Conductance Enhancement in Blue Phase Liquid Crystals via Silver Nanoparticle Incorporation

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Abstract

This work demonstrates that silver (Ag) nanoparticle doping markedly enhances both the electrical conductance and thermal stability of Blue Phase Liquid Crystals (BPLCs). Unlike undoped BPLCs, which exhibit limited conductance dominated by slow ion migration and molecular reorientation, Ag-doped samples show smooth, frequency-dependent conductance indicative of efficient free carrier transport. Temperature-dependent analysis reveals a significant broadening of the stable blue phase range and an upward shift in the isotropic transition temperature, attributed to improved ionic mobility and defect stabilization by Ag nanoparticles. These findings position Ag nanoparticle doping as a powerful strategy to tailor BPLC properties, unlocking their potential for high-performance, fast-response electro-optic devices.

Key words: - Blue phase liquid crystal, nano particles, Dielectric spectroscopy, Conductance

1. INTRODUCTION

It has been over a century since the discovery of liquid crystals (LCs), a fascinating and dynamic class of soft matter often regarded as the fourth state of matter. Since then numerous LC phase have been studied. These phases can be found in biological and industrial materials such as cell membranes, phospholipids, snail slime, crude oil, DNA, and even the mantles of neutron stars and have ubiquitous applications [10-12]. Among these, blue phase liquid crystals (BPLCs) represent a particularly intriguing subclass within soft condensed matter physics due to their self-assembled 3D cubic structures [1-4], unique optical properties, and fast electro-optic response [5-9]. The striking advantage of BPLCs lies in their ability to operate without alignment layers, exhibit sub-millisecond switching times, and possess inherent optical isotropy in their field-free state. These properties make BPLCs highly promising for next-generation technologies, including fast-response displays, tuneable photonic devices, smart windows, and adaptive lenses. While traditional nematic LCs have revolutionized modern electronics, BPLCs are poised to play a key role in advancing the frontier of high-performance, multifunctional optoelectronic systems.

Despite the remarkable optical and electro-optic properties of blue phase liquid crystals (BPLCs), their widespread application remains constrained by key limitations—namely, a narrow temperature stability range and the requirement for high operating voltages [5-8]. These factors reduce their practicality for real-world devices, particularly in environments with fluctuating thermal conditions or low-power requirements. To address these challenges, several strategies have been developed, including polymer stabilization, chiral dopant tuning, and nanoparticle doping. Among these, nanoparticle doping has emerged as a particularly promising approach due to its ability to modify the physical properties of BPLCs without significantly altering their inherent structure.

In this study, we investigate the influence of silver (Ag) nanoparticle doping on the dielectric behaviour of BPLCs. Silver nanoparticles are known for their high electrical conductivity, chemical stability, and ability to interact with liquid crystal molecules, potentially enhancing dielectric anisotropy and improving charge transport mechanisms [13-14]. By incorporating Ag nanoparticles into the BPLC host matrix, we aim to examine how such doping affects key dielectric parameters—specifically, conductance—over a range of temperatures.

Using temperature-dependent dielectric spectroscopy, we analyse the dynamic response of both pure and Ag-doped BPLC systems. This technique allows us to probe polarization mechanisms, charge accumulation effects, and ionic mobility under varying thermal and frequency conditions. Through this investigation, we seek to understand how Ag nanoparticles influence the dielectric landscape of BPLCs which is a key step towards enabling practical, next-generation BPLC-based electro-optic devices.

2. Experimental

Blue-phase liquid crystal mixtures were prepared by combining two nematic liquid crystals (H_1: 5CB and H_2: 3,4-difluoro-4′-(trans-4-propyl-cyclohexyl biphenyl)) with the chiral dopant CB-15. Two samples were studied: the undoped host system (S_1), and silver nanoparticles (Ag NPs, ~10 nm, PlasmaChem GmbH, Berlin) (S_2). Dopant concentration was fixed at 1 wt.%.

Samples were prepared by first mixing the nematic hosts with the chiral dopant in the isotropic state. For S_2, Ag NPs (having optical, electrical, catalytic, and antimicrobial properties) [13-14] were introduced in the isotropic phase to promote homogeneous incorporation. The mixture was then filled through capillary action into ITO-coated glass cells with a thickness of $25 \pm 1\mu m$, defined by Mylar spacers. The glass plates were purchased from Techinstro having dimensions $100mm \times 100mm \times 1.1mm$ and resistivity 20 $Ohms/sq$. Dielectric measurements were performed using a GW INSTEK LCR-8110G impedance analyser across $50Hz - 5MHz$.The phase transition temperature of sample S_1 and S_2 is given in Table 1.

