescent wave [5] whose

amplitude decays as $e^{-\frac{Z}{p}}$, where Z is the distance from the sample-substrate interface and p is the penetration depth that depends on the complementary angle of incidence A , prism angle α , prism refractive index n , fluid refractive index n_2 and wavelength of light λ . In terms of the geometry in Figure 2

$$p = \frac{\lambda}{2\pi \sqrt{n^2 \sin^2(\alpha - \gamma) - n_2^2}} \quad (1)$$

Note that there is no dependence on the substrate refractive index n_1 , which only has to be larger than that of the fluid. However, a difference between n_1 and n controls reflection at prism substrate interface and thus can contribute to the signal to noise ratio of the system.

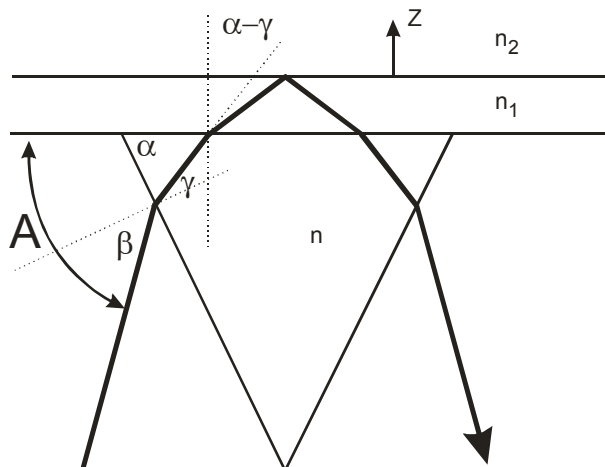


Figure 2. Details of beam geometry (stray reflections omitted)

Figure 3 shows dependence of penetration depth on incidence angle for typical values of refractive indices, 60 degrees prism and green light. Complementary incidence angles in the range of 20-30 degrees are readily achieved, so it is easy to attain sensitivity to particles within 0.2 microns from the interface. In fact, the effective sensitivity distance is at most half that value, as experimental observables are proportional to beam intensity rather than amplitude. For many pigment dispersions this method offers sub-monolayer sensitivity.

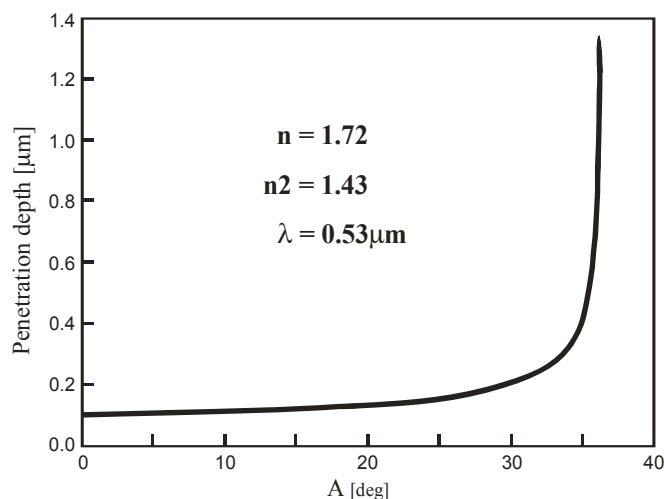


Figure 3. Penetration depth as function of complementary incidence angle for typical indices of refraction, 60 degrees prism and green light.

Electrophoretic field

Particle concentration proximate to the transparent conductor interface can be modulated by application of an electric field. Two approaches were employed to generate electrophoretic motion of the particles: 1) charge injection from external device and 2) electric field application from a counter electrode. In the

first method, net charge in the fluid creates a field that draws particles to the grounded ITO electrode. Intrinsic chemical charge is not essential, since charge is introduced into the liquid from an external source.

In the second method, electric fields are applied by a secondary metal electrode separated from the ITO-coated glass by a thin Mylar spacer. Electrophoretic motion of chemically charged colorant particles in the vicinity of the ITO electrode can be monitored by the optical signal. Figure 4 is a photograph of the apparatus showing the secondary electrode, fluid containment with spacer, ITO-coated slide and refracting prism. Applied field magnitude, direction and duration can be conveniently adjusted in this configuration with a pulse generator and amplifier.

