FiberDrops: Designing a Fluidic System for Dot-Based Gradient Patterns with Colored Droplets

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Image/teaser.png

Fig. 1. (A) Changing droplet density in a tube. (B) Overall system. (C) Woven tubes. (D) A tube wound around a 3D object. (E) Multi-color expression.

This paper presents FiberDrops, a tubular system that generates diverse patterns, from discrete dot-based expressions to gradients, by flowing colored droplets within transparent liquid. While previous studies have explored visual expression using droplets, FiberDrops introduces two distinctive features. First, it employs ElectroHydroDynamic (EHD) pumps, providing a lightweight and silent alternative to conventional mechanical pumps. Second, by incorporating a custom connector based on microfluidic techniques, it generates fine droplets from parallel flows of transparent and colored liquids and enables precise density control. Compared with conventional on/off pump switching between colored and transparent liquids, this approach achieves finer and more stable droplet spacing, while allowing flexible variation of flow speed even for the same patterns. These capabilities enable visual effects such as continuous color transitions and dynamic motifs, expanding the design space of fluidic displays and wearable interfaces. This paper details the system's design, fabrication, and control methods and demonstrates representative applications.

Additional Key Words and Phrases: Programmable Materials, Fluid Interface, Liquid Actuation, Droplet generation, Electrohydrodynamics

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1 INTRODUCTION

Designing interfaces increasingly involves engaging with the material properties of physical substances. In the field of Human–Computer Interaction (HCI) and Art, liquids have attracted growing attention because of their diverse properties, such as thermal conductivity, density, coloration, and chemical reactivity which offer potential for novel forms of interaction and interface design [9, 13, 16, 20, 22, 24, 27].

In particular, flowing colored liquids in tubes have been explored as an interface for visual expression. This is enabled by the deformability of the tubular structures and the programmability of the internal fluids, which together support the dynamic display of visual information. Using mechanical components such as solenoid valves and pumps to insert liquids into tubes and control their flow, previous research has explored both display systems and artistic expressions by injecting long segments of colored liquids to change its overall color, inserting short segmented liquids and moving them to express dynamic flow, and controlling the position of droplets and aligning them to show letters and symbols. [12, 15, 21, 23, 24]. However, intricate visual expressions such as gradients have yet to be fully explored. Gradient expression has been explored in painting and design, both as a means of enhancing visual depth through shading and as a decorative technique. Particularly in the field of painting, the expression of gradational colors is achieved not only through the selection of hues, but also by varying the density of brushstrokes, such as in pointillism [7].

Inspired by this approach, we propose FiberDrops, a tubular system to express gradient patterns, through a custom-designed connector based on microfluidic techniques [6, 25]. Flows are driven by compact ElectroHydroDynamic (EHD) pumps, providing a lightweight and silent alternative to conventional mechanical pumps. With this approach, gradient expression can be achieved even using single-colored droplets flowing in a transparent liquid.

In conventional methods for flowing colored liquids in tubes, visual effects are generated by alternately switching pumps for colored and transparent liquids on and off. While this approach has been used to control the position of individual droplets, it is limited in achieving finer spacing control for continuous droplet streams and droplet density adjustments to express gradient patterns. In contrast, our method enables finer control of droplet spacing while maintaining smooth flow, and can dynamically adjust flow speed according to the application context, even when producing the same patterns. These capabilities support richer visual expression and broaden the design space of fluidic displays and wearable interfaces.

In summary, we contribute:

(1) A novel tubular system for expressing color gradients in tubes through droplet density control, expanding the expressive potential of liquid-based interfaces.
(2) A design of a custom connector to generate droplets.
(3) A controlling method for modulating droplet density.
(4) Design examples demonstrating how density-controlled gradients can broaden the design space of fluid displays and wearable interfaces.

2 RELATED WORK

2.1 Colored Liquid Expression Within Tubes

Colored liquid expression within tubes has gained attention in the fields of art and HCI, due to the deformability of tubular structures and the programmability of internal fluids. Various studies have been conducted to explore their potential as a medium for visual display.

Some research has focused on controlling the position of liquid droplets for information display. For example, Bit.Flow [21] consists of aligned tubes and displays text by precisely positioning droplets. Tuve [24], a shape-changing tube display, visualizes symbolic patterns and text through controlled droplet positioning.