3. Results

3.1 Dielectric behaviour

Dielectric spectroscopic analysis offers valuable insights into a material's structural characteristics, including grain boundaries, grain interiors, charge transport behaviour, and charge storage capacity. The dielectric properties of a material are influenced by various factors, such as its chemical composition and the synthesis or preparation method used [15-16].

Here, we present the effect of silver nanoparticle doping on temperature and frequency dependence of dielectric measurements of Blue Phase Liquid crystals. We also present how the application of bias alter the doping effect on these parameters.

(a) pure blue phase liquid crystal(BPLC)

❖ **Frequency dependent Conductance analysis**

The understanding of the electrical conduction process contributes to studying the dynamics of charge carriers, the effects of the field and temperature on charge motion, and the transport properties of materials. As the ac conductivity is frequency-dependent, it is beneficial in gaining better knowledge of the electrical conductivity of a substance [17]

Fig. 1(a-f) illustrates logarithmic graph of change in conduction against frequency for the pure Blue Phase Liquid Crystals (BPLCs) throughout the frequency range of $1Hz - 5MHz$ at 1℃ below, 1℃ above T_b and 1℃ below T_c measured without and with bias (1V-5V). Where T_b and T_c are onset temperature of blue phase and isotropic phase.

In Fig.1a, the conductance increases with frequency for all temperatures, indicating a clear dispersion behaviour. This trend can be divided into two distinct regions. In the low-frequency region (up to approximately $2 \times 10^6 Hz$, the conductance remains nearly constant or increases slowly (plateau region), representing dc conductance dominated by successful hopping of ions between neighbouring vacant sites [17-18]. At such low frequencies, the electric field changes slowly, allowing mobile ions to respond effectively. This behaviour aligns with the hopping conduction mechanism proposed by Funke [19], who explained it in terms of two types of relaxation processes: successful and unsuccessful hops, where the latter refers to ions that hop to neighbouring sites and return to their original position, contributing to polarization rather than net conduction [19].

In the high-frequency region (above $2 \times 10^6\ Hz$), the conductance increases more sharply with frequency, signaling the onset of AC conduction, also known as the dispersion region. This behavior is primarily due to unsuccessful ionic hops, which occur more frequently as the electric field oscillates too rapidly for ions to complete full migration, leading to enhanced dielectric polarization. Additionally, increasing temperature boosts both the mobility of charge carriers and the number of available hopping sites, enabling carriers to move between sites with less required energy [20]. The hopping frequency, which corresponds to the frequency at which dispersion begins, generally shifts to higher values as temperature rises. This observed behaviour is consistent with Jonscher's Universal Dielectric Response, attributing the frequency dependence to relaxation phenomena driven by the dynamics of mobile charge carriers [20-22]. According to Jonscher's theory, the frequency dependence of AC conductivity in disordered materials originates from relaxation phenomena associated with mobile charge carriers. These carriers undergo hopping motion between localized states, residing transiently in intermediate energy configurations situated between potential energy minima. Jonscher's universal power law quantitatively describes this behaviour, attributing the relaxation to the dynamics of charge carriers as they transit from an initial potential well to adjacent sites. This model has been widely applied to analyse AC conductivity across various materials and is expressed mathematically by double power law as [20-22]:

$$G(w) = G_{dc} + Aw^{s_1} + Bw^{s_2} \qquad (1)$$

where G_{dc} is the dc conductance, A and B are constant depending on temperature, s_1 and s_2 are frequency exponents The exponent s_1 ($0 \leq s_1 \leq 1$) characterizes the low-frequency region, equivalent to the movement of translational, described also as hopping over short-range(dc conductance)[20]. While, the exponent s_2 ($1 < s_2 < 2$) corresponds to high-frequency localized reorientation mechanisms like Correlated Barrier Hoping (CBH) Mechanism, Quantum Mechanical Tunneling (QMT) model, Nearly Constant Loss (NCL) and Super Linear Power Law (SLPL) [23-29], respectively, designating the presence of localized or reorientation mechanism [30].

