

Polaritons as Liquid Light: Visual and Physical Behaviors

Introduction

Exciton-polaritons are quantum quasiparticles that blend light and matter – effectively photons coupled strongly to excitons (electron-hole pairs in a semiconductor) ¹ ². Because they carry a tiny effective mass and can interact with one another, polaritons can **condense** into a single quantum state (a Bose-Einstein condensate) and behave collectively like a **fluid** ³ ⁴. In other words, under special conditions light can exhibit liquid-like behavior, flowing around obstacles rather than always traveling in straight lines ³. This phenomenon is often dubbed “*liquid light*” – an evocative term for a polariton condensate ⁵. In this memo, we summarize key polariton phenomena (superfluid flows, vortices, interference beats, and coherence) and discuss how each can be translated into visual metaphors using Three.js/WebGL GLSL shaders. We assume a semi-technical perspective, briefly defining physics terms for clarity, and focus on capturing the **essence** of these behaviors in a shader-based visualization rather than an exact simulation.

Polaritons and Superfluid Light

Once formed in a microcavity, a polariton condensate can act as a **superfluid** – much like ultra-cold liquid helium – meaning it flows with virtually zero viscosity (zero friction) ⁶ ⁷. In a superfluid state, polaritons encounter obstacles without dissipative turbulence: the light-fluid streams around an impurity smoothly, instead of forming turbulent eddies or a wake ⁸ ⁹. Researchers have observed exactly this behavior: polariton condensates flowing around defects in a semiconductor with no ripples when in the superfluid regime, essentially **light flowing like a liquid** ⁸. By contrast, if the polariton fluid is not in a pure superfluid state (i.e. has some viscosity), the flow past an obstacle looks more like an ordinary fluid – it produces ripples and a trail of vortices behind the obstacle ⁸ ⁹. **Figure 1** illustrates this striking difference: in the top panel, a normal polariton fluid creates a disturbed wave pattern behind the blocker, whereas in the bottom panel the superfluid polariton stream remains *undisturbed*, continuing on its way without turbulence ¹⁰.

Figure 1: Fluid light flow around an obstacle. Top: a polariton condensate with some viscosity shows a wake of waves and vortices after flowing past an obstacle (similar to water flow). Bottom: in the superfluid regime, polariton flow exhibits no turbulence or wake – the “liquid light” glides cleanly around the obstacle.

Shader concept – Flow Field: To visualize superfluid flow in a shader (GLSL), one can simulate a 2D flow field where an obstacle diverts the “liquid light.” For example, you might use a velocity field that streams around a circular object. In a **normal fluid** mode, you would introduce slight perturbations or noise downstream of the obstacle to mimic ripples and a vortex street. In the **superfluid** mode, you would suppress those perturbations – the flow field remains smooth around the object, with the shader showing no trailing disturbances. This could be implemented by adjusting a “viscosity” parameter in a GPU-based fluid simulation (lower viscosity approaching zero yields little to no wake). The key visual effect is that in the superfluid case, the shader’s flow lines or advected particles would continue forward **unaltered by the**

obstacle ¹¹, whereas in the normal case, the flow field would shed swirling patterns behind it. Even without a full physical simulation, a simple vector field approximation can convey how light behaves like a fluid, gliding around geometry when in the superfluid state.

Vortices and Quantum Vorticity

An exciting manifestation of polariton superfluidity is the formation of **quantized vortices** – essentially tiny whirlpools in the polariton fluid that carry discrete circulation. Vortices are a hallmark of superfluids and were observed in polariton condensates soon after their discovery ¹². In experiments, scientists have seen spontaneous, pinned vortices appear in the condensate's phase profile, analogous to eddies in a flowing liquid ¹³. These have been poetically described as “eddies of light” when a polariton fluid with some viscosity forms a trail of swirling patterns behind an obstacle ¹⁴. Each vortex in a polariton condensate has a quantized **phase winding** (e.g. the polariton wavefunction's phase rotates by 2π around the vortex core), which is a quantum effect with no counterpart in ordinary classical fluids. Notably, the presence of quantized vortices in a polariton fluid draws a clear parallel to superfluid helium and atomic Bose–Einstein condensates ¹³, reinforcing that this “liquid light” shares key physics with other quantum fluids.