Other studies have examined the materiality and affordances of liquids in tubes. Liu et al. [12] explored the expressive potential of fluid fiber materials through hands-on workshops. Computer 1.0 [15] exhibited textiles that present dynamic flowing patterns, and Fluid Dress [3] integrated fluidic expression into knitted tubular structures. Ruten [27] is an installation in which droplets are formed by slug flow and pass through a stable tube shaped structure that is bent into different shapes and widths. Though the droplets are generated at fixed intervals for viewers to closely observe their motions, in this research we aim to expand the droplet-based expressions by dynamically modulating the droplet density, while also using flexible tubes. In addition to tubes, milleCrepe [14] has developed multilayer structures where water in multiple colors can be aligned or mixed in different patterned chambers. Although these studies have demonstrated the broad design space for liquid-based expressions, we propose an additional method that achieves droplet-based color gradient expression by controlling the density of droplets flowing through tubes.

2.2 Droplet Generation in Microfluidics

Our method is based on droplet generation technology in the field of microfluidics. Since its emergence in the late 1980s, microfluidics has evolved as a technology that enables the precise manipulation of fluids within channels typically ranging from tens to hundreds of micrometers in size [25]. In particular, droplet generation techniques have been actively developed to enable the processing of small volumes of reagents in microchannels, especially in the fields of biomedical and biopharmaceutical research. A number of configurations have been developed for droplet generation, including T-junction [26], flow-focusing [1], and co-flow configurations [6].

In this research, we have designed a connector which applies the co-flow configuration to generate droplets on a scale of millimeters and to realize droplet-based color gradients in tubes. In addition, as the co-flow configuration is designed within the connector, we have achieved a more compact system compared to the acrylic liquid channels that have been previously proposed [2].

2.3 Electrohydrodynamics (EHD)

The electrohydrodynamic (EHD) phenomenon induces dielectric liquid flow by applying a high voltage between electrodes, generating an electric field that causes charged particles within the fluid to migrate along the channels.

While existing fluidic systems typically rely on complex and bulky mechanical components, EHD pumps enable compact, lightweight, and silent fluid manipulation without relying on mechanical components. This technology has recently gained attention even in the field of HCI [8, 10, 11, 17–19]. Liquebits [2] is a notable example of research exploring colored liquid expressions using EHD pumps. However, Liquebits mainly focuses on the silent expression of colored liquids and does not address color gradation. In response, our work aims to expand the expressive potential of liquid-based interfaces by enabling more intricate color expression through the control of droplet density.

3 FIBERDROPS

Our system can generate diverse patterns, from discrete dot-based expressions to gradients driven by EHD pumps. In this section, we describe the system configuration, the design of the connector, the method for generating droplets and controlling their density, and the position control method.

3.1 EHD pump

An EHD pump is an electrically driven pump that provides a lightweight and silent alternative to conventional mechanical pumps. Figure **??** illustrates the mechanism for generating dielectric liquid flow. When a high voltage is applied to the electrodes, an electric field is formed between the comb-shaped electrodes. Ionized particles in the dielectric liquid are attracted toward the electrodes, and their movement induces a corresponding flow of the dielectric liquid. The stronger the electric field between the electrodes, the greater the resulting pressure and flow rate generated by the pump.

3.2 System Configuration

As shown in Fig. 3, the system is broadly composed of two components: the liquid actuation part and the display part.

The liquid actuation part consists of EHD pumps, the high voltage control unit, Pump reservoir, check valves, syringe, colored liquid reservoir tube, and connector. The liquid flow is generated by the EHD pumps which is controlled by the high voltage control unit.

Novec 7100 is used as the dielectric transparent liquid, and the operating voltage of the pumps ranges from approximately 5 to 9 kV. As the droplets are created by using two immiscible liquids, we used Novec 7100 and colored water. Droplets are generated as the transparent liquid flow breaks the colored liquid flow into droplets using a custom connector based on microfluidic technique. In this study, the transparent liquid is the continuous phase, and the colored, droplet-forming liquid is the dispersed phase.

Image/3-1_EHD.png

Fig. 2. EHD pumps.

The display part which consists of a tube can be deformed due to the flexibility of the material. We demonstrate this potential in the design examples section. For the tubes we used Tygon® tubing with an inner diameter of 2 mm and an outer diameter of 4 mm. The outer diameter of the connector's inlets and outlets is determined by the inner diameter of the tube. Since all connectors are 3D printed, their size can be customized for the intended applications. However, the narrower the diameter, the higher the internal resistance in the tube, requiring appropriate adjustment of the pump output.

