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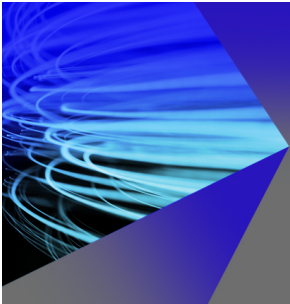
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ABSTRACT

Since the discovery of controlled rotation in soap films under electric fields in 2009, the rotation of suspended liquid films has drawn attention across disciplines. While prior studies identified surface charge as a primary driver—particularly in polar liquids and liquid crystals—our work introduces a new influencing factor: the permittivity of the supporting frame. We show that the frame-to-film permittivity ratio governs the transition between slip and no-slip rotational modes. Using both Particle-Image Velocimetry (PIV) and visual inspection, we characterize these modes. Although PIV offers precise measurements, we demonstrate that the two rotational states can be visually distinguished through their color patterns. Films in no-slip rotation exhibit vivid, colored spiral fringe patterns, while slip modes display steady central patterns. These spiral fringes result from white light interference between the incident wave and the portion transmitted through the film and reflected back from the second surface. When the film's thickness is below the temporal coherence length of white light, and its geometry resembles a hybrid lens-spiral-phase element, concentric fringes transform into dynamic, colored spirals. We propose that in the no-slip mode, the rotating film behaves as a lens-like spiral-phase object. The observed spiral pattern thus serves as both a qualitative signature and a physical indicator of the no-slip regime. This finding provides an accessible optical method for identifying rotational modes and offers new insights into the interplay between electromechanical forces, geometry, and optical behavior in thin liquid films.

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I. INTRODUCTION

Thin liquid films, commonly observed in soap bubbles, have long fascinated people due to their iridescent colors. The simplest of such films, made of soapy water surrounding a delicate sphere of air, are about ten times thinner than human hair ($\sim 1 \mu\text{m}$). Due to their thinness, they exhibit interesting optical properties caused by light interference, which is well understood in optics. This interference causes the rainbow-like colors observed in the film.¹

Recently, the study of liquid films has gained attention in soft condensed matter physics. Researchers are exploring these films for their potential applications in materials science and optical devices.^{2,3}

When an external stress disturbs a fluid layer from its equilibrium state, the resulting instability can lead to complex, chaotic, or turbulent flow patterns. This is especially true for liquid crystals, where anisotropy affects the pattern's symmetry and turbulence. Electro-convection can occur in nonuniform smectic films, where

variations in thickness help visualize the flow. The film transitions into convection when a sufficiently large direct current (DC) voltage is applied.^{4–6}

The rotation of suspended liquid films is an interesting phenomenon for researchers due to its intriguing physics and potential applications. In particular, when an electric current flows through a suspended liquid film in the presence of an external electric field perpendicular to the current, the film begins to rotate. In 2009, Amjadi and his colleagues made an important observation about soap films: the rotation of the soap film under an electric current in the presence of an external electric field is perpendicular to the current.⁷ They demonstrated that this rotation is perfectly controllable by tuning experimental parameters. Subsequent research by this group revealed that this phenomenon is not limited only to soap layers but occurs also in other pure liquids.⁸ Furthermore, they discovered that this rotation manifests not only in polar liquids but also in liquid crystals.⁹ Other studies have corroborated their findings, identifying the presence of induced surface charges on the film as the primary cause of this intriguing behavior.^{10,11} In another study, Shirsavar *et al.* investigated the role of liquid film permittivity in determining the type of rotation exhibited by the film.¹² Their observations revealed that some liquids exhibit a “slipping” rotation, while others display a “no-slip” rotation (see below). Consequently, they concluded that altering the liquid permittivity directly influences the rotational behavior of the layer. However, the critical threshold values for the appearance of each of these rotational behaviors remain undetermined.

Previous studies have primarily focused on the role of surface electric charge in explaining this induced rotation, often overlooking the significance of permittivity. In our work, we experimentally demonstrate that the permittivity of both the liquid and its bounding frame plays a crucial role in determining the type of rotation observed in the film.

This study further explores the rotational dynamics of a liquid film under the influence of an electric field and current. Two categorically different rotational types are observed: In the first type, the rotational flow reaches its maximum (tangential) velocity at a point between the film’s center and its edges; in the second, the rotation occurs mostly near the edges. We refer to the first type as the “no-slip” and the second as the “slip” rotational mode. To differentiate between these rotational behaviors, we utilized both the Particle-Image Velocimetry (PIV) technique and visual inspection. While PIV provides detailed results, it can be time-consuming. Our findings show that by adjusting the rotational parameters for a relatively lower rotational speed, visual identification becomes possible through distinct color patterns for each mode. Films exhibiting no-slip rotation display a characteristic spiral color pattern, whereas slip rotations maintain a relatively stable pattern at the center of the thin film, showing only minor fluctuations akin to the disordered motion observed in the film’s unforced state. We propose that films in the no-slip mode, with their spiral color patterns, could function as optical tools with rotating phases, similar to spiral phase plates, and potentially be used in generating vortex beams. These observations enhance our understanding of the rotational dynamics of the films and provide valuable insights with implications for fluid dynamics, materials science, and potential applications in optics.

