CHEMISTRY LETTERS, pp. 837-842, 1973. Published by the Chemical Society of Japan

CONDUCTIVITY EFFECTS ON CUT-OFF FREQUENCY OF ELECTROHYDRODYNAMIC INSTABILITY IN NEMATIC LIQUIDS

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Conductivity effects on the cut-off frequency f_c of the electrohydrodynamic instability were studied, using nematic liquids doped with an organic electrolyte in different concentrations. The values of f_c were obtained from the optical observation. It was found that f_c is proportional to the conductivity (ρ^{-1}) of the nematic liquids, just as $f_c = K\rho^{-1}$; $K = 1.25 \times 10^{12}\,\Omega\text{cm/sec}$. This relation supports that the space charge is responsible for the electrohydrodynamic instability.

Since the change of optical properties in a nematic liquid subjected to an electric field was found by Williams,[1] a variety of studies have been carried out to elucidate the electric instabilities, which are responsible for electro-optical phenomena in a nematic liquid.[2-10] However, studies on the fundamental mechanism governing the electro-optical phenomena are yet far from complete.

In this letter, we present systematic measurements for conductivity effects on the cut-off frequency of the electrohydrodynamic instability, and we discuss the instability from a viewpoint of the space charge relaxation.

EXPERIMENTAL

The experimental cell was of a conventional sandwich-type, as is shown in Fig. 1. It was consisted of two transparent tin-oxide coated glass electrodes separated by a teflon spacer of 10 μm thickness.

The nematic liquid used in this study was a mixture of nematic liquid crystalline Schiff-bases with negative dielectric anisotropy.[11] Its nematic temperature range was from -6 to 65°C. The samples were prepared by doping the nematic liquid with an organic electrolyte, tetraethylammonium bromide (TEAB), in different concentrations. Table I gives the relation between doping concentrations and resistivities at 25°C measured at 25 Vdc. Figure 2 shows that the resistivity decreases rapidly with the increase in doping amount of the electrolyte.

We applied an ac sine-wave voltage across the electrodes, sandwiching the nematic liquid layer, up to 90 V rms, the frequency being varied in the range of 7-4000 Hz, and we observed the

TABLE I. Samples doped with tetraethylammonium bromide in different concentrations and their resistivities

Sample symbol	Doping concentration (Wt. %)	Resistivity ρ at 25°C (Ωcm)
E - 0	0	1.64×10^{11}
E - 1	1.00×10^{-3}	3.80×10^{10}
E - 2	1.60×10^{-3}	2.62×10^{10}
E - 3	7.85×10^{-3}	2.85×10^{9}
E - 4	1.57×10^{-2}	1.58×10^{9}
E - 5	2.60×10^{-2}	7.80×10^{8}

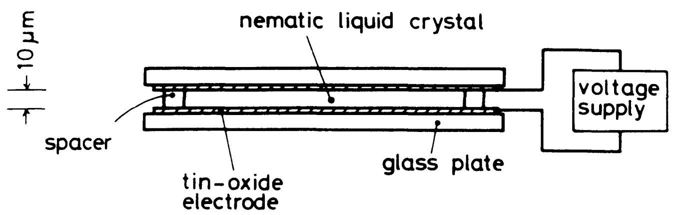


Fig. 1. Schematic drawing of experimental cell.

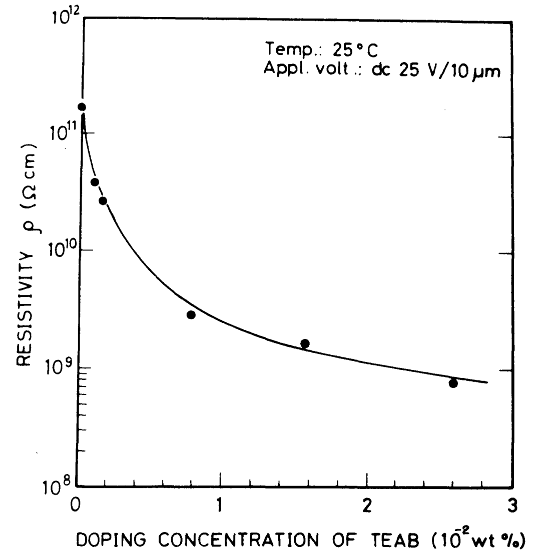


Fig. 2. Resistivity vs doping concentration for samples doped with an electrolyte (TEAB).