Before activating this system, the colored water containing syringe is pushed to load it into the reservoir tube. Then, high voltage is applied to both EHD pumps; one pump drives the dielectric liquid as the continuous phase, while the other controls the dielectric liquid to push the colored water as the disperesed phase towards and through the connector. The two immiscible liquids meet within the connector, and droplets are formed as they are pushed into the display tube.

To prevent backflow, check valves are installed in the pump system. By adjusting the balance of the pumps' output, the density of the droplets can be modulated, enabling the expression of color gradients using liquid. These droplets travel through the display section and return to the pump reservoir, allowing the dielectric liquid to be reused. Because the colored liquid is less dense than the dielectric liquid, it floats to the upper layer of the reservoir. To prevent the colored liquid from reaching the pump inlets, a partition with a hole at the bottom is installed inside the reservoir. This way, mainly dielectric liquid is drawn back into the pumps, while the returned colored liquid is manually collected.

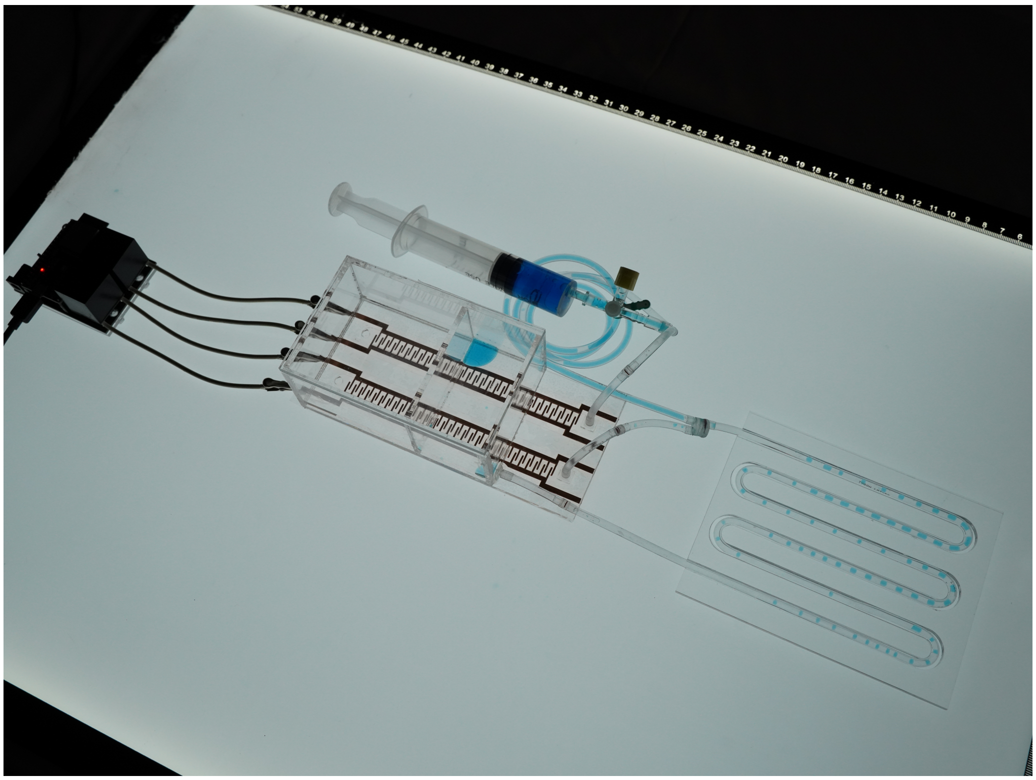

Fig. 3. System overview. (A) EHD pumps, (B) dielectric liquid reservoirs (C) check valves, (D) syringe, (E) colored liquid reservoir tube, (F) connector, (G) reservoir for storing the ejected liquid. (H) tube for the display part.

3.3 Design of the Microfluidic Inspired Connector

This section describes the design of the connector where transparent and colored liquids merge and generate colored droplets. As shown in Fig. 4(A), the connector applies the co-flow configuration, a common droplet generation method in microfluidics [6]. The co-flow configuration was chosen because both liquids flow in the same direction, allowing the pumps and connector to be arranged in a straight-line layout which simplifies the connector's design. As shown in Fig. 4(A), the connector consists of two inlets, a chamber, and an outlet, where each liquid enters its assigned inlet, merges within the chamber and exits from the outlet. The colored liquid is segmented into droplets by the combined effects of shear stress exerted by the continuous phase and the interfacial tension between the two immiscible liquids.