The interference of a plane wave with itself after passing through any optically transparent volume—whose geometry

includes light paths characteristic of both a conventional lens and a spiral phase plate (SPP), and involves reflection from a secondary surface before recombining at the entry interface—can produce a spiral fringe pattern under coherent monochromatic illumination. When illuminated with multichromatic light, this pattern manifests as a colored spiral fringe. Since the film’s thickness is less than the temporal coherence length of white light, interference effects can arise when illuminated by white light. Such phase objects are widely used to generate optical vortex beams carrying orbital angular momentum (OAM), primarily through the use of SPPs.^{13,14} These plates have an azimuthally varying thickness, resulting in a helical phase front when a Gaussian beam passes through them. Multiple fabrication techniques—such as electron-beam lithography, direct laser writing, and electron-beam deposition—have been employed to create SPPs, although these processes can be complex and costly, and require specialized equipment.^{13,15} To overcome these challenges, recent studies have explored the use of metasurfaces—both reflective and transmissive—for the generation of OAM vortex beams, observing analogous spiral phase profiles and fringe patterns under similar optical illumination conditions.¹⁶ In this context, we propose that liquid thin films exhibit spiral color patterns in the no-slip regime function analogous to solid spiral phase plates. These films can generate optical vortex beams, as supported by the observed spiral fringe patterns and their correlation with the underlying no-slip rotational dynamics. This connection provides both a physical and qualitative foundation for identifying and characterizing rotational modes optically. Although this article emphasizes the experimental observation and interpretation of rotational regimes influenced by frame permittivity, a rigorous theoretical treatment of spiral fringe formation is beyond its scope. A detailed analysis of such interference effects and their implications for vortex beam generation can be found in Ref. 16. Interested readers are also referred to further foundational works for comprehensive theoretical insights.^{13–15} The unique properties of optical vortex beams—including their orbital angular momentum and ring-shaped intensity distributions—make them promising for a variety of applications, such as optical trapping, high-resolution microscopy, micro-/nano-scale material processing, and optical communication systems.¹⁵ The simplicity, tunability, and cost-effectiveness of our liquid-film-based approach provide a compelling alternative for spiral phase and vortex beam generation.

II. EXPERIMENTAL SETUP, MATERIALS, AND METHODS

A. Experimental setup

We employed the experimental configuration outlined by Amjadi *et al.* to achieve controlled rotation in a suspended liquid film.^{7,8} Figure 1(a) presents a schematic representation of this setup.

The experimental observations involve three key components: (i) induced charges generated from the interaction between the liquid and the applied electric field; (ii) body force that acts on the liquid, initiating its rotational movement; and (iii) direction of rotation, which is crucial in understanding the behavior of the liquid film under external forces.

To generate the liquid film, we utilized a phenolic resin frame, which is electrically insulating and has a relative permittivity $\epsilon = 8$ with respect to vacuum [Fig. 1(a)]. The experiments were carried out

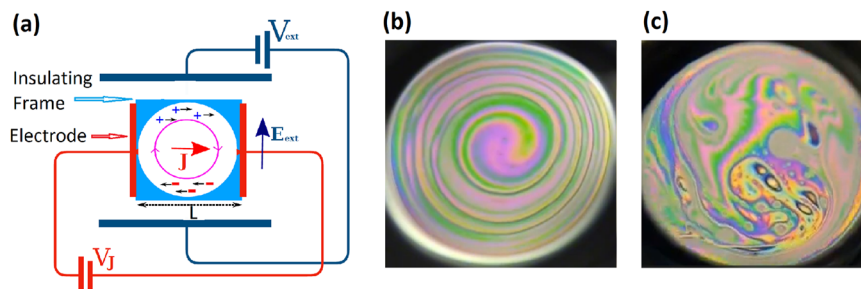


FIG. 1. (a) Schematic diagram of the experimental setup: This panel illustrates the key components of the experimental arrangement. We observe induced charges, the body force acting on the fluid, and the direction of rotation, all depicted schematically. (b) and (c) Images of two typical films with no-slip and slip rotational mode. These frames showcase two rotating liquid films subjected to an applied electric field E_{ext} and a potential difference V_J . The films rotate in a direction determined by the cross-product of E_{ext} and the overall electronic current direction J within the films. The liquid films lie horizontally. In (b), the rotation velocity remains zero near the frame, reaching its maximum value at an inner radius of the film. This configuration characterizes a no-slip flow. Conversely, in (c), the rotation velocity is nearly zero at the film center, gradually increasing toward the vicinity of the frame. This behavior corresponds to a slip flow. Background multimedia displays a combination of two separate videos, each recorded from distinct thin films at different times. One video features benzyl chloride with a relative permittivity of 7, and the other showcases chlorononane with a relative permittivity of 3.428 (Multimedia 1 available online).

at room temperature, $\sim 25^\circ\text{C}$, under a typical laboratory environment with a relative humidity of around 40%. A wet pad containing the liquid was drawn over the frame, forming a suspended film across the frame's aperture. Thin electrodes coated on opposite sides of the frame were used to conduct the current J . Applying an electric voltage V_J across the electrodes produced a small electric current, $\sim 1\ \mu\text{A}$, within the film.⁸

The frame was positioned between the plates of a large capacitor to apply an external electric field, E_{ext} , parallel to the film's plane and perpendicular to the electric current J . When this external electric field was applied, the liquid film rotated in the direction given by $E_{ext} \times J$.

Videos of various rotating thin films were recorded under a range of external factors, illuminated by a 50 W white incandescent lamp. The lamp and a CCD camera (Sony DCR-DVD105 DVD Handycam Camcorder with a $20\times$ optical zoom) were positioned above the thin film at incidence and reflection angles of 40° . To eliminate visibility of the lamp's filaments in the recordings, a layer of diffuser paper was placed between the lamp and the film, thereby softening the light and improving image quality.

Figures 1(b) and 1(c) show the details of the liquid film's behavior. Both panels illustrate the film's rotation under the influence of an external electric field, E_{ext} , and an applied potential difference, V_J , with the films oriented horizontally.

Figure 1(b) illustrates a typical no-slip flow condition. In this case, the rotational velocity is zero near the frame's edge and reaches its maximum in the vicinity of the film's center. In this context, the liquid adheres tightly to the frame. The velocity distribution for a similar case is illustrated in Fig. 2 of the referenced work by Shir-savar *et al.* A representative time-evolution of the film is shown in the accompanying multimedia (Multimedia 1 available online).

In contrast, as shown in Fig. 1(c), the rotation velocity is vanishing at the film's center, gradually increasing toward the edge of the frame. This distribution corresponds to a slip flow, where the liquid moves along the boundary without significant resistance. The velocity distribution for a similar case can be seen in Fig. 2 of Ref. 12. A representative evolution of the film over time is presented in

the accompanying multimedia (Multimedia 1 available online). It is important to note that Multimedia 1 combines two distinct videos, each captured from different thin films at separate times: one of benzyl chloride (with a relative permittivity of 7) and the other of chlorononane (with a relative permittivity of 3.428).