However, as the applied voltage increases (1 V to 5 V) [Fig. 1(b-f)], the conductance–frequency profiles become progressively more nonlinear and dispersive, particularly in the mid-frequency range ($10^3 - 10^5 Hz$). From 1 V onward, the graphs exhibit distinct peak–dip patterns indicative of complex relaxation phenomena and unsuccessful ionic hops, as described in Funke's jump relaxation model [27]. These features emerge due to the increasing influence of field-induced structural distortions, dipolar reorientations, and Maxwell–Wagner–Sillars (MWS) interfacial polarization, which become more pronounced at higher voltages and lower temperatures [31]. At 3 V and above, the conductance curves show sharp dips and multiple peaks, particularly at 25°C and 27°C, indicating that the field is strong enough to disrupt the BPLC lattice, creating localized traps or resistive barriers.

Temperature plays a crucial moderating role at higher temperatures ($74°C$), conductance consistently increases and the frequency response becomes smoother, due to enhanced thermal activation of ionic carriers and reduced structural constraints. The thermal energy allows more effective dipolar relaxation and ion mobility, resulting in broader and elevated conductance curves across all applied voltages. This supports findings by Friedrich Kremer (2003), who demonstrated that elevated temperature reduces energy barriers for relaxation and enhances dynamic responses in BPLC materials [32].

This conclude that, while low bias reveals basic hopping conduction and dielectric relaxation, high-field conditions expose the nonlinear, field-enhanced ionic and interfacial dynamics intrinsic to BPLC structures. The transition from monotonic to oscillatory conductance with increasing voltage underscores the onset of non-Ohmic behaviour and the complex coupling between electric field, molecular alignment, and ionic motion in blue phases. These results not only validate the theoretical frameworks of Jonscher and Funke but also highlight the practical significance of field and temperature control in BPLC-based electro-optic devices.

