

## Polarization of light and its use in LCD technology

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### Abstract

Polarization is a fundamental property of light that describes the orientation of the electric field vector during wave propagation. The control and manipulation of polarized light play a crucial role in many optical devices, particularly liquid crystal display (LCD) technology. LCDs rely on polarized light, liquid crystal molecular alignment, and electro-optic effects to modulate light intensity and generate images. This paper presents a detailed discussion on the principles of light polarization, different methods of producing polarized light, and the working mechanism of LCDs based on polarization control. The structure, operation, advantages, limitations, and applications of LCD technology are also discussed.

**Keywords:** Polarization; Polarized light; Liquid crystal display; LCD; Electro-optic effect

### 1 Introduction

Light, at its most fundamental level, is an electromagnetic wave composed of oscillating electric and magnetic fields that are oriented perpendicular to the direction in which the wave travels. In natural light sources such as sunlight or the glow from incandescent bulbs, the orientations of the electric field vectors are random—they vibrate in every possible plane perpendicular to the direction of propagation. This type of light, which lacks any preferred orientation of its electric field, is known as unpolarized light.

When this randomness is removed and the vibrations of the electric field are confined to a single plane or direction, the light becomes polarized. Polarization is, therefore, a process that reveals the wave-like nature of light, offering a means to control and manipulate light in ways that unpolarized light does not permit.

The study of polarization has played a crucial role in the advancement of optical science and engineering. Its applications are diverse and impactful, ranging from the analysis of mechanical stress in transparent materials to the reduction of glare in photography. In recent decades, the phenomenon of polarization has become especially significant in the realm of electronic display technologies.

Among the many practical applications of polarization, liquid crystal displays (LCDs) stand out as a ubiquitous example. LCD technology is integral to the operation of everyday devices such as televisions, computer monitors, smartphones, tablets, and a wide array of digital instrumentation. LCDs make ingenious use of the principles of polarization to control the passage of light, enabling precise modulation and the formation of high-quality images on screens that are now central to modern life.

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## 2 Fundamentals of Polarization of Light

### 2.1 Unpolarized and Polarized Light

Light emitted from common sources such as the sun, incandescent bulbs, or fluorescent lamps is typically unpolarized. In this state, the electric field vectors associated with the light waves vibrate randomly in all directions perpendicular to the direction of travel. Because of this randomness, unpolarized light lacks any specific orientation or pattern in its oscillations.

In contrast, polarized light has electric field oscillations that are either confined to a particular direction or follow a defined, predictable pattern. When light is polarized, the electric field vibrations are organized in such a way that they exhibit a specific orientation or symmetry, which can be linear, circular, or elliptical in nature. Understanding the distinction between unpolarized and polarized light is fundamental to many optical phenomena and applications.

### 2.2 Types of Polarization

Polarization can be classified into several types based on how the electric field vector behaves as the light propagates:

- **Linear Polarization:** In linear polarization, the electric field oscillates along a single, fixed direction or plane as the light travels. This is the simplest form of polarization and is commonly produced by passing light through a polarizing filter.
- **Circular Polarization:** In this type, the electric field vector rotates at a constant rate in a circular path around the direction of propagation. This rotation can be either clockwise (right-handed) or counterclockwise (left-handed), depending on the phase relationship between the orthogonal components of the electric field.
- **Elliptical Polarization:** This is the most general form of polarization, where the tip of the electric field vector describes an ellipse as the light propagates. Both linear and circular polarization are special cases of elliptical polarization.

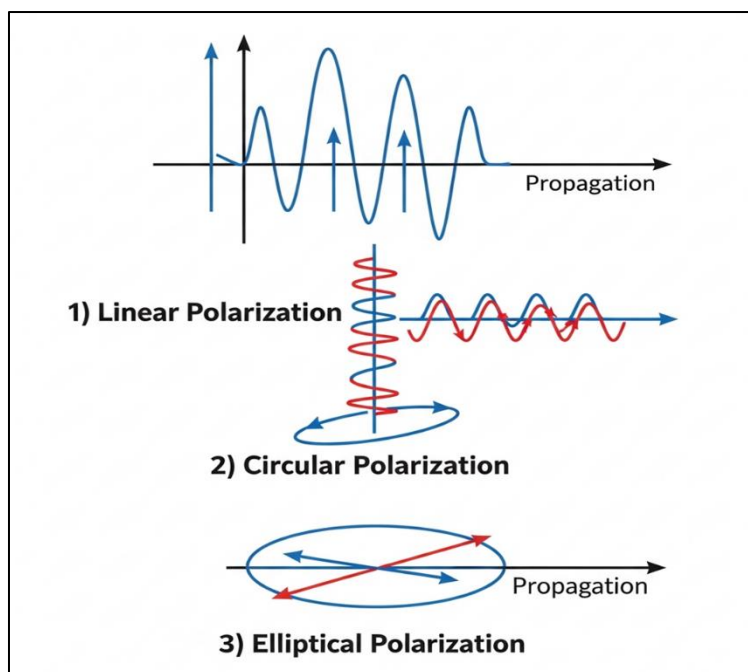
Figure 1 illustrates the differences among linear, circular, and elliptical polarization, showing how the electric field vector traces out different paths in each case.