Shader concept – Vorticity: In a shader-based visualization, vortices can be represented by introducing **swirl** into the flow field. One approach is to imprint a rotational velocity field around certain points (vortex cores). For example, you can program a circular flow around a point such that any texture or dye in the shader fluid spins around that core, illustrating a whirlpool. The **quantized** nature of polariton vortices (only specific circulation values allowed) can be metaphorically shown by giving each vortex a consistent rotation speed or a distinct phase pattern (like a fixed number of arms in a spiral interference pattern). A GLSL fragment shader could also use the phase of a complex wave field to visualize vortices: for instance, map phase to color and show a singularity at the vortex core (all colors meeting at a point). Computing the **vorticity** (curl of the velocity field) in the shader and highlighting regions above a threshold can help identify vortex locations as well. The main idea is to create **whirlpool-like structures** in the rendered image, conveying how polariton condensates can sustain little rotating droplets of “light fluid.” This could be done artistically with procedural noise or physics-based field equations, as long as the result is a swirling pattern signifying a vortex. By toggling parameters, one could show a stable lone vortex or even a lattice of multiple vortices, analogous to patterns seen when many quantized vortices appear in a condensate.

Interference Patterns and Beating Phenomena

Because polaritons are part-light waves, a polariton condensate exhibits **wave interference** effects much like laser light. When two or more coherent polariton waves overlap, they form interference fringes – alternating bands of higher and lower intensity due to constructive and destructive interference. For instance, if two regions of a polariton condensate expand and overlap, the overlapping area will show a stripe pattern, indicating a well-defined phase relationship between them ¹⁵. The appearance of clear interference fringes is actually used as a signature of coherence in experiments ¹⁵ (bright and dark fringe contrast signifies the polaritons in the two regions are phase-locked). Moreover, if the overlapping polariton waves have slightly different energies or frequencies, the interference pattern will **oscillate in time**, creating a *beating* effect. This *quantum beat* is analogous to the beating of two close-frequency musical tones. In polariton condensates, researchers have observed oscillations in the light emission intensity due to two condensate energy levels interfering – essentially the condensate's density ripples in time as it “beats” between two states ¹⁶. These beats can persist for many cycles, reflecting the coherent oscillation of the condensate as a whole.

Shader concept – Wave Interference and Beating: A GLSL shader is well-suited to illustrating interference patterns. One can model the polariton condensate's optical field as a sum of waves. For example, start with two sinusoidal wave patterns (representing two coherent polariton sources or modes) and overlay them. In the shader's output (perhaps mapping wave amplitude to brightness), their sum will produce stationary **fringes** – bright lines where waves add and dark lines where they cancel, just like a double-slit interference pattern. To incorporate **beating**, give the two waves slightly different frequencies (or angular velocities) and let the shader animate over time. The result will be a pattern of fringes that move or pulsate, simulating the temporal beat: bright bands will slide or oscillate intensity as the phase between the two waves evolves. For instance, if one wave is $\sin(kx - \omega_1 t)$ and another is $\sin(kx - \omega_2 t)$ with $\omega_2 \approx \omega_1$, their superposition will create an interference envelope that oscillates at the difference frequency $\Delta \omega = |\omega_2 - \omega_1|$. In the visualization, you'd see the whole fringe pattern **fade in and out or shift periodically** – a direct analog of polariton quantum beats observed in experiments ¹⁶. By adjusting parameters, the shader can demonstrate everything from a static interference (no beat, $\omega_1 = \omega_2$) to slow beats (very close frequencies) to fast oscillations. This approach conveys the idea of **coherent wave interaction** in the condensate and how slight energy differences lead to rhythmic intensity fluctuations, all within a visually captivating shader animation.

Coherence and Phase Uniformity

Coherence is the backbone of all the phenomena above – it refers to the polariton condensate behaving as a single giant wave with a well-defined phase. In a fully coherent condensate (at least within a finite region), any two points in the fluid have a fixed phase relationship, which is why you can get clear, stable interference fringes across the whole cloud ¹⁵. Achieving long-range coherence in “liquid light” is nontrivial (especially in two dimensions where true long-range order is destroyed by fluctuations), but polariton systems can exhibit quasi-long-range coherence where a large fraction of polaritons share the same phase ¹⁷ ¹⁸. The greater the coherent fraction, the higher the contrast of interference patterns (approaching 100% fringe visibility for a perfectly coherent wave) ¹⁹ ¹⁵. In practical terms, a highly coherent polariton condensate emits light like a laser – with a narrow linewidth and fixed phase – whereas an incoherent or thermal cloud would produce washed-out fringes and speckle. Coherence also underpins superfluidity: a uniform phase means the flow can be laminar and dissipationless, while random phase breaks the constructive interference that allows frictionless flow.