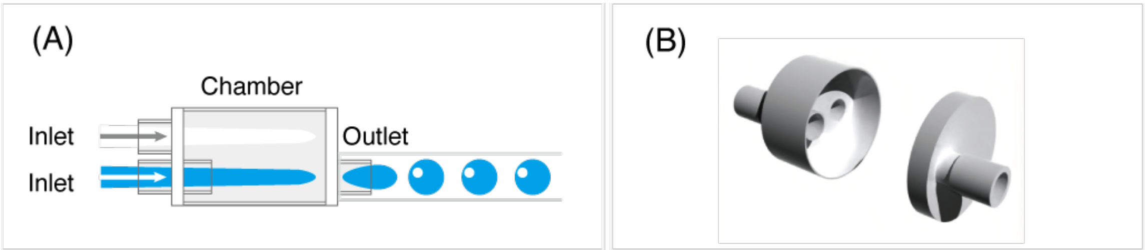

Fig. 4. The design of the connector. (A) Inner structure of the connector. (B) 3D image of the connector parts.

3.4 Principle of Droplet Control

FiberDrops can generate diverse patterns—from discrete dot-based expressions to gradients—by conveying colored droplets within a transparent liquid. For dot-based expressions, patterns are produced by alternately switching the pumps that drive the continuous and dispersed phases, as in prior work on flowing liquid in tubes. By contrast, gradients rely on a different control regime: both EHD pumps run continuously while the continuous and dispersed phases through the custom microfluidic connector; at the junction, the continuous phase shears and pinches off the dispersed stream to form fine droplets. In this paper, our method applies the co-flow configuration [6]. The flow rate ratio between the dispersed and continuous phases is a key parameter for adjusting droplet density. As the pump output for the dispersed phase increases, droplets are generated more frequently, resulting in a higher droplet density.

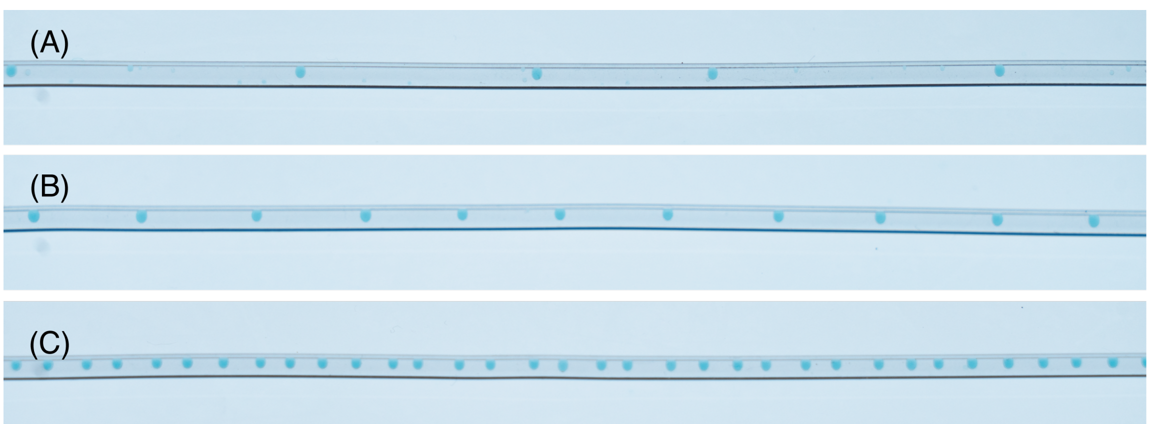

Fig. 5. Result. While the EHD pump for the continuous phase is controlled at 5kV, the EHD pump for the dispersed phase is controlled at 7kV in (A), 7.5kV in (B), and 8kV in (C).

Figure 5 shows the differences in droplet generation frequency from (A) to (C). While keeping the voltage applied to the pump of the continuous phase constant, the voltage applied to the pump driving the dispersed phase is increased. As the flow rate ratio of the dispersed phase becomes higher than that of the continuous phase, the droplet density increases. As shown in Figure 6, this method allows us to control droplet density within a single tube. It enables gradient representations using droplets, expanding the visual expressiveness of liquid-based displays.