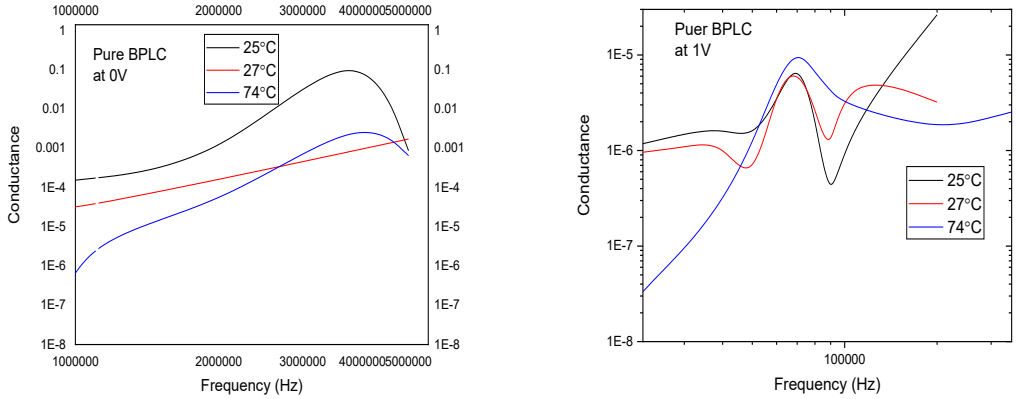

Figure 1(a-b), Pure BPLC conductnace vs frequency at 0V and 1V

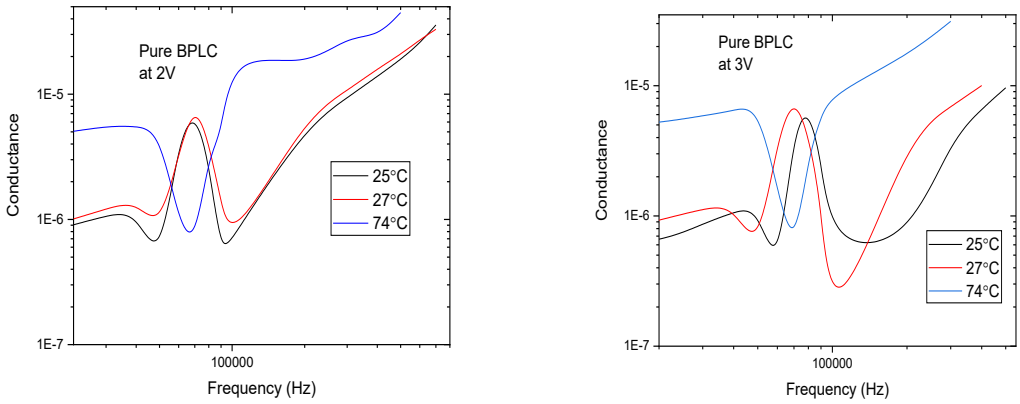

Figure 1(c-d) ,Pure BPLC conductnace vs frequency at 2V and 3V

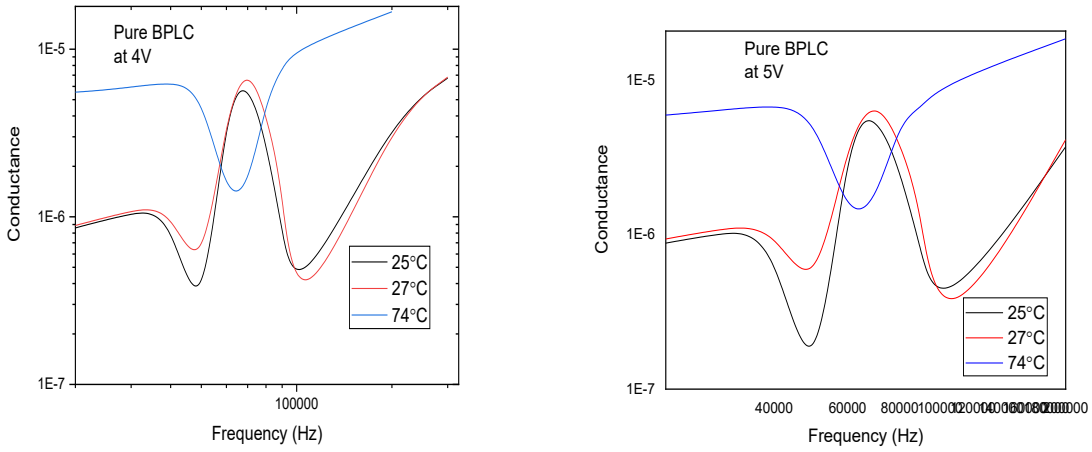

Figure 1(e-f) ,Pure BPLC conductnace vs frequency at 4V and 5V

❖ Temperature dependent conductance analysis

Fig. 2 shows the variation of conductance of pure BPLC with temperature at a fixed frequency of 80 Hz. Initially, as temperature rises from ~20 °C to ~30 °C, conductance increases due to enhanced ionic mobility, corresponding to the more ordered BPI and BPII phases. Between ~30 °C and ~60 °C, conductance fluctuates slightly and then decreases, marking the transition to the less ordered BPIII phase, which appears at higher temperatures than BPI/BPII.

According to Koop's theory and Maxwell–Wagner polarization, changes in molecular order and interfacial polarization affect ion transport during these transitions. A sharp drop in conductance around 60–70 °C indicates the transition to the isotropic phase, where loss of structure hinders charge movement. Beyond 70 °C, conductance rises again due to increased thermal activation of ions. Overall, the conductance behaviour of pure BPLC as a function of temperature is closely linked to its phase sequence—BPI → BPII → BPIII → isotropic and reflects the complex interplay between phase structure, ion mobility, and polarization mechanisms in BPLCs. The observed trends support classical models such as Maxwell–Wagner interfacial polarization, Koop's theory, and thermally activated conduction [31,33,34].

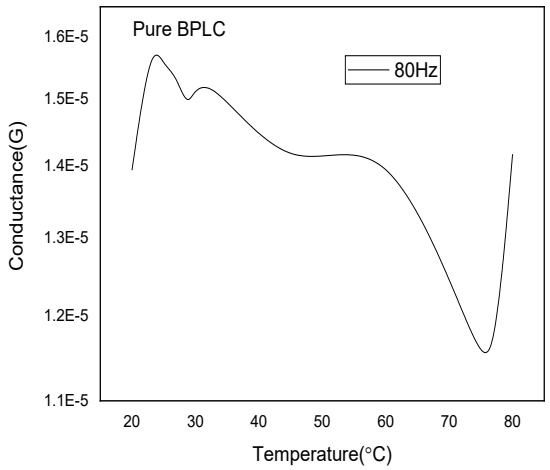

Figure 2 Conductance vs temperature for pure BPLC at 80Hz

(b) Silver (Ag) doped BPLC

❖ **Frequency dependent Conductance analysis**

Fig. 3(a-f) gives the frequency-dependent conductance behaviour of silver (Ag) doped Blue Phase Liquid Crystals (BPLCs) at 1℃ below, 1℃ above T_b and 1℃ below T_c, measured without and with bias (1V-5V). Where T_b and T_c are onset temperature of blue phase and isotropic phase.