### 2.3 Methods of Producing Polarized Light

Polarized light can be generated through several physical processes, each exploiting a different property of light-matter interaction:

- **Polarization by Reflection:** When unpolarized light strikes a non-metallic (dielectric) surface at a specific angle—known as Brewster's angle—the reflected light becomes partially or completely polarized parallel to the surface. This effect is commonly observed in glare reflected off water or roads.
- **Polarization by Absorption:** Certain materials, such as Polaroid filters, are designed to absorb one component of the electric field while transmitting the other. When unpolarized light passes through such a filter, only the component aligned with the filter's transmission axis emerges, resulting in linearly polarized light.

**Polarization by Double Refraction (Birefringence):** Some crystals, like calcite or quartz, have different refractive indices for light polarized in different directions. When unpolarized light enters such materials, it splits into two polarized rays traveling at different speeds and directions. This phenomenon, known as birefringence, is widely used in optical instruments. Table 1 provides a summary of these methods along with their underlying principles.



**Figure 1** Representation of linear, circular, and elliptical polarization of light

**Table 1** Methods of Producing Polarized Light

Method	Principle	Example / Application
Reflection	Selective polarization at Brewster's angle, where reflected light becomes plane polarized	Glare reduction from water or glass surfaces
Absorption	Selective absorption of one component of the electric field	Polaroid sunglasses
Double Refraction (Birefringence)	Splitting of incident light into two plane-polarized rays with different velocities	Calcite crystals (Nicol prism)
Scattering	Preferential scattering of certain polarization components by particles	Polarization of skylight
Dichroism	Differential absorption of light based on polarization direction	Tourmaline crystals

By understanding these fundamental mechanisms and types of polarization, one can appreciate both the natural phenomena and technological applications that rely on the manipulation of light's polarization state. Unpolarized light contains electric field vibrations in all directions perpendicular to propagation. Polarized light, on the other hand, has electric field oscillations confined to one direction or following a defined pattern.

### 3 Liquid Crystals and Their Optical Properties

Liquid crystals are a unique class of materials that display physical properties intermediate between those of conventional liquids and solid crystals. While the molecules within a liquid crystal can flow and move past one another, much like in a liquid, they also exhibit a degree of long-range orientational order similar to that found in crystals. This duality gives liquid crystals their name and underpins their remarkable behaviors and technological applications.

#### 3.1 Types of Liquid Crystals

Liquid crystals are categorized into several distinct types based on their molecular arrangement and physical characteristics:

- **Nematic Liquid Crystals:** In the nematic phase, the rod-like molecules are aligned so that their long axes tend to point in the same direction, known as the director. However, the molecules do not possess any positional order—they are free to move as in a liquid. Nematic liquid crystals are particularly sensitive to external electric fields, which can reorient the molecules rapidly and reversibly. This property makes nematic liquid crystals the preferred choice for use in liquid crystal displays (LCDs).
- **Smectic Liquid Crystals:** Smectic phases exhibit a higher degree of order compared to nematic phases. Here, the molecules not only align along a common direction but also arrange themselves into distinct layers. Within each layer, the molecules have some freedom of movement, but movement between layers is restricted. Smectic liquid crystals are used in some specialized display applications and research.
- **Cholesteric (or Chiral Nematic) Liquid Crystals:** Cholesteric liquid crystals are similar to nematic but have a helical structure due to the presence of chiral (handed) molecules. The orientation of the molecules twists in a helical fashion along an axis perpendicular to the molecular layers. This structure enables cholesteric phases to selectively reflect certain wavelengths of light, producing vivid iridescent colors seen in some displays and security features.