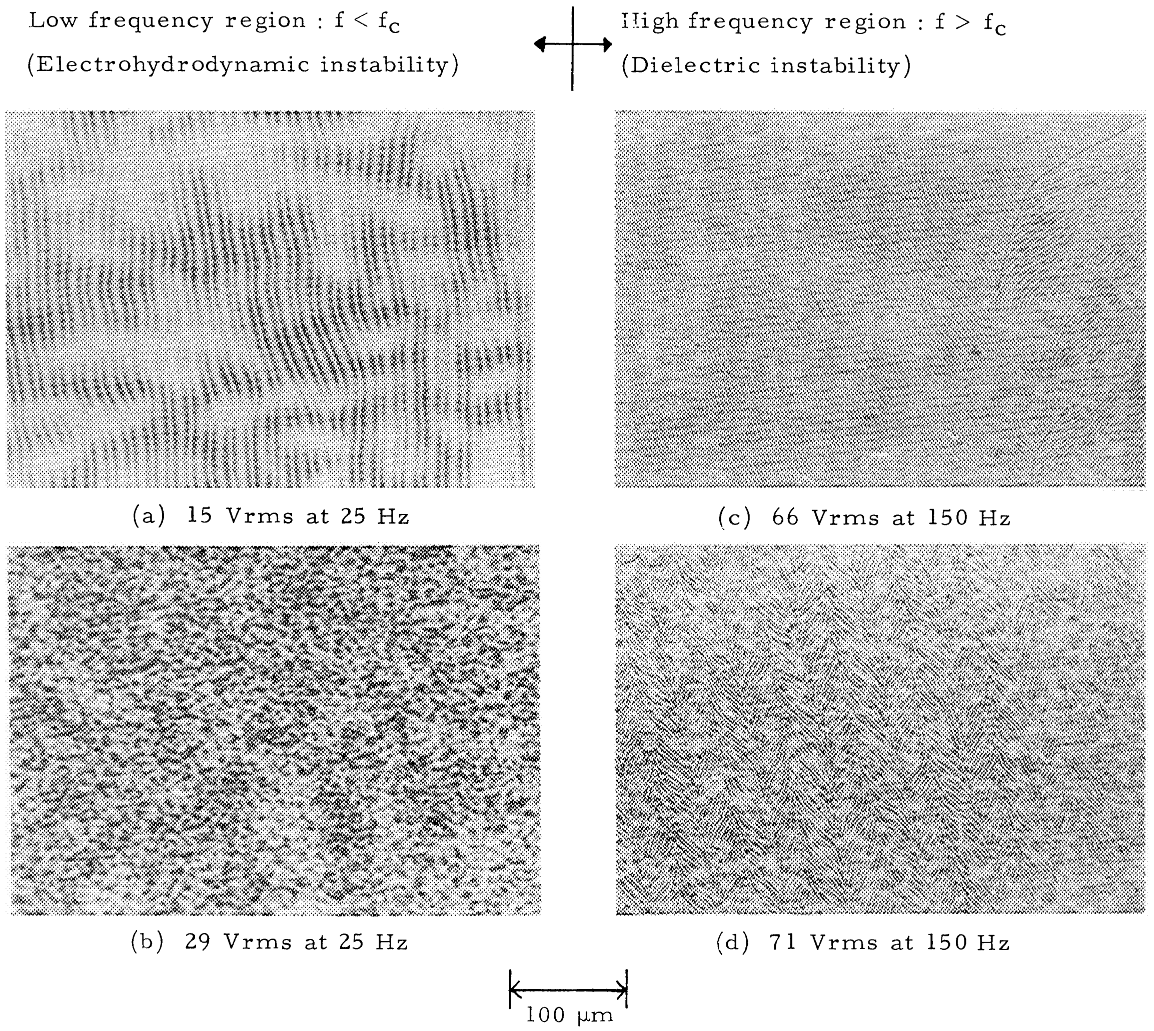
optical behaviour due to electric instabilities in the layer under a polarizing microscope in the transmission mode. These experiments were performed at 25 ± 0.2°C.