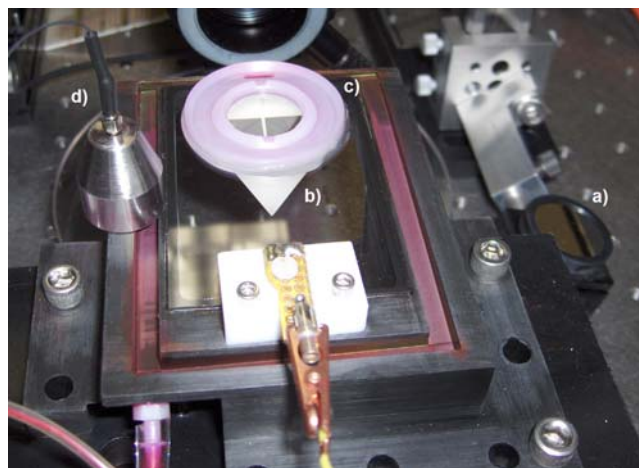


Figure 4. Evanescent wave apparatus for monitoring electrophoretic motion of charged colorant particles in a dielectric fluid. Green diode laser beam is incident from right. a) beam mirror, b) prism, c) fluid containment, d) removable counter electrode

Experimental measurements

Pigment dispersions were prepared by bead milling magenta pigment in a dielectric carrier fluid, producing particle distributions with diameter centered around 250 nm. Dispersion conductivity was controlled by the concentration of cationic surfactant added to the solution, and pigment concentration was adjusted by dilution with the dielectric carrier fluid. When using external charge injection, a uniform fluid layer first was spread over the surface of the ITO glass with a wire wound rod to produce a film thickness of about 20 μm. Reflectance of the laser beam incident on the ITO-fluid interface was then measured while a single charge impulse was applied to the upper surface of the fluid layer.

Data from such a measurement are presented in Figure 5 for two samples having conductivities of 4.2 and 230 pS/cm. A negative charge impulse of 25 ms duration was applied during the reflectance measurement. Electric field between the charge injector and substrate electrode of 0.7 V/μm was applied about a second before and after the charge pulse. Prior to charging, light undergoes almost total internal reflection at the ITO-fluid

interface, and the normalized intensity is 1.0 for both samples. The reflectance drops coincident with the charge impulse for both samples and remains constant over the duration of the impulse. However, several seconds after turning off the charge impulse, the reflectance of the high conductivity sample has returned to its initial level, whereas that of the low conductivity sample has remained unchanged. Matrix charge in the high conductivity sample neutralizes the adsorbed particle charge, eliminating the electrostatic force holding the particles to the substrate. Discharge occurs much more slowly in the 4.2 pS/cm sample, so pigment particles remain bound to the substrate over the measurement interval.

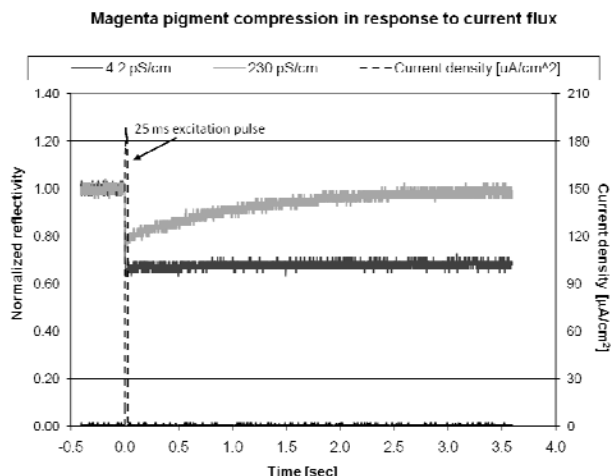


Figure 5. Reflectance from ITO-fluid interface subjected to 25 ms charge impulse for two samples: a) $\sigma=4.2$ pS/cm and b) $\sigma=230$ pS/cm. Magenta pigment concentration = 0.5 wt% and fluid film thickness equals 20 μm for both samples

