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Geometric-phase versus gradient-index: a showdown for ultimate liquid crystal lenses

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Abstract

Liquid crystal lenses can be achieved with either geometric phase or gradient refractive index. Which solution will ultimately prevail is open to debate. This article aims to provide a theoretical background, review the latest seminal research findings, and shed light on their pros and cons from multiple perspectives.

Keywords: Liquid crystal lens, Geometric phase, Gradient refractive index, Flat optics

Geometric-phase (GP) liquid crystal lenses (LCLs)[1–3], also known as Pancharatnam-Berry phase liquid crystal (LC) lenses, are composed of a layer of LC, whose molecular orientations are patterned to produce a lens-like phase profile. Gradient-index (GI) LCLs[4–6] are also composed of a layer of LC, whose refractive index changes gradually across its volume. In the literal meaning, the former emphasizes orientation, while the latter refractive index. As LC is an anisotropic material, its refractive index is linked to its orientation. It appears that the two terms can be used interchangeably. However, as shown in Fig. 1, there is a fundamental difference in the way they modulate phase. For GI LCLs, the phase shifts φ of ordinary and extraordinary waves are purely propagation phases, which can be written as[7]

$$\varphi_o = \frac{2\pi}{\lambda} n_o d \tag{1}$$

and

$$\varphi_e = \frac{2\pi}{\lambda} \frac{n_o n_e}{\sqrt{n_o^2 sin^2\theta + n_e^2 cos^2\theta}} d \tag{2}$$

respectively, where λ is the wavelength, n_o/n_e the ordinary/extraordinary refractive index, d the thickness, and θ the angle between the wavevector and the crystal or optic axis (OA) of LC. For GP LCLs, under certain conditions, when the incident polarization is circular and the phase retardation equals an odd multiple of half a wavelength[2], the phase shifts φ of ordinary and extraordinary waves will become

$$\varphi_o = \frac{2\pi}{\lambda} n_o d + 2\alpha \tag{3}$$

and

$$\varphi_e = \frac{2\pi}{\lambda} \frac{n_o n_e}{\sqrt{n_o^2 sin^2\theta + n_e^2 cos^2\theta}} d + 2\alpha \tag{4}$$

respectively, where α is the angle between the OA of LC at a specific reference point and that at a target point, and the common second term 2α is called geometric phase. Since the geometric phase is a coincidental byproduct of Jones matrix operations[8], from a mathematical perspective, GP LCLs are supposed to be way more susceptible to variations in polarization and retardation than GI LCLs.

According to Web of Science's science citation index expanded database, from 2023 to 2025, 315 regular and review articles were published under the topic of LCL, of which 23 and 10 are related to GP and GI, respectively. Obviously, GP is more actively researched than GI. Among

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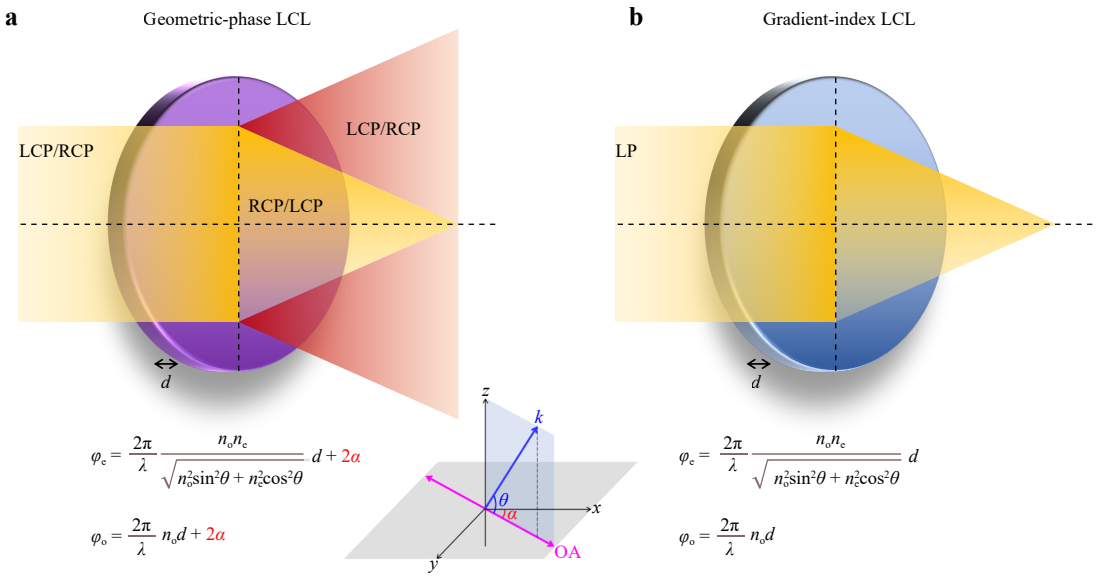