Fig. 3a illustrates the variation of conductance with frequency for silver nanoparticle (Ag)-doped Blue Phase Liquid Crystal (BPLC) without bias. The curves at all temperatures exhibit highly nonlinear and oscillatory behaviour, which is markedly different from the smoother trends observed in pure BPLC at similar bias. The presence of Ag nanoparticles introduces additional relaxation processes and localized charge accumulation, resulting in multiple peaks and dips in the mid-frequency range ($\sim 10^3 - 10^5\, Hz$). This complex pattern is attributed to space charge polarization, interfacial interactions, and disrupted molecular ordering caused by the metal–LC interaction, consistent with the Maxwell–Wagner–Sillars (MWS) interfacial polarization theory [30-31].

At lower temperatures (22℃ *and* 24℃), sharp dips and irregular fluctuations indicate localized trapping and constrained ionic mobility. These features suggest that at low thermal energy, the Ag nanoparticles act as scattering centre's or energy barriers, hindering the movement of mobile charges and causing relaxation failures [27]. In contrast, at 40℃, the conductance curve smoothens and rises consistently at higher frequencies, indicating that thermal activation overcomes the trapping effects, enhancing both dipolar relaxation and hopping conduction. The enhanced conductance at 40℃ also reflects temperature-assisted percolation or tunnelling between Ag nanoparticles, facilitating easier charge movement through the medium. At this low bias, the Ag nanoparticles appear to dominate the electrical response by introducing additional dielectric interfaces, resulting in complex, frequency-dependent conductance variations that differ significantly from undoped BPLC.

As the bias voltage increases to 1 V and 2 V [Fig. 3(b-c)], there is a marked increase in conductance by several orders of magnitude, with a noticeable transition from relaxation-dominated behaviour toward free carrier conduction. At these

moderate voltages, the frequency-dependent conductance becomes smoother, reflecting enhanced carrier mobility under the influence of the electric field.

When the voltage is further increased to 3 V, 4 V, and 5 V [Fig. 3(d-f)], the conductance rises significantly, indicating strong field-driven carrier transport and a near-complete suppression of relaxation features. Across all bias voltages, temperature plays a crucial role conductance is consistently highest at 24℃, suggesting that this temperature corresponds to an optimal phase or structural arrangement in the Ag-doped BPLC that facilitates efficient charge transport. At 40℃, conductance improves at higher frequencies due to thermally activated charge carriers, while at 22℃, conductance remains lower, likely due to reduced molecular mobility.

Compared to undoped blue phase liquid crystals (BPLCs), Ag doping significantly enhances electrical conductance across all voltage ranges, primarily due to the introduction of additional charge carriers and the formation of efficient charge transport pathways enabled by metallic silver nanoparticles [35]. Undoped BPLCs generally exhibit lower conductance values with pronounced ionic and dipolar relaxation peaks, which indicate a conduction mechanism dominated by molecular reorientation and slow ion migration. In contrast, Ag-doped BPLCs demonstrate smoother, frequency-dependent conductance curves with increasing voltage, reflecting a shift toward free carrier, field-driven conduction. This improved charge transport is critical for enhancing electro-optic performance, such as faster switching speeds and lower operating voltages, which are essential for advanced display technologies and optical devices [36]. Furthermore, temperature-dependent studies reveal that Ag doping not only increases conductivity but also stabilizes the blue phase over a wider temperature range [37], with peak conductance observed around 24℃ corresponding to optimal molecular ordering. This thermal robustness is advantageous for practical applications requiring stable operation under variable environmental conditions, such as flexible displays, tuneable photonic devices, and adaptive lenses.