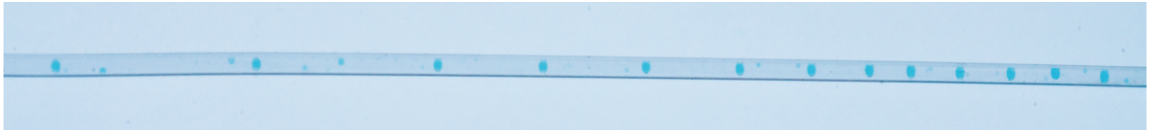

Fig. 6. Changing droplet density in a single tube.

3.5 Position Control

The positioning of droplet patterns is influenced by the hydraulic resistance inside the tube, which depends on both droplet density and tube length. Therefore, when controlling droplet pattern positions, the pump activation time must be adjusted according to the desired pattern density and tube length. The key parameters for droplet generation are the applied voltage and duration of the pumps for the continuous and dispersed phases. For each application, preliminary experiments are required to determine the baseline values. To achieve accurate droplet positioning, we compensate the applied duration according to the cumulative influence of previously generated patterns. Each pattern type is assigned a resistance factor r_j, and the adjusted duration T_i for the i-th pattern is computed as:

$$T_i = T_{\text{base}} \times \left(1 + \sum_{j=1}^{i-1} r_j\right) \tag{1}$$

where T_{base} is the baseline duration. This formulation accounts for residual flow effects, enabling finer control of droplet spacing.

4 IMPLEMENTATION

This section covers the fabrication process of EHD pump, Droplet generating connector, and High voltage control unit.

4.1 EHD pump

Figure **??** shows a schematic of the fabricated pump. The pump consists of a base layer of transparent polyester (PET) OHP film (thickness 0.10 mm), electrodes formed from adhesive-backed copper tape (thickness 0.03 mm), a channel defined by VHB tape (thickness 1.0 mm), a partition layer with a small through hole (acrylic; thickness 3.0 mm), a top layer (acrylic; thickness 3.0 mm), reservoir components (acrylic; thickness 3.0 mm) and 3D printed connectors for the inlet and outlet. Figure **??** illustrates the fabrication process. First, adhesive-backed copper tape is laminated onto a PET OHP film and patterned into the desired electrode geometry using a cutting plotter (Silhouette Cameo 4), with cutting parameters configured to cut only the copper tape and leave the PET film intact. The electrode design follows prior work on stretchable pumps [4, 5]. Next, excess copper tape surrounding the electrode pattern is removed with tweezers. Next, VHB tape is laser-cut (VLS3.60DT) to define the channel geometry and laminated onto the electrode layer. Next, the partition layer, top layer, and reservoir components are laser-cut (VLS3.60DT) and assembled. The top layer is adhered to the channel using VHB tape, and the other acrylic components are solvent-bonded with an acrylic solvent adhesive. Finally, 3D-printed connectors are fabricated by an SLA printer (Form 2, Formlabs Inc.) using White Resin and bonded in place with a UV-curable adhesive.

4.2 Droplet generating connector

As shown in Fig. **??**, the connector is inspired by co-flow microfluidics: within the chamber, the nozzle for the dispersed phase is slightly longer than that for the continuous phase. To realize this geometry, the connector is fabricated in two parts using an SLA printer (Form 2, Formlabs) with Clear Resin and assembled with a UV-curable adhesive. The port diameters are set to match the tube inner/outer diameters. Because the part is 3D-printed, its dimensions are readily scalable and can be adjusted per application by editing the CAD.

4.3 High voltage control unit

To modulate the flowing colored liquid inside the tube, the system uses a two-channel high-voltage driver that provides linearly programmable outputs. Each channel employs a high-voltage amplifier (HVBT-10P-5, Matsusada Precision; up to 10 kV) with an analog setpoint. An ESP32, programmed in the Arduino environment, generates the setpoint via its on-chip DAC (0–3.3 V); a non-inverting NJM2732D stage ($R_1 = 2\,\mathrm{k\Omega}$, $R_2 = 1\,\mathrm{k\Omega}$; gain $1 + R_2/R_1 = 1.5$) expands the range to ~0–5 V, and a push–pull buffer using 2SC1815 devices provides drive. Driving the amplifier with this ~0–5 V setpoint enables linear high-voltage output. The electronics reside on a custom PCB, Wi-Fi connectivity is provided by the ESP32 for wireless operation, and the assembly fits in a compact 55 × 65 × 34 mm enclosure.

4.4 Software

5 EVALUATION

Compared with conventional on/off pump switching between colored and transparent liquids, this approach achieves finer and more stable droplet density, while allowing flexible variation of flow speed even for the same patterns. In this section, we evaluate

5.1 Finer droplet density

5.2 Variation of flow speed

6 DESIGN EXAMPLE

In this section, we present three design examples that demonstrate the unique features and potential applications of our proposed system.