RESULTS AND DISCUSSION

For nematic liquids of lower conductivity (sample E-0, E-1, E-2), we found there are two distinct types of optical behaviour , which depend on the value of excitation frequency. As typically shown in Fig. 3, they are characterized by the appearance of quite different optical patterns:

(1) In the low frequency regime, above a threshold voltage, there appears a pattern of striations with a period of the order of magnitude of the sample thickness (Fig. 3-a). This pattern is usually called the "Williams striations-pattern".[1] Upon raising the applied voltage, the pattern is followed by the dynamic scattering (Fig. 3-b).

(2) In the high frequency regime, the parallel narrow-striations with a much shorter period than the Williams striations appear at a much higher threshold voltage (Fig. 3-c). However, just slightly above the threshold, they deform easily into a twisted pattern (Fig. 3-d). This pattern is usually called the "chevron striations-pattern".[7]



(a) 15 Vrms at 25 Hz

(b) 29 Vrms at 25 Hz

(c) 66 Vrms at 150 Hz

(d) 71 Vrms at 150 Hz

Fig. 3. Typical microscopic observation on the optical behaviour due to electric instabilities in a nematic liquid (sample E-2) under ac electric fields (Sample thickness, 10 μm; Temperature, 25 °C) : (a) Williams striations-pattern; (b) Dynamic scattering (turbulence); (c) Parallel narrow-striations; (d) Chevron striations-pattern.

For nematic liquids of higher conductivity (sample E-3, E-4, E-5), we failed to observe the chevron striations-pattern because of the shortage of our applied voltage.

Thus, the electric instabilities under ac electric fields are clearly divided into these low and high frequency regimes at a critical frequency, as will be shown typically in curve b in Fig. 4. These observed results are essentially in accordance with those presented recently by Orsay Liquid Crystal Group,[7] and Kashnow and Cole,[9] although their samples were simple nematic liquids and ours were the electrolyte-doped mixed nematic liquids.

According to the extended Carr-Helfrich model on the electric instabilities, which has been presented by Orsay Liquid Crystal Group,[7] the instability in the low frequency regime may be called the "electrohydrodynamic instability" and the instability in the high frequency regime may be called the "dielectric instability". Figure 4 shows plots of threshold voltage V_{th} of these two kinds of instabilities versus excitation frequency f, for typical samples at 25°C. The values of V_{th} were determined from the optical observation. From these V_{th}-f curves, the following phenomena are found :

(1) Cut-off frequency f_c of the electrohydrodynamic instability increases with the conductivity of the nematic liquid.

(2) Just below f_c, threshold V_{th} of the instability in the nematic liquid of higher conductivity increases more steeply with frequency, up to f_c.

For curve c in Fig. 4, there is no transition point from the electrohydrodynamic instability to the dielectric one. This may be caused by the shortage of our applied voltage.

In Fig. 5, f_c obtained from the V_{th}-f curve for each sample[12] is plotted against resistivity ρ at 25°C, on the log scale. This figure shows that f_c can be written as

$$f_c = K\rho^{-1}, \qquad (1)$$

where K is a constant; the numerical value of K in this work is 1.25 x 10^{12} Ωcm/sec. Equation (1) shows that f_c is proportional to the conductivity of the nematic liquid doped with an electrolyte.