In practical terms, the enhanced conductivity and stability of Ag-doped BPLCs make them promising candidates for next-generation fast-response liquid crystal displays (LCDs), where rapid electro-optical switching and low power consumption are critical [35]. Additionally, the ability to tailor conductivity via nanoparticle doping can be exploited in smart windows and optical communication devices, where dynamic control of light modulation is essential. In contrast, undoped BPLCs, with their slower response times and limited conductivity, are less suited for these advanced applications but may still find use in simpler devices where cost or chemical purity is prioritized. Overall, the integration of metallic nanoparticles into BPLCs represents a significant advancement in liquid crystal technology, offering improved electrical, optical, and thermal properties that open avenues for innovative optoelectronic applications.

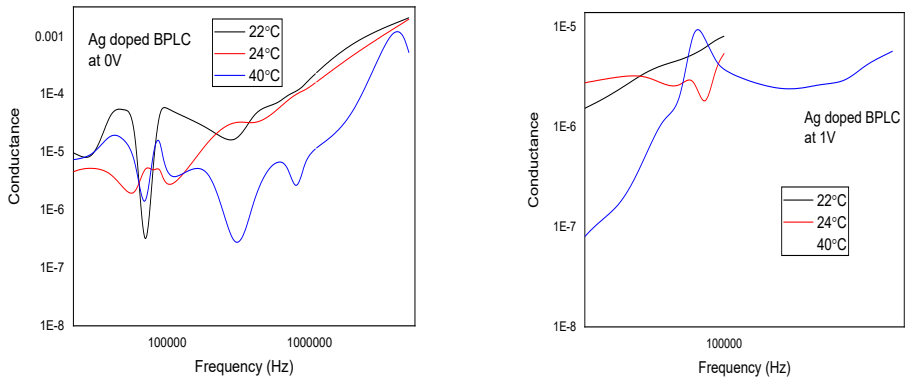

Figure 3(a-b) , Ag doped BPLC conductnace vs frequency at 0V and 1V

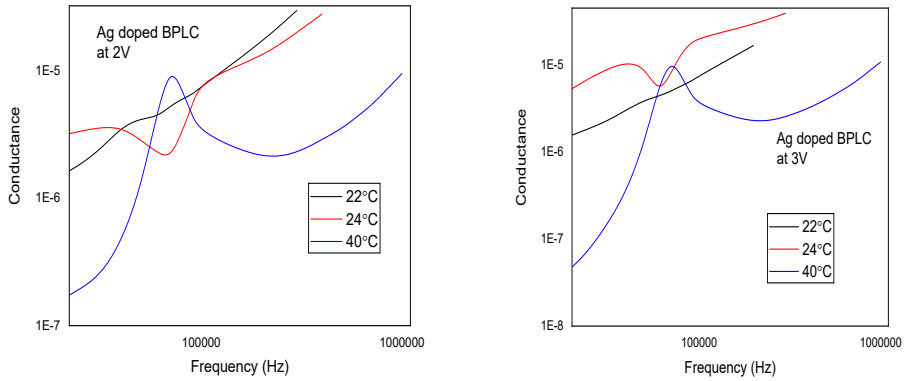

Figure 3(c-d) , Ag doped BPLC conductnace vs frequency at 2V and 3V

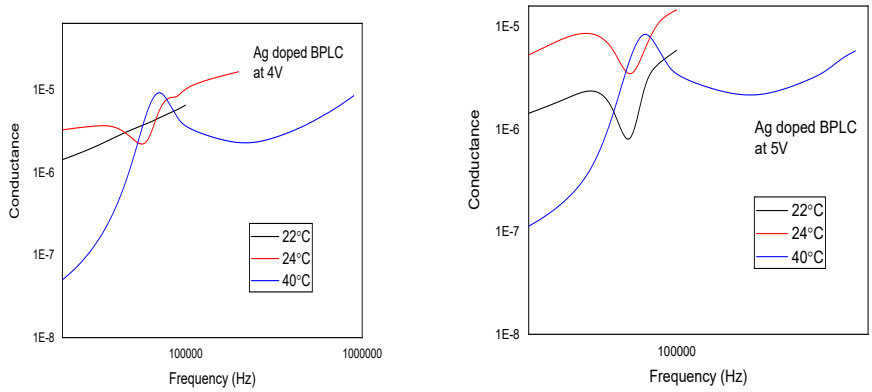

Figure 3(e-f) , Ag doped BPLC conductnace vs frequency at 4V and 5V

❖ **Temperature dependent conductance analysis**

Fig. 4 illustrates the effect of temperature on conductance of Ag-doped Blue Phase Liquid Crystal (BPLC) at a fixed frequency of $80Hz$. From 10℃ to around 20℃, conductance increases steadily due to thermally activated ion movement within the more ordered BPI and BPII phases. In this region, the presence of Ag nanoparticles enhances charge transport by increasing carrier density and modifying defects. Between 20℃ and 35℃, the conductance remains high and stable, corresponding to the BPIII phase, where the structure is more disordered but still allows ions to move freely. Here,