In our series of experiments, we explored the behavior of a liquid thin film within frames of different shapes: circular (7 mm diameter) and square (6.5 mm diameter). The applied voltage, V_J , ranged from 5 to 250 kV, while the external electric field, E_{ext} , was maintained at a constant value of 10 kV/2 cm, except in a few cases for comparison, as indicated in the corresponding movies. Interestingly, we observed that the behavior and direction of the rotation of the liquid film remained unchanged, irrespective of frame shape. In addition, the rotation speed could be fine-tuned by varying the applied voltage.

The thickness of a thin film affects its color when exposed to white light. Figure 2 displays several frames of a mesitylene thin film under a constant current while the external field is zero. The different frames exhibit distinct predominant colors, indicating that the film's thickness varies over time. The timestamps for each frame are noted at the top. In Multimedia 2 corresponding to this figure, the overall color changes of the mesitylene thin film are shown under the same conditions—constant current and zero external field. This thin film has high volatility, resulting in thickness variations on the order of the wavelength of visible light over the 2 min and 14 s of the visualization. Observing the movie reveals that the thin film displays a predominant color pattern, including purple, green, red, and yellow, that is, it nearly reflects all components of the white light spectrum at different times due to the non-uniform thickness of the film (Multimedia 2 available online).

B. Materials

We acquired a variety of pure liquids from Merck Inc., Kenilworth, NJ. These liquids are categorized in Tables I and II according to their relative permittivity (ϵ) and experimentally observed no-slip

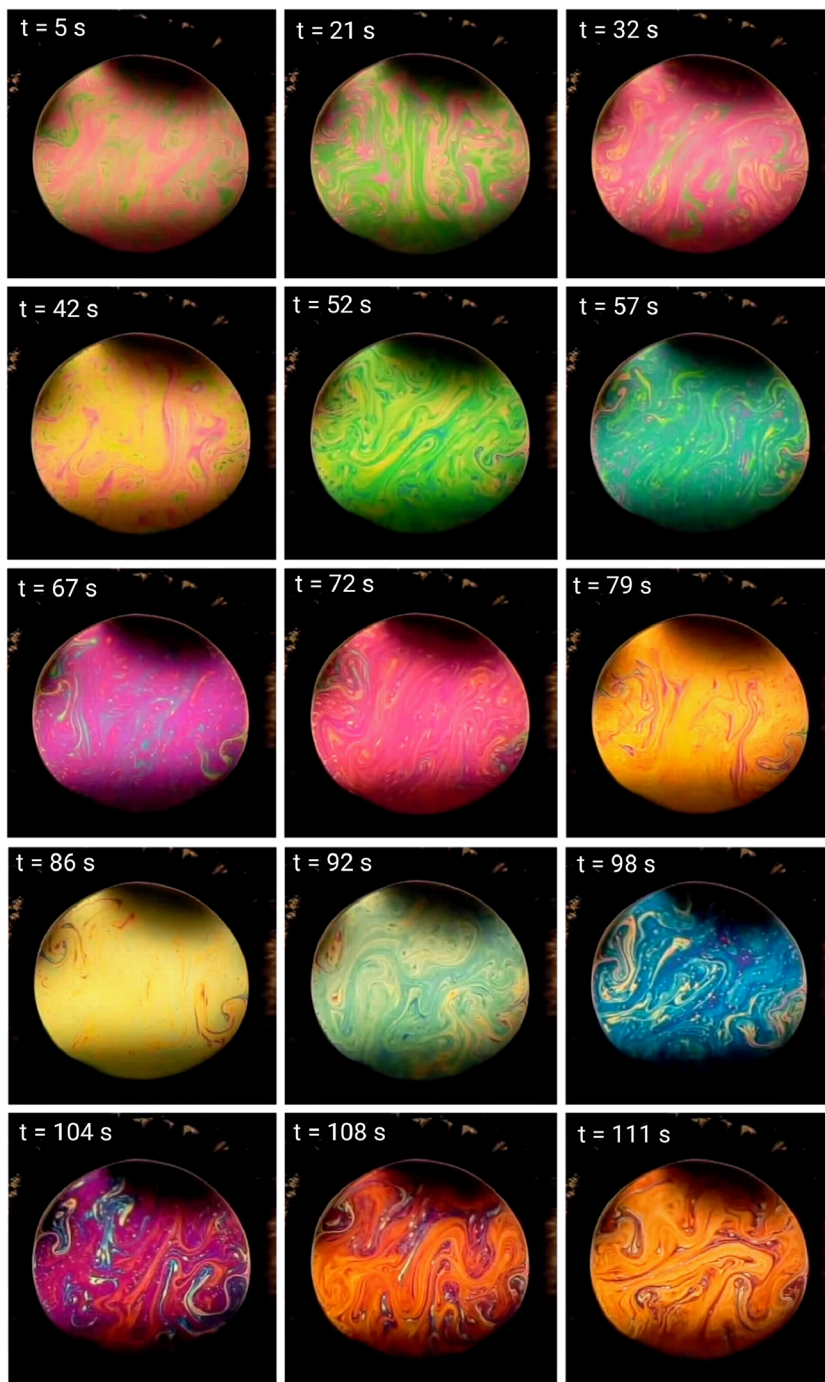


FIG. 2. Color variations in a mesitylene thin film under constant current and zero external field, demonstrating how changes in film thickness influence light interference patterns over time (Multimedia 2 available online).

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and slip features, respectively. The dimensionless relative permittivity is the ratio of a material's absolute permittivity to that of a vacuum. Table I presents 25 liquids with relative permittivities exceeding the threshold value of 4; this threshold is approximately half of the relative permittivity of the frame, which approximately

equals 8. In contrast, Table II includes liquids with relative permittivities less than or slightly above the threshold value. In our experiments, we treated the variation in relative permittivity as a tuning parameter. All liquids had a purity exceeding 95% and were used without any additives or solvents.

