Breakthrough Progress: New Inorganic Electro-Optic Materials May Pave the Way for 5G Communication

The Team from Huazhong University of Science and Technology Reveals the Electro-Optic Effect Mechanism and Future Applications of Ferroelectric Materials.

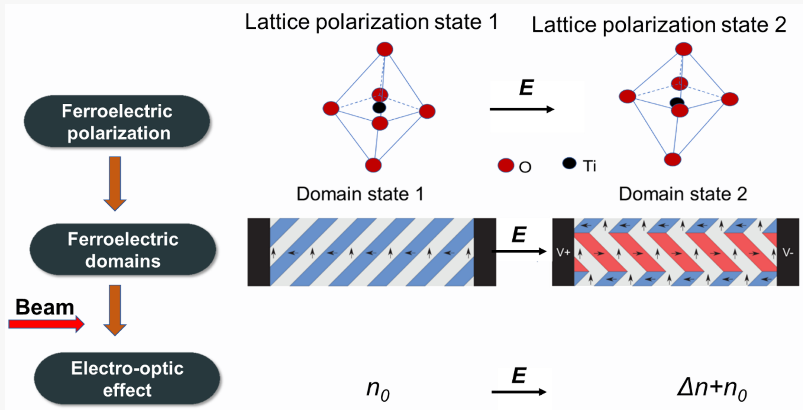

Fig.1 The EO effect in relation to the polarization tuning.

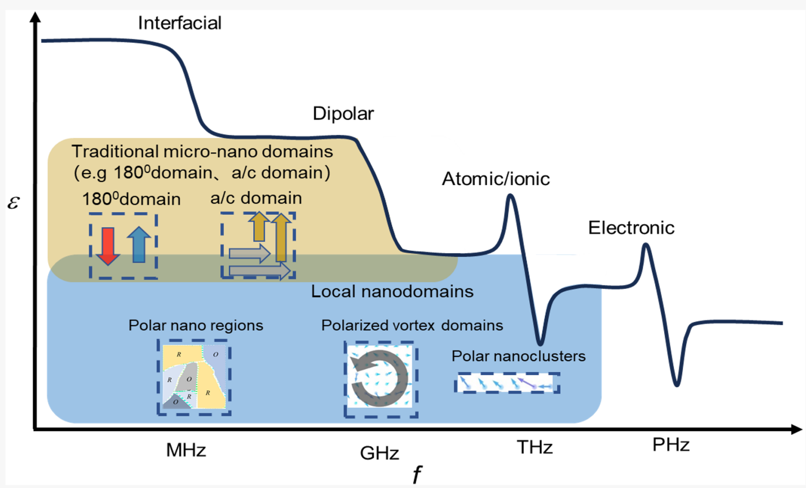

Fig.2 Frequency characteristics of dielectric constant in relation to the domain structures at different scales.

GA, UNITED STATES, May 13, 2025 /EINPresswire.com/ -- With the advent of the 5G era, the demand for high-speed and large-capacity data transmission in optical fiber communication is becoming increasingly urgent. As a core component of optical communication, the performance of electro-optic modulators highly depends on the electro-optic coefficient, response speed, and stability of the material. However, traditional materials (such as lithium niobate) are limited by low electro-optic coefficients and high driving voltages, making it difficult to meet the needs of future ultra-high-speed communication.

Recently, the team of Professor Fu Qiuyun and Associate Researcher Dong Wen from the School of Integrated Circuits at Huazhong University of Science and Technology published a review article titled "Advancing Inorganic Electro-Optical Materials for 5G Communications: From Fundamental Mechanisms to Future Perspectives" in the journal Light: Science & Applications. The article systematically summarized the research progress of inorganic electro-optical materials, revealed the intrinsic connection between ferroelectric polarization and the electro-optical effect, and proposed design directions for future high-performance materials.

This review proposes two main directions. First, to further delve into the theoretical and experimental studies of the correlation mechanism between ferroelectric polarization and the electro-optic effect, particularly the intrinsic relationship between the polarization response dynamics of ferroelectric materials and the refractive index modulation under electric field, including theoretical methods such as higher-precision first-principles calculations and phase-field simulations, as well as ultrafast dynamic characterization of polarization structures. Second, to conduct multi-physics device simulations that include the direction of the electric field, ferroelectric polarization, and optical field. This will link the electrical and optical behaviors of the intrinsic polarization structure of thin-film materials, enabling meticulous simulation design of devices and optimization of their performance. Finally, to thoroughly investigate the loss characteristics of inorganic materials in optical transmission, device insertion loss, and stability properties, and to seek methods for improvement. The ultimate goal is to predict and explore the next-generation inorganic EO materials that may potentially replace LNO. It is hoped that this review will promote further development in this field.