Among these types, nematic liquid crystals are the most widely utilized in LCD technology because of their excellent electro-optical response, ease of alignment, and relatively simple manufacturing requirements.

### 3.2 Optical Anisotropy

A key property of liquid crystals is their optical anisotropy—that is, their optical characteristics, such as refractive index, depend on the direction of light propagation and the polarization of the incident light. This directional dependence arises from the anisotropic shape and orientational order of the liquid crystal molecules.

Liquid crystals typically exhibit birefringence, meaning they have two distinct refractive indices depending on whether the electric field of the light is parallel or perpendicular to the molecular alignment (the director). When polarized light enters a birefringent material like a liquid crystal, its polarization direction can be rotated or altered as it passes through. The extent of this rotation depends on the thickness of the liquid crystal layer, its birefringence, and the alignment of the molecules.

This ability to manipulate the polarization state of light is the foundation of LCD operation. By applying an electric field across a layer of nematic liquid crystal, the orientation of the molecules—and hence the optical properties—can be precisely controlled. As a result, the light transmission through the display can be modulated, enabling the formation of images and patterns essential for modern display devices.

## 4 Working Principle of LCD Technology

### 4.1 Basic Structure of an LCD

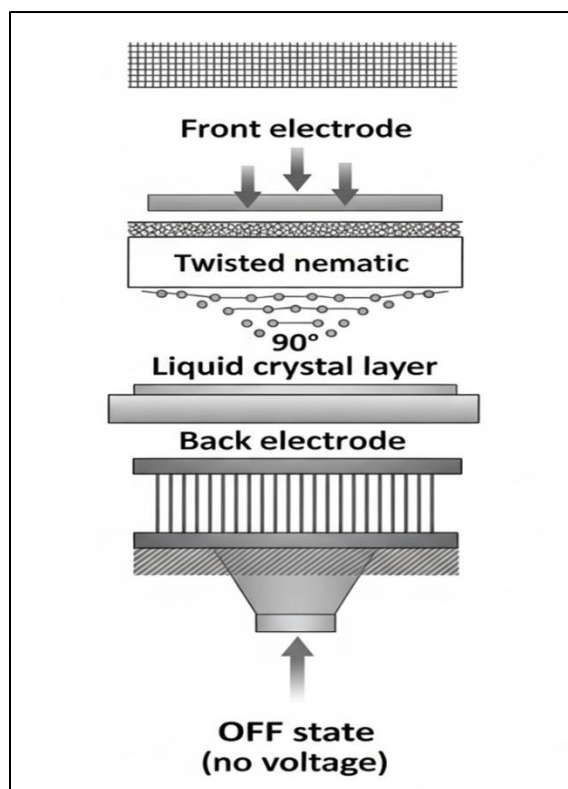
A typical liquid crystal display (LCD) comprises a carefully engineered stack of layers, each serving a specific function in the modulation of light and image formation. The essential layers (as shown schematically in Figure 2) include:

- **Backlight source:** Provides uniform illumination across the display, typically using LEDs in modern LCDs.
- **Rear polarizer:** Converts the unpolarized light from the backlight into linearly polarized light.

**Glass substrate with transparent electrodes:** Houses patterned, transparent electrodes (commonly made of indium tin oxide) that apply electric fields across selected regions of the display.

- **Liquid crystal layer:** Contains the liquid crystal material, whose orientation is controllable via applied voltage.
- **Front polarizer:** Positioned orthogonally to the rear polarizer; serves to analyze the polarization state of transmitted light.

**Color filter (for color LCDs):** Divides pixels into red, green, and blue sub-pixels, enabling full-color image reproduction.