TABLE I. Relative permittivity (ϵ) of liquids with permittivities higher than half of the relative permittivity of the phenolic resin frame ($\epsilon \approx 8$), demonstrating no-slip behavior. The values are measured at $\sim 25^\circ\text{C}$ under a typical laboratory environment with a relative humidity of around 40% and are compiled from various material handbooks and scientific publications^{8,17–20} (Multimedia 3a to 3y available online).

Film material	Relative permittivity (ϵ)	Name of the related multimedia file (movie)
Benzyl chloride	7	Multimedia 3a
1 nonanol	8.3	Multimedia 3b1–3b3
1 hexanol	13.03	Multimedia 3c
Soap film	81	Multimedia 3d1 and 3d2
2-5 hexanedione	5.68	Multimedia 3e
Acetic acid	6.2	Multimedia 3f
1-bromo-2-fluorobenzene	4.72	Multimedia 3g
Benzonitrile	25.9	Multimedia 3h
Diethyl oxalate	8.266	Multimedia 3i
Diiodomethane	5.32	Multimedia 3j
Dimethyl sulfoxide	47.24	Multimedia 3k
Ethylene glycol	41.4	Multimedia 3l
Formic acid	51	Multimedia 3m
Dimethylaniline-N,N	4.4	Multimedia 3n
1-dodecanol	5.8	Multimedia 3o
Cyclohexanol	16.4	Multimedia 3p
N-butanol	17.84	Multimedia 3q
1-propanol	20.8	Multimedia 3r
Cyclohexanone	18.2	Multimedia 3s
Ethyl acetoacetate	15	Multimedia 3t
Cyclopentanone	13.5	Multimedia 3u
Formamide	84	Multimedia 3v
Ethyl benzoate	6	Multimedia 3w
O-toluidine	6.13	Multimedia 3x
1-bromo-3-fluorobenzene	4.85	Multimedia 3y

TABLE II. The relative permittivity (ϵ) of the liquids that are less than half or slightly above that of the phenolic resin frame ($\epsilon \approx 8$), resulting in slipping rotation. These permittivity values, measured at $\sim 25^\circ\text{C}$ under a typical laboratory environment with a relative humidity of around 40%, are obtained from various material handbooks and scientific literature^{8,17–20} (Multimedia 3 α to 3 μ available online).

Film material	Relative permittivity (ϵ)	Name of the related multimedia file (movie)
1-chlorononane	3.428 (100 °C)–4.22 (20 °C)	Multimedia 3 α
Dodecane	2.1	Multimedia 3 β
tert-butylcyclohexane	2.07	Multimedia 3 γ
5-nonanol	3.54	Multimedia 3 δ
cis-decahydronaphthalene	2.23	Multimedia 3 ζ
Styrene	2.4737	Multimedia 3 η
1,2-dimethoxybenzene	4.09	Multimedia 3 θ
1-bromo-4-fluorobenzene	2.6	Multimedia 3 ι 1 and 3 ι 1
Mesitylene	2.2	Multimedia 3 κ 1 and 3 κ 2
Phenylhexane	2.3	Multimedia 3 λ and 3 μ

C. Methodology for detection of slip and no-slip rotation

We distinguish between slip and no-slip rotational modes with visual inspection as well as the PIV method.

Figure 3 displays a single frame from each of the movies recorded with the liquids listed in Tables I and II. These frames are shown in Figs. 3(a)–3(y) and 3(α)–3(μ). (The corresponding multimedia files, Multimedia 3a–3y and 3α–3μ, are available online) All of the selected movie frames corresponding to liquids given in

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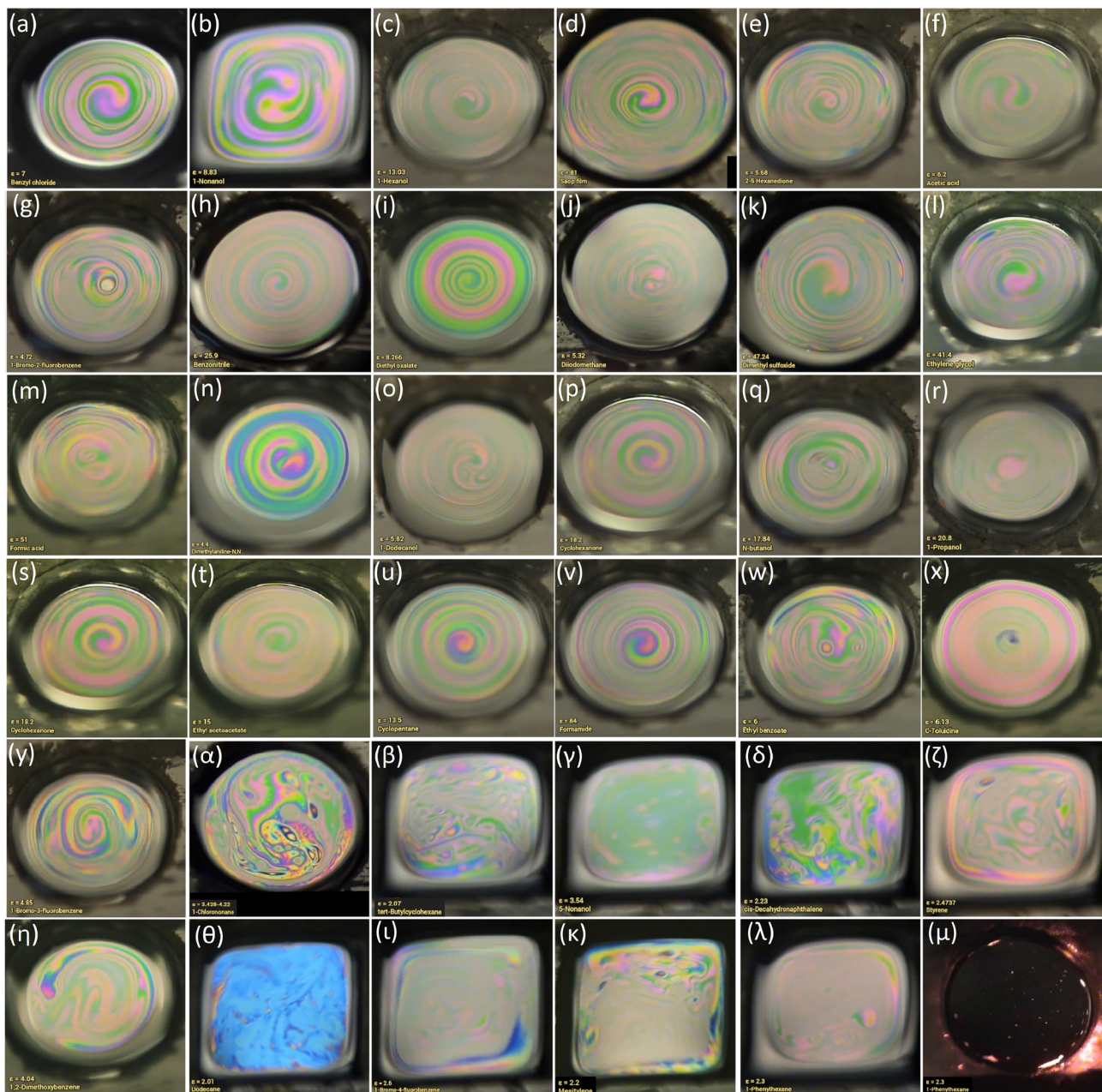