Shader concept – Phase and Coherence: Representing coherence in a shader can be done by visualizing the **phase field** of the wave. One technique is to use color hues to encode the local phase of a complex wavefunction (as is often done for visualizing quantum vortices). A coherent state would then appear as large areas of uniform color (phase) or smoothly varying hues, indicating a well-ordered phase across space. An incoherent state could be depicted by rapidly fluctuating colors from point to point (random phase), which would result in an absence of clear interference patterns. Another visualization approach is to actually show the **interference fringe contrast**: for a given simulated two-beam interference, the shader could adjust the visibility of fringes based on a “coherence parameter.” At full coherence, the interference contrast is maximal (bright clear stripes), whereas lowering the coherence could be simulated by blending the interference pattern with a uniform background (fringes fading out). This mimics experimental observations where *“the intensity pattern exhibits interference fringes, indicating the emergence of extended coherence”* ¹⁵ – in the shader, as you dial up coherence, a fringe pattern gradually emerges from noise. By animating or toggling this, one can illustrate how a polariton condensate transitions from a disordered phase to a coherent fluid. In GLSL, this might involve mixing a coherent wave field with random noise or phase disruptions. The end result is a compelling visual metaphor: coherence turns a chaotic, flickering

image into an organized, stable pattern, just as it transforms ordinary light into *liquid light* with superfluid properties.

Conclusion

Polaritons exemplify how quantum physics can give light **fluid-like behavior**, and each phenomenon – superfluid flow, quantized vortices, interference beats, and long-range coherence – paints a vivid picture that can inspire graphical shaders. By framing these concepts in a Three.js/WebGL context, we focus on **evocative visualization**: flowing fields, swirling vortices, oscillating interference, and phase maps, all driven by shader programs. This approach provides an intuitive bridge between complex quantum-light physics and interactive graphics. While the shader implementations are not literal simulations of the underlying equations, they capture the *spirit* of polariton dynamics. A developer or digital artist can thus use these metaphors to create visuals where light behaves like a liquid – flowing, swirling, and waving – grounded in real physics phenomena ⁴ ³, yet flexible enough for creative exploration. By adjusting a few parameters (flow speed, vorticity injection, phase coherence), one can seamlessly transition between scenes of calm superfluid light and turbulent photonic “waterfalls,” illustrating the rich behaviors of polariton condensates in a visually engaging way.

Sources: The information above is drawn from recent research and explanations on exciton-polariton condensates and superfluid “liquid light,” including popular science summaries ⁷ ²⁰, educational blogs ⁴ ⁶, and research publications on polariton superfluid hydrodynamics ⁸, quantized vortices ²¹, interference coherence measurements ¹⁵, and oscillatory quantum beats in condensates ¹⁶. All these sources underpin the described phenomena and guided the translation of physics concepts into shader-based visualization strategies.

¹ ⁴ ⁵ ⁶ ⁸ ¹⁴ Liquid Light | Azimuth

<https://johncarlosbaez.wordpress.com/2011/11/28/liquid-light/>

² ¹⁵ ¹⁷ ¹⁸ ¹⁹ Coherence measurements of polaritons in thermal equilibrium reveal a power law for two-dimensional condensates

<https://arxiv.org/html/2308.05100v3>

³ ⁷ ⁹ ¹⁰ ¹¹ ²⁰ For The First Time, Scientists Achieve 'Liquid Light' at Room Temperature : ScienceAlert

<https://www.sciencealert.com/scientists-create-fifth-state-of-matter-liquid-light>

¹² ¹³ ²¹ Quantized vortices in an exciton-polariton condensate | Nature Physics

https://www.nature.com/articles/nphys1051?error=cookies_not_supported&code=d59e8400-d4a3-4569-9b21-a494beab16f1

¹⁶ Quantum Beats of a Macroscopic Polariton Condensate in Real Space

<https://www.mdpi.com/2673-3269/6/4/53>