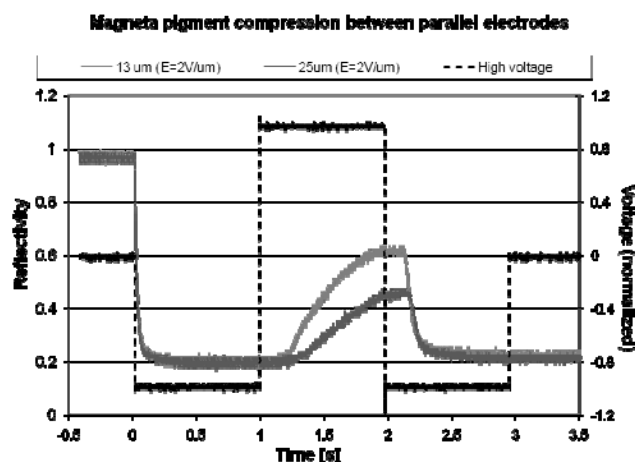


Figure 6. Reflectance and conductivity data from fluids excited by a bi-polar field of 2×10^6 V/m and 1 s pulse half width. Magenta pigment concentration = 0.5 wt% and electrode spacing was 13 and 25 μm .

Introduction of a secondary electrode affords the flexibility of applying a bi-polar square wave voltage. In this implementation, effects of injected charge are primarily masked by electrostatic fields. Temporal dependence of the optical signal sheds light on

particle motion and field-induced removal of electrophoretically deposited material. Data from a magenta pigment solution sandwiched between electrodes spaced either 13 or 25 μm apart are presented in Fig. 6. Positively charged pigment particles are attracted to the negative ITO electrode in the first 100 ms of the 1 s duration initial pulse. The optical signal during the first pulse is independent of spacing, suggesting that pigment motion in the vicinity of the ITO electrode is comparable in the two samples and that absorption saturates before all pigment is plated from solution. Given the small amount of pigment in these measurement volumes, saturation occurs within an average layer thickness less than the average particle diameter.

Reversing polarity strips pigment from the ITO electrode. The optical signal shows a delay of about 200 ms after switching voltage polarity, indicating that adhesion of the film dominates pigment release. Some pigment remains on the electrode as evidenced by the reduced saturation level, and the thicker the deposited layer the more pigment remains. Switching the voltage polarity again supports the adhesion model hypothesis. In contrast to the first pulse, where charged pigment particles in solution respond rapidly to the applied field, there is a significant delay for reflectivity to decrease. This delay is similar to that seen in the second part of the waveform and most likely is due to adhesion of pigments on the counter electrode.

CONCLUSIONS

A new measurement method was presented for characterizing electrophoretic motion and interface adhesion of pigment particles in a dielectric carrier. An ITO-coated glass slide serves dual purpose as an electrode in an electrophoretic cell and an optical element that exhibits total internal reflection. Evanescent wave absorption at the interface between ITO and the working fluid translates to a high sensitivity measurement of pigment particle concentration within about 100 nm of the ITO surface. Application of a voltage to the ITO electrode alters particle concentration near the electrode, allowing one to study electrophoretic motion and particle-interface adhesion.

References

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Author Biography

Henryk Birecki is a Senior Scientist at Hewlett Packard Laboratories. He received PhD in physics from MIT in 1976 and joined HP Labs in 1978. While at HP he worked on displays, optical computing, optical recording and other mass storage technologies. He managed projects on optical recording materials and devices and organized international conferences on the subject. Since 2006 he's been working on printing technologies.

Thomas Anthony received his Ph.D. in Materials Science and Engineering from Stanford University in 1984 and joined HP Laboratories that same year. During his career at HP Labs he has worked as a technical contributor and project manager on magnetoresistive recording heads and spin tunneling memory devices (MRAM). He currently is a Distinguished Technologist in the Commercial Print Engine Laboratory of HP Labs, where his research focus is on materials and processes relating to LEP technology.