FIG. 3. Selected frames from the movies listed in Tables I and II. Frames (a) to (y) showcase spiral color patterns in the non-slipping films, while frames (α) to (μ) display irregular central patterns with elongated color fringes in sliding films. For further visual context, please refer to Multimedia 3a–3y and 3α–3μ. The frame (μ) is extracted from Multimedia 3μ recorded for the PIV method (Multimedia 3a–3y and 3α–3μ available online).

Table I exhibit a certain spiral color pattern [see Figs. 3(a)–3(y)], indicating a no-slip rotation. In contrast, the movie frames corresponding to liquids in Table II display an irregular pattern at the center and elongated color fringes, indicating the slipping rotation of the corresponding thin films [see Figs. 3(α)–3(μ)].

Multimedia 3b1–3b3 illustrate the no-slip rotation of a 1-nonanol film. Multimedia 3b2, in particular, combines eight distinct segments recorded under varying V_f values, ranging from 50 to 350 V. As the applied voltage increases, the rotational velocity also increases. In all cases, a spiral pattern is observed, which can be

used to identify the rotational mode. However, at lower velocities, visual inspection of this pattern is more straightforward. Multimedia 3b3 combines two different thin films—one with a circular frame and the other with a square frame—both of which exhibit the same rotational mode (Multimedia 3b1–3b3 available online).

Multimedia 3d1 and 3d2 demonstrate the no-slip rotation of a thin soap film. Multimedia 3d2 specifically combines four distinct segments from a long-duration video, recorded under varying external parameters for comparison. It is observed that increasing either of the external parameters, V_f and E , results in a higher rotational velocity. When the applied force becomes significantly stronger, the rotational speed increases accordingly. In all cases, a spiral pattern is evident, which can be used to determine the rotational mode. However, at lower velocities, visual inspection of this pattern is much easier (Multimedia 3d1 and 3d2 available online).

Similar to Multimedia 3b2, which demonstrates the no-slip rotation, Multimedia 3i2 features two thin films of 1-bromo-4-fluorobenzene with a relative permittivity of 2.6 framed in circular and square shapes (Multimedia 3i2 available online). In both cases, the films exhibit the same slipping rotational mode. The same behavior is observed in Multimedia 3k2 for mesitylene with a relative permittivity of 2.2 (Multimedia 3k2 available online).

We have also used the PIV method to determine the rotational velocity pattern, similar to our previous studies.¹² As an instance to corroborate the visual inspection method and confirm the consistency of both methods, we provide Multimedia 3λ for visual inspection and Multimedia 3μ for particle tracking in the PIV method, both for a phenylhexane film (cf. Fig. 2 of our previous work¹²). Both movies reveal the slip feature of the thin film made of phenylhexane (Multimedia 3λ and 3μ available online).

The PIV method involves adding microparticles to the film and capturing the motion of the rotating film using high-speed imaging. These particles act as tracers, allowing us to visualize and measure the flow dynamics.

However, the PIV method is time-consuming and requires additional imaging equipment. During our experiments, we found out that visual inspection can also effectively differentiate between slip and no-slip rotation without the need for added particles, provided the rotational parameters are adjusted for a relatively lower rotational velocity for visual inspection.

In all the movies listed in the third column of Table I, films exhibiting no-slip rotation display a distinct spiral color pattern at their center. This pattern suggests the possible presence of an asymmetric bulge near the center that rotates with the film. While we do not have direct measurements of this bulging, the spiral-like color pattern serves as visual evidence that an off-axis bulge may form within the film's volume in the vicinity of the center during the no-slip rotational phase. Further investigation would be needed to quantify any observed bulging. To preserve this feature, the rotational speed must remain relatively low. As the angular velocity increases, the bulge stretches and eventually merges with the rest of the film, resulting in an almost symmetric shape. This effect is clearly demonstrated in the 1-nonanol film in Multimedia 3b2, as V_f increases from 50 to 350 V (Multimedia 3b2 available online).

Conversely, for slip cases, as listed in the third column of Table II, the (irregular) color pattern remains steady at the center with stretched patterns near the edges. Increasing the angular velocity in these cases leads to the formation of a uniform color pattern at

the vicinity of the edge of the frame, and further increases in angular velocity cause the radial width of this area to expand toward the center of the film (see Multimedia 3α, which is available online).

Thus, by adjusting the parameters to achieve a relatively slow rotation, we can visually distinguish between slip and no-slip cases.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In our experimental setup, we used a frame made of phenolic resin with a relative permittivity (dielectric constant) of 8.²¹ The experiment demonstrated that when an electric field and voltage are applied, the liquid films within the frame rotate.