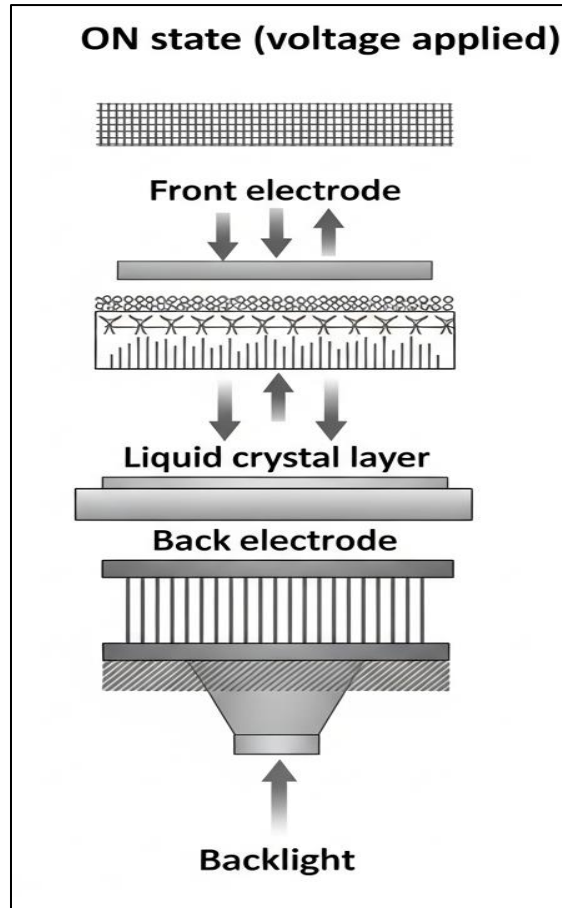


**Figure 2** Layered structure of a typical liquid crystal display

#### 4.2 Polarization-Based Light Modulation

The operation of an LCD relies fundamentally on the manipulation of light's polarization:

The backlight emits unpolarized light, which first encounters the rear polarizer. This polarizer only allows light with a specific polarization direction to pass through, producing linearly polarized light. This polarized light then enters the liquid crystal layer. In the default, field-free state, nematic liquid crystals are arranged in a twisted configuration (typically  $90^\circ$ ). As light traverses this layer, its plane of polarization is rotated by the same amount due to the optical anisotropy of the liquid crystal. The rotated polarized light then reaches the front polarizer, which is aligned perpendicular to the rear polarizer. Under these circumstances, the  $90^\circ$  rotation ensures the light can pass through, resulting in a bright pixel. When an electric field is applied across the liquid crystal layer (by activating the transparent electrodes), the molecules reorient themselves parallel to the field, eliminating the twist. The polarized light now passes through the liquid crystal unchanged—its polarization is not rotated. As a result, it is blocked by the front polarizer, which allows only the orthogonal polarization to pass, producing a dark pixel.



**Figure 3** Operation of an LCD pixel with and without applied voltage

#### 4.3 Twisted Nematic (TN) LCD Operation

Twisted nematic (TN) LCDs are the most widely used type due to their simplicity, low power consumption, and fast response times. In TN LCDs, the degree of molecular twist (and thus, the amount of polarization rotation) can be modulated continuously by adjusting the voltage applied across the liquid crystal layer. Partial twists, resulting from intermediate voltages, allow partial transmission of light through the front polarizer, creating various shades or grayscale levels. By controlling the voltage at each pixel, images and text can be displayed with high precision. Table 2 compares the major light transmission states in an LCD pixel:

**Table 2** Light Transmission States in LCD Operation

Voltage Applied	LC Molecular Alignment	Polarization Rotation	Transmission Through Front Polarizer	Pixel Appearance
No voltage	Twisted (90°, default state)	Yes (90° rotation)	Allowed	Bright
High voltage	Aligned with electric field	None	Blocked	Dark
Intermediate voltage	Partially twisted	Partial rotation	Partial transmission	Grayscale

Through this voltage-controlled modulation of light transmission, LCDs can generate dynamic images, text, and full-color displays with high efficiency and clarity. The clever use of polarization and the properties of liquid crystals form the foundation of this ubiquitous technology.

## 5 Conclusion

The phenomenon of light polarization represents a cornerstone of modern optics, providing a means to manipulate and control the direction and intensity of light with remarkable precision. This capability is at the heart of liquid crystal display (LCD) technology, which ingeniously exploits both the polarization of light and the unique electro-optic properties of liquid crystal materials. By carefully controlling the orientation of liquid crystals in response to electric fields, LCDs can modulate the passage of polarized light, enabling the creation of crisp, vibrant images for a wide range of electronic devices. A thorough understanding of the interplay between polarized light and liquid crystal behavior is essential for engineers and scientists seeking to design, improve, and innovate display systems. Such knowledge not only informs the optimization of image quality, viewing angles, and energy efficiency but also paves the way for the development of advanced display technologies. Although LCDs face competition from emerging technologies such as OLEDs and microLEDs, they continue to dominate the display market due to their proven track record of efficiency, reliability, scalability, and cost-effectiveness. Ongoing research into materials science and optical engineering promises to further enhance the performance of LCDs and broaden their applications.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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