interfacial polarization and space charge effects dominate, aiding conduction. However, beyond 35℃, there is a sharp decline in conductance as the system transitions into the isotropic phase, where molecular order is lost, disrupting ionic pathways and reducing polarization effects. From about 42℃ onward, conductance levels off at a lower value, reflecting minimal charge transport in the fully disordered phase. Overall, Ag nanoparticle doping effectively improves conductance in the blue phases but its influence diminishes as the material enters the isotropic phase. This behaviour highlights the interplay between structural order, temperature, and nanoparticle doping on the electrical properties of BPLCs.

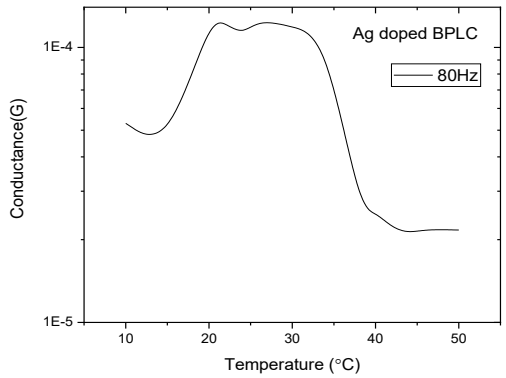

Figure 4, Conductance vs temperature for Ag doped BPLC ta 80Hz

4. Conclusion

Our finding reflects that silver (Ag) nanoparticle doping profoundly enhances the conductance and thermal stability of Blue Phase Liquid Crystals (BPLCs) [35]. Undoped BPLCs exhibit relatively low conductance characterized by pronounced ionic and dipolar relaxation peaks, indicative of charge transport dominated by molecular reorientation and sluggish ion migration [38-39]. In stark contrast, Ag-doped BPLCs reveal smooth, frequency-dependent conductance profiles with increasing voltage, signifying a transition to efficient, free carrier-driven conduction [39]. Such improved charge transport is pivotal for advancing electro-optic functionalities, enabling faster switching speeds and lower operating voltages essential for cutting-edge display and photonic technologies.

Temperature-dependent conductance analysis further underscores the transformative effect of Ag doping. While pure BPLCs show a limited temperature range with a sharp conductance drop near the blue phase–to–isotropic transition [40-41], Ag-doped samples maintain markedly higher conductance over a substantially broader temperature window. This enhanced plateau within the blue phase region reflects the nanoparticles' ability to augment ionic mobility and reinforce phase stability by interacting with defect structures and enhancing space charge polarization. Notably, the peak conductance observed near 24 °C aligns with optimal molecular ordering, and the shift of the isotropic transition to higher temperatures highlights the superior thermal resilience imparted by Ag incorporation.

Collectively, these findings establish Ag nanoparticle doping as a highly effective strategy to tailor the dielectric and conductive properties of BPLCs, thereby unlocking their full potential for next-generation electro-optic devices that demand high performance, stability, and rapid response.

Acknowledgments

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Table 1: Phase transitions before and after nanoparticles doping

Cooling(°C)	→		→		→	
Phase transition	Iso	BPIII	BPIII	BPII/BPI	BPII	N
Pure BPLC	76.5		27.5		20	
NPs-doped BPLC	41.6		23.8		20	

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Figure captions:

Table1: Phase transitions before and after nanoparticles doping

Figure 1(a-f): Pure BPLC conductnace vs frequency at 0V,1V, 2V, 3V, 4V and 5V.

Figure 2: Conductance vs temperature for pure BPLC at 80Hz.

Figure 3(a-f): Ag doped BPLC conductnace vs frequency at 0V, 1V, 2V, 3V, 4V and 5V.

Figure 4: Conductance vs temperature for Ag doped BPLC ta 80Hz