We observed that films with a permittivity greater than a certain threshold—approximately half the relative permittivity of the frame—exhibit no-slip rotation (refer to the 28 videos listed in Table I). In contrast, films with relative permittivities below or slightly above that threshold display slip rotation (see the 13 videos listed in Table II).

These results underscore the significance of the frame's permittivity, highlighting the crucial role of boundary conditions in inducing the rotation. Therefore, it is essential to consider both the permittivity of the frame and the liquid film, along with the boundary conditions, when analyzing the behavior of these rotating films.

By inspecting Multimedia 3α, we observe that gradually increasing the film's rotation speed to a certain threshold—controllable through external factors during the experiment—creates distinct visual patterns under white light illumination. These patterns rotate with the film without rapid deformation, suggesting they move in sync with the film. While we do not directly observe a bulge, the presence of spiral-like color patterns at the film's center indicates that such a bulge may exist within the thin film's volume during the no-slip rotational phase (Multimedia 3α available online).

While variations in film thickness can influence color patterns across different regions, assuming minimal thickness variation over a short period, we infer that the rotation of the color pattern corresponds to the rotation of the entire film volume.

Tables I and II detail the attached videos, which have been edited to display only frames where the distinction between slip and no-slip rotational phases is visually identifiable. One of the videos, recorded using the PIV method, involves the introduction of light-scattering particles (see Multimedia 3μ, which is available online).

In the first set of videos listed in Table I, nearly all films show a spiral-like color pattern. In contrast, the films in Table II exhibit non-rotational color patterns in their central regions, with rotation observed only near the film boundaries.

We propose that films operating in the no-slip rotational mode, characterized by a spiral color pattern, could function as optical tools. Their regular variation in thickness along the azimuthal direction at intermediate radial distances introduces a rotating phase to a plane beam passing through them, as evidenced by the observed spiral fringe patterns.²² Similar to spiral phase plates,^{13,14,23–25} these films have potential applications in generating vortex beams. This work is currently under study and in the experimental phase, and we hope to complete it in the near future. Finally, it is important to note that the formation of a bulging area within the film volume

in the no-slip case warrants further investigation regarding the fluid dynamics. This phenomenon may be related to the fluid behavior observed in the no-slip condition between two co-axial cylinders.²⁶

A. Quantitative analysis of spiral fringe rotation as a function of applied voltage

To quantitatively evaluate the influence of applied voltage on the rotational dynamics of spiral fringes, we revisit the behavior of the 1-nonanol film. Multimedia 4, associated with Fig. 4, presents a compilation of four separate video recordings of the film subjected to applied voltages (V_J) of 25, 40, 100, and 200 V. Representative frames extracted from these videos are shown in Fig. 4, illustrating the evolution of spiral patterns under increasing electric field strengths.

Each spiral pattern includes a reference marker placed at $t = 0$, whose subsequent motion is tracked to visualize the rotation path. These trajectories reveal that the spiral fringes undergo approximately uniform circular motion, with angular velocity increasing monotonically with the applied voltage.

Over a 0.32-s time interval, the number of complete rotations observed at each voltage level is as follows: 0.45 ± 0.02 rev at 25 V, 0.92 ± 0.02 rev at 40 V, 1.74 ± 0.02 rev at 100 V, and 2.66 ± 0.02 rev at 200 V. The uncertainty in these measurements, estimated at ± 0.02 rev, corresponds to an angular resolution of $\sim 7^\circ$ in tracking the rotation. These values reflect a clear increase in rotational speed with applied voltage. The corresponding angular velocities, expressed in revolutions per second, are presented in Table III.

TABLE III. Angular velocity of spiral fringe rotation as a function of applied voltage.

Applied voltage V_J (V)	Angular velocity (rev/s)
25	1.40 ± 0.06
40	2.86 ± 0.06
100	5.44 ± 0.06
200	8.32 ± 0.06

The data in Table III indicate a clear positive correlation between the applied voltage and the angular velocity of spiral rotation across the studied range (25–200 V). While the angular velocity increases consistently with voltage, the curvature of the plot bends downward, meaning that the incremental gain in angular velocity diminishes as the voltage increases. This behavior suggests a sublinear response, where the system exhibits progressively smaller increases in angular velocity per unit of voltage, especially at higher voltages. Such a trend points to the onset of asymptotic behavior, implying that the system may be approaching a saturation limit in angular velocity under strong electric fields. Further investigation into the mechanisms underlying this asymptotic trend is planned for future studies. Figure 5 illustrates a strong positive correlation, with angular velocity increasing as the voltage rises. However, the rate of increase diminishes at higher voltages, indicating the onset of asymptotic behavior in the system’s response.