6.1 Volumetric display

Figure **??** illustrates a single-tube volumetric display that renders patterns along the tube by conveying colored droplets within a transparent liquid. A single continuous tube is folded back and forth and laid out in parallel runs, thereby functioning as a one-dimensional display and can express patterns ranging from discrete dot trains to smooth gradients by controlling droplet density and advection speed. The flow speed can be varied depending on the motif to be displayed. Owing to the deformability of the tubular medium, the display can be formed into desired shapes, such as arcs or loops, without rigid substrates.

6.2 Wearable tubular accessory

Figure **??** shows a tubular accessory, highlighting its potential deformability for weaving and its suitability for the body. Its softness allows it to naturally conform to the wearer. Because droplets remain stationary when the pumps are turned off, users can set a desired pattern, wear the accessory with the pattern held in place, and later re-generate a new pattern on demand. The form factor is enabled by the deformability of the tubing and by EHD pumps, which provide a lightweight, silent alternative to conventional mechanical pumps.

6.3 Existing object wrapped with multi colored tubes

Figure **??** shows a multicolor gradient expression realized by weaving several tubes, each carrying droplets of a different dye (three colors). This design highlights the deformability of tubes wound around an existing object. A multicolored gradient can be applied, and the color composition can be dynamically reconfigured according to events, time, or situations, enabling the lamp to adapt its appearance. In addition to controlling patterns by varying droplet density, weaving tubes with different colored droplets can simulate color-blending effects at crossings where droplets appear to overlap.

Image/4-1_design.png

Fig. 7. Design examples. (A) Tube display to show gradient. (B) Wearable tube accessory. (C) Multi-color Wreath Configuration.

7 DISCUSSION

7.1 Limitation

Control of droplet behavior depends on the tube's hydrodynamic resistance and static head, which vary with tube length and geometry, the number and density of droplets and outlet height. Consequently, the baseline control parameters are application specific. For each application, we conduct a brief calibration to establish nominal voltage setpoints and actuation durations. Moreover, because the resistance also varies with the rendered pattern, we segment patterns—as described in Section **??**—and apply multiplicative corrections to pump actuation time for each segment based on the droplet density of the preceding segment.

7.2 Safety of high voltage actuation

We describe safety aspects for high voltage actuation. The EHD pump is driven at kilovolt potentials, and in our experiments we apply 3–7 kV. Although high voltage is present, shock hazard is governed primarily by the available current; in our design the output is limited to the microampere (μA) range, so even accidental contact at the high-voltage node is not expected to cause harm.

7.3 Safety of dielectric liquid

We use Novec 7100 (3M) as the dielectric liquid. It is a hydrofluoroether (HFE) commonly used in immersion cooling for data centers and electronics thermal management. According to the manufacturer's documentation, Novec 7100 is non-conductive, non-flammable, and characterized by low toxicity; under normal use, inhalation and skin/eye contact are not expected to cause significant adverse effects.

7.4 Future work

7.4.1 Automated colored liquid recirculation. In the current system configuration, the dielectric liquid circulates from the reservoir through the display part and back to the reservoir, allowing for its reuse. In contrast, the colored liquid has not yet been fully automated; it still requires manual refilling into the reservoir using a syringe or manual recovery of floating colored liquid that returns to the reservoir. Moving forward, we aim to develop a circulation system for colored liquids by incorporating sensors such as color sensors and water level sensors, thereby automating the reuse of all materials.

7.4.2 Interactive interface. This work focuses on pattern control via fluid properties. Looking ahead, we aim to couple the system to interactive inputs and embed it in soft substrates (e.g., clothing, bags) so that fluidic displays respond to users' behaviors in real time, for example, motion-responsive gradients while preserving the lightweight, silent characteristics of EHD

8 CONCLUSION

We presented FiberDrops, a tubular system that renders visual patterns—from discrete dot arrays to smooth gradients—by advecting colored droplets within a transparent carrier liquid. By pairing lightweight, silent EHD pumps with a microfluidic co-flow–based connector, FiberDrops generates fine droplets with precise density control, achieving finer and more stable spacing than conventional on/off pump switching and allowing flexible flow-speed variation for a fixed pattern. These capabilities enable continuous color transitions and dynamic motifs, expanding the design space for fluidic displays and wearable interfaces.

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