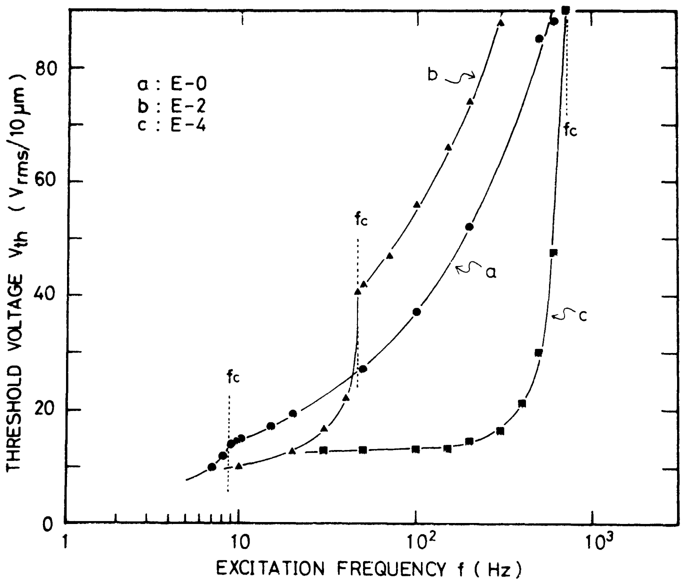


Fig. 4. Threshold voltage of electric instabilities vs excitation frequency at 25°C, for typical samples doped with an electrolyte (TEAB) in different concentrations. The region of f < f_c : electrohydrodynamic instability ; the region of f > f_c : dielectric instability.

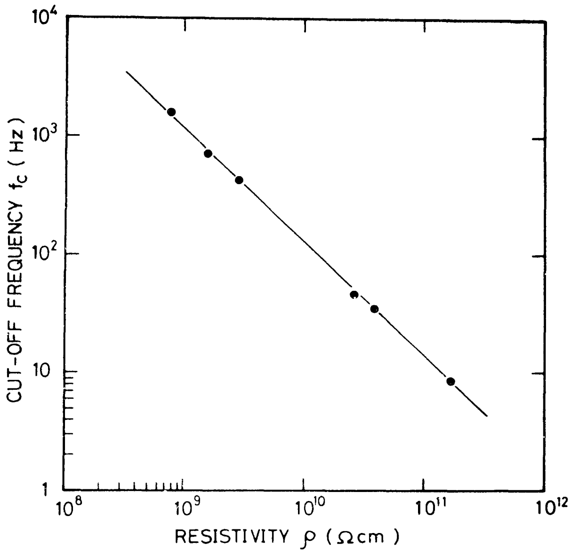


Fig. 5. Conductivity (ρ^{-1}) dependence of the cut-off frequency of electrohydrodynamic instability at 25 °C, for samples doped with an electrolyte (TEAB) in different concentrations. Solid line : straight line with a slope of - 1.

After the Carr-Helfrich model,[3,4] the electrohydrodynamic instability is induced by a shear torque due to the space charge in addition to a dielectric polarization torque. So, the higher excitation-frequency limit for inducing the instability may be principally determined by the space charge relaxation time. For our experimental cell of a sandwich-type configuration, the relaxation time is expressed by $\varepsilon\rho/4\pi$, where ε and ρ are dielectric constant (F/cm) and resistivity (Ωcm), respectively.[13] Therefore, this gives the following relation:

$$f_c \approx 2\varepsilon^{-1}\rho^{-1}, \qquad (2)$$

Thus, the conductivity dependence of f_c shown in Eq. (1) proves to be compatible with the theoretically predicted relation. This supports that the space charge is responsible for the electrohydrodynamic instability.

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11. A mixture consisting of 4-methoxybenzylidene-4'-aminophenyl butyrate (10 wt.%), crotonate (14 wt.%), hexanoate (16 wt.%) and 4-methoxybenzylidene-4'-n-butylaniline (60 wt.%).
12. As for samples E-3, E-4 and E-5, the frequency at V_{th} = 90 V rms in the V_{th}-f curve was regarded, for convenience, as the experimental values of f_c.
13. The values of ε and ρ are anisotropic quantities in a strict treatment.

(Received June 1, 1973)