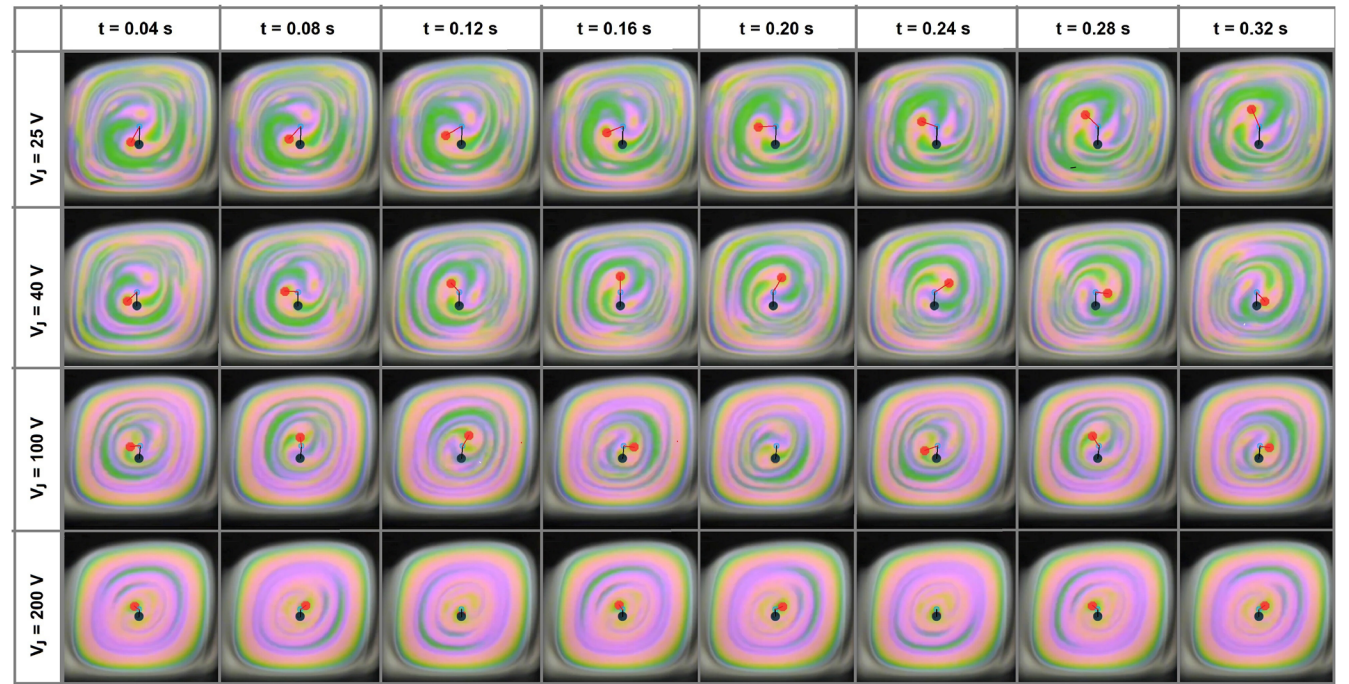


FIG. 4. Successive frames from four separate recordings of a 1-nonanol film subjected to V_J values of 25, 40, 100, and 200 V, respectively. A black dot marks a reference point on each spiral at time $t = 0$, with subsequent positions shown in pink. These trajectories trace nearly circular paths, indicating uniform rotation, with angular velocity increasing as a function of applied voltage. Multimedia 4 (available online) provides additional close-up footage of the central region. (Multimedia available online).

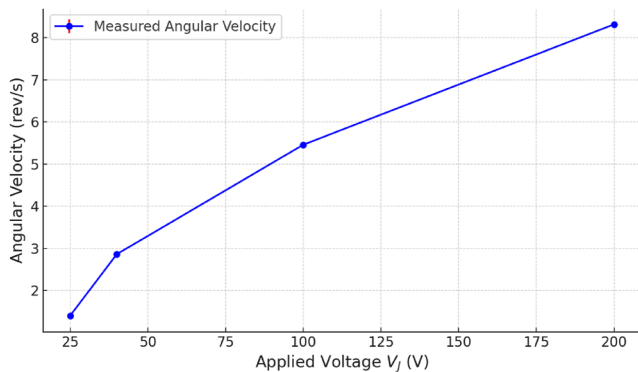


FIG. 5. Angular velocity of spiral fringe rotation as a function of applied voltage, based on data from Table III. The uncertainty of the used data is ± 0.06 rev/s. The plot shows a strong positive correlation, with the angular velocity increasing with voltage. The diminishing rate of increase at higher voltages suggests the emergence of asymptotic behavior in the system's response.

An additional observation from Fig. 4 is the increasing spatial compactness of the spiral patterns at higher voltages. As the rotation rate increases, the fringes become more densely packed and tend to converge toward the film's center. This behavior indicates a voltage-dependent compression of the spiral structure, possibly driven by variations in surface tension gradients or electrohydrodynamic effects acting across the film.

IV. CONCLUSION

In conclusion, our study demonstrates the utility of combining visual inspection with Particle Image Velocimetry (PIV) to effectively distinguish between slip and no-slip rotational behaviors in suspended liquid films subjected to orthogonal electric fields. Through controlled experiments and analysis of interference fringe patterns, we reveal that the permittivity ratio between the film and its enclosing frame plays a decisive role in determining the nature of rotational motion. Specifically, no-slip rotation occurs when the film's permittivity exceeds half the permittivity of the frame, while slip rotation is observed below this threshold. This distinction is visually evident: no-slip films produce characteristic spiral color patterns due to their solid-body-like rotation, whereas slip films resemble conventional soap films with smooth, concentric interference patterns. These findings not only provide a simple optical method to infer rotational mode but also yield important theoretical insights, suggesting the need to revisit and potentially refine existing models of electrohydrodynamic rotation in thin films to incorporate frame-film dielectric interactions. Moreover, these results hold promise for practical applications in materials science and microfluidics. For instance, the ability to control and predict rotational behavior through dielectric properties could be employed in boundary flow control, directional transport, or mixing strategies in lab-on-a-chip platforms. In addition, films exhibiting stable no-slip spiral rotation may serve as novel optical components—such as dynamic spiral phase plates—for generating structured light beams, including optical vortices. Finally, as the supplementary material, we provide a curated set of 44 short videos showcasing the rotational

dynamics of various liquids under external fields. These recordings are intended to support researchers in related fields, offering a rich visual dataset for comparative studies and cross-disciplinary applications.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Saifollah Rasouli: Conceptualization (lead); Data curation (equal); Formal analysis (lead); Funding acquisition (lead); Investigation (lead); Methodology (lead); Project administration (lead); Resources (lead); Software (equal); Supervision (lead); Validation (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (lead). **Reza Shirsavar:** Conceptualization (equal); Data curation (lead); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Resources (equal); Software (equal); Supervision (equal). **Saeid Mollaei:** Data curation (equal); Software (equal). **Behnam Shirsavar:** Data curation (equal); Software (equal); Visualization (equal). **Ammar Nejati:** Validation (equal); Writing – review & editing (equal). **Ahmad Amjadi:** Resources (equal); Visualization (equal).