Fig. 1 Principle of **a** geometric-phase LCL and **b** gradient-index LCL. LCP: left-handed circular polarization. RCP: right-handed circular polarization. LP: linear polarization. $\varphi_{o/e}$: phase shift of ordinary/extraordinary wave. k: wavevector. d: thickness. θ: angle between wavevector and OA of LC. α: angle between OA of LC at a specific reference point (not shown or x-axis) and that at a target point (shown).

them, 6 are selected to represent the major breakthroughs in this field. In May 2023, Aishwaryadev Banerjee *et al*. (University of Utah) reported a varifocal Fresnel-type GI LCL for the application of smart contact lenses[9]. In September 2023, Prof. Shin-Tson Wu *et al*. (University of Central Florida) proposed to combine a broadband GP LCL, a half-wave plate, and a red-blue GP LCL to cancel out the chromatic dispersion[10]. In June 2024, Prof. Lei Li *et al*. (Sichuan University) built a GP LCL-based electric zoom system, which was designed with a super-resolution generative adversarial network[11]. In July 2024, Prof. Philip Bos *et al*. (Kent State University) delivered a 50-mm aperture, 1.6-diopter tunable GI LCL with a 28-segmented phase profile controlled by concentric ring electrodes[12]. In August 2025, Prof. Yi-Hsin Lin *et al*. (National Yang Ming Chiao Tung University) stacked two GI LCLs with their alignment directions perpendicular to each other, thereby realizing polarization independence[13]. In September 2025, Prof. Hak-Rin Kim *et al*. (Kyungpook National University) demonstrated a two-GP-LCL system in conjunction with switchable circular polarizers, which could support up to 9 focuses to vary the image distances from 26 to 333 cm[14].

As summarized in Table 1, GP and GI LCLs are compared in the following aspects. (1) Type of phase to be modulated: geometric phase for GP and propagation phase for GI. (2) Form factor: both can be flat. (3) LC alignment: LC molecules in GP are aligned horizontally, whereas those in GI can be aligned both horizontally and vertically. (4) Maximum phase shift: GP is 2π, whereas GI can easily exceed 2π by increasing the thickness. (5) Focus tunability: GP is normally fixed, whereas GI can be electrically tunable. For GP to be tunable, a multi-lens system is needed. (6) Polarization dependence: GP can only work with circular polarizations, whereas GI can be polarization independent. (7) Wavelength dependence: GP is more sensitive to wavelength than GI. (8) Angular dependence: both are sensitive to angle. (9) Thickness dependence: GP must strictly meet the half-wave requirement, whereas the GI does not. (10) Manufacturing: GP is usually prepared via photoalignment, whereas GI via patterned electrodes. To our surprise, GI LCLs outrival GP LCLs in nearly every metric. That said, from a research perspective, GP has more scientific problems pending for investigation.

As to the question raised in the title, i.e., which is the ultimate LCL, GP or GI, it is still too early to tell. This is because we have yet to discuss the possibility of merging GP and GI into one single hybrid lens or a cemented doublet, in which both the geometric and propagation phases are exploited. For some unknown reason, the research on GP and GI has always been conducted separately. For researchers, who are pro-GP, they tend not to adopt any GIs in their designs, and vice versa. Hopefully, this situation will change soon.

We are witnessing a dramatic shift in the optical lens industry. At the heart of this transformation lies in the rise of flat optics such as GP and GI LCLs. While challenges remain, the rapid progress in this field indicates that they are on a clear path to becoming ubiquitous in the next-

Table 1 Comparison between GP and GI LCLs.

	GP LCLs	GI LCLs	Winner
Type of phase	Geometric phase	Propagation phase	n/a
Form factor	Flat	Flat	tie
LC alignment	Planar	Planar and vertical	GI
Maximum phase shift	2π	2π or above	GI
Focus tunability	Fixed	Tunable	GI
Polarization dependence	Circular only	Linear and unpolarized	GI
Wavelength dependence	Strong	Moderate	GI
Angular dependence	Strong	Strong	tie
Thickness dependence	Strong	Weak	GI
Manufacturing	Difficult	Easy	GI

generation devices, e.g., augmented/virtual reality eyewear[15–18].

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Chao Ping Chen contributed to the majority of manuscript, including the title, abstract, main text, Fig. 1, Table 1, and references. Miao Xu assisted with literature review, Fig. 1, and references.

Data availability
All data are available from the corresponding authors upon reasonable request.

Conflict of interest
The authors declare no conflicts of interest.

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