DATA AVAILABILITY

All data are available within the article or in the multimedia files.

REFERENCES

- ¹S. A. Akhmanov and S. Y. Nikitin, *Physical Optics* (Oxford University Press, 1997).
- ²M. Kleman and O. D. Lavrentovich, *Soft Matter Physics: An Introduction* (Springer, 2003).
- ³D. Lovett and J. Tilley, *Demonstrating Science with Soap Films* (CRC Press, 2017).
- ⁴S. W. Morris, J. R. de Bruyn, and A. D. May, "Electroconvection and pattern formation in a suspended smectic film," *Phys. Rev. Lett.* **65**, 2378 (1990).
- ⁵Z. A. Daya, S. W. Morris, and J. R. de Bruyn, "Electroconvection in a suspended fluid film: A linear stability analysis," *Phys. Rev. E* **55**, 2682 (1997).

- ⁶C. Langer and R. Stannarius, "Electroconvection in freely suspended smectic-c and smectic-c* films," *Phys. Rev. E* **58**, 650 (1998).
- ⁷A. Amjadi, R. Shirsavar, N. H. Radja, and M. R. Ejtehad, "A liquid film motor," *Microfluid. Nanofluid.* **6**, 711–715 (2009).
- ⁸R. Shirsavar, A. Amjadi, A. Tonddast-Navaei, and M. R. Ejtehad, "Electrically rotating suspended films of polar liquids," *Exp. Fluids* **50**, 419–428 (2011).
- ⁹R. Shirsavar, A. Amjadi, M. R. Ejtehad, M. R. Mozaffari, and M. S. Feiz, "Rotational regimes of freely suspended liquid crystal films under electric current in presence of an external electric field," *Microfluid. Nanofluid.* **13**, 83–89 (2012).
- ¹⁰M. Nasiri, R. Shirsavar, T. Saghaei, and A. Ramos, "Simulation of liquid film motor: A charge induction mechanism," *Microfluid. Nanofluid.* **19**, 133–139 (2015).
- ¹¹R. Shirsavar, A. Ramos, A. Amjadi, J. Taherinia, M. Mashhadi, and A. Nejati, "Induced soap-film flow by non-uniform alternating electric field," *J. Electrostat.* **73**, 112–116 (2015).
- ¹²R. Shirsavar, S. Mollaei, M. Moeini Rizi, A.-R. Moradi, A. Amjadi, M. Habibi, and A. Najafi, "Effect of permittivity on the electric-field-driven rotation dynamics in a liquid film," *Appl. Mech.* **3**, 78–87 (2022).
- ¹³V. V. Kotlyar, A. A. Kovalev, R. V. Skidanov, S. N. Khonina, O. Y. Moiseev, and V. A. Soifer, "Simple optical vortices formed by a spiral phase plate," *J. Opt. Technol.* **74**, 686–693 (2007).
- ¹⁴S. S. R. Oemrawsingh, J. A. W. van Houwelingen, E. R. Eliel, J. P. Woerdman, E. J. K. Versteegen, J. G. Kloosterboer, and G. W. 't Hooft, "Production and characterization of spiral phase plates for optical wavelengths," *Appl. Opt.* **43**, 688–694 (2004).
- ¹⁵G. Kostyuk, V. Shkuratova, A. Petrov, D. Stepanyuk, and R. Zakoldaev, "Spiral phase plate for generation of scalar vortex beam made on fused silica by laser-induced microplasma," *Opt. Quantum Electron.* **55**, 344 (2023).
- ¹⁶S. Yu, N. Kou, L. Li, and Z. Cui, "Reflective and transmission metasurfaces for orbital angular momentum vortex waves generation," in *Electromagnetic Metamaterials and Metasurfaces: From Theory to Applications*, edited by L. Li, Y. Shi, and T. J. Cui (Springer, 2023), Chap. 7, pp. 223–287.
- ¹⁷D. R. Lide, *CRC Handbook of Chemistry and Physics* (CRC Press, 2004), Vol. 85.
- ¹⁸C. Wohlfarth, *Static Dielectric Constants of Pure Liquids and Binary Liquid Mixtures: Supplement to IV/6* (Springer Science & Business Media, 2008), Vol. 17.
- ¹⁹C. Wohlfarth and B. Wohlfarth, "Pure liquids: Data: Datasheet from landolt-börnstein," in *Surface Tension of Pure Liquids and Binary Liquid Mixtures, Group IV Physical Chemistry* (Springer-Verlag Berlin Heidelberg, 1997), Vol. 16.
- ²⁰I. Smallwood, *Handbook of Organic Solvent Properties* (Butterworth-Heinemann, 2012).
- ²¹The Engineering ToolBox, Relative permittivity—The dielectric constant, 2010, accessed 28 April 2024.
- ²²M. M. Masouleh, S. Rasouli, and R. Shirsavar, "No-slip rotation liquid films: Liquid spiral phase plates," in *Proceedings of the 31st Conference on Optics and Photonics and the 17th Photonic Engineering and Technology Conference of Iran* (Iran University of Science and Technology, Tehran, Iran, 2025), presented contribution.
- ²³V. V. Kotlyar, H. Elfstrom, J. Turunen, A. A. Almazov, S. N. Khonina, and V. A. Soifer, "Generation of phase singularity through diffracting a plane or Gaussian beam by a spiral phase plate," *J. Opt. Soc. Am. A* **22**, 849–861 (2005).
- ²⁴C. Rotschild, S. Zommer, S. Moed, O. Hershcovitz, and S. G. Lipson, "Adjustable spiral phase plate," *Appl. Opt.* **43**, 2397–2399 (2004).
- ²⁵D. Hebri and S. Rasouli, "Combined half-integer Bessel-like beams: A set of solutions of the wave equation," *Phys. Rev. A* **98**, 043826 (2018).
- ²⁶R. Di Prima and H. L. Swinney, "Instabilities and transition in flow between concentric rotating cylinders," in *Hydrodynamic Instabilities and the Transition to Turbulence* (Springer, 2005), pp. 139–180.