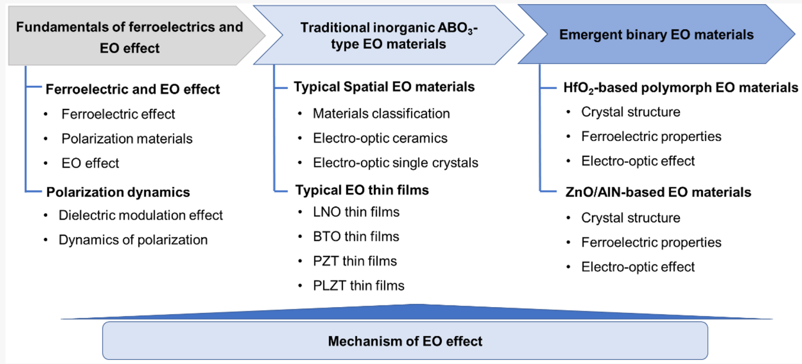

Fig.3 Outline of the review

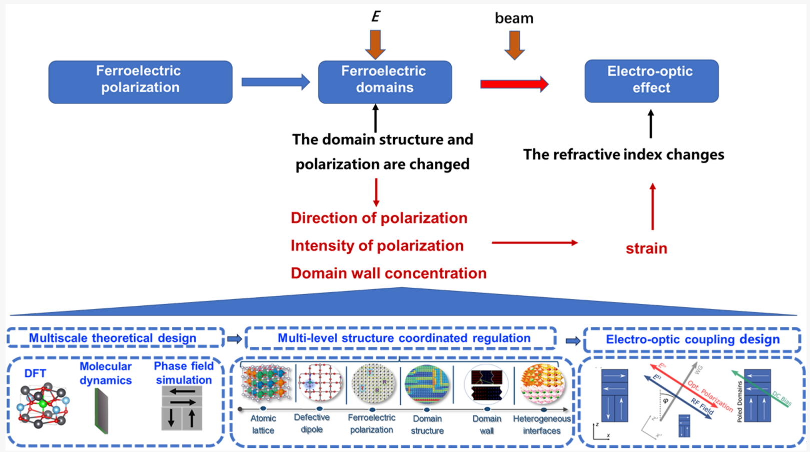

Fig.4 Proposed approach for future research on EO mechanism and property optimization of inorganic ferroelectrics.

Electro-Optic Effect in Ferroelectric Materials: A Brief Introduction

Based on the different responses of polarization to the applied electric field, dielectric materials can be classified into linear dielectrics, classical ferroelectrics, relaxor ferroelectrics, and antiferroelectrics. Ferroelectricity, characterized by reversible polarization due to ionic displacement, was experimentally discovered a century ago and has sparked research into its fundamental properties and potential applications. Here, ferroelectrics (such as BTO) typically refer to classical ferroelectrics with microscale domain structures. In contrast, relaxor ferroelectrics, such as PZT, exhibit nanoscale polarization domains and usually higher piezoelectricity. Compared to traditional ferroelectrics, they have a lower switching barrier between two stable polarization states, making polarization switching easier. In relaxor ferroelectrics, nanoscale domains or polar nanoregions (PNRs) modulate domain wall configurations, leading to a macroscopic reduction in hysteresis, often manifesting as thin hysteresis loops. Compared to classical hysteresis loops, their hysteresis can be negligible, and the observed nonlinearity is apparently related to the presence and movement of polarization within nanoscale domains.

Ferroelectric materials can exhibit spontaneous polarization, and the direction of their polarization vector can be reoriented by an external electric field, displaying a hysteresis loop. Meanwhile, ferroelectric materials also demonstrate excellent electro-optic (EO) effects when subjected to an electric field. The inherent spontaneous polarization in ferroelectrics endows the crystal with macroscopic properties similar to those of an electric dipole, and this polarization can be reoriented in response to an external electric field. Such polarization reversal is usually accompanied by domain switching, that is, the reorientation of microscopic regions (domains) within the material to align with the applied field. The speed and mechanism of this domain switching process will directly affect the EO characteristics of the material. This effect can be directly observed from the change in the refractive index Dn under the tuning electric field DE, as shown in Figure 1.

The dielectric response is intrinsically related to the polarizable structures or elements within the crystal. As shown in Figure 2 (upper part), traditional ferroelectric domain structures, such as antiferroelectric domains and 180° domains, mostly have sizes ranging from tens of nanometers to micrometers, and most of their polarization response frequencies are below the GHz range. Therefore, it is difficult for them to exhibit significant dielectric polarization responses in the THz or higher frequency ranges, not to mention the true 1500 nm optical wavelength electric field. Typical local nanodomains, with relative sizes reaching below 10 nanometers and even a few lattice constants, allow response frequencies higher than those of traditional ferroelectric domains, such as polar nanoregions, polar vortices, and polar nanoclusters.

Inorganic electro-optic materials

We have reviewed the progress of perovskite-based ferroelectric EO materials and emerging CMOS-compatible inorganic non-perovskite counterparts, highlighting the general focus on ferroelectric and EO modulators. Inorganic electro-optic materials have evolved from silicon-based to LNO, and then to BTO, PZT, etc., at the material level, and from bulk materials to thin-film materials (e.g., LNO thin films, BTO thin films, PZT thin films, PLZT thin films) in terms of form. Although the performance of these materials has been improving, the standards required by their application fields have also been increasing, including high bandwidth, minimal optical loss, low power consumption, and high signal-to-noise ratio. Traditional silicon-based, III-V, and compound semiconductor modulators are apparently unable to meet all these requirements simultaneously. Although lithium niobate is highly esteemed in the optoelectronics industry for its excellent crystal properties, its applicability is greatly reduced due to the complexity of processing, doping waveguide structures, large size, high cost, limited bandwidth, and increased driving voltage. On the other hand, thin-film lithium niobate ($LiNbO_3$, LNO), despite being relatively new in development, has a promising future. There is still a lot of room for growth in its technology and performance, requiring further research and iterative development. Emerging ferroelectric oxide materials, such as $BaTiO_3$ (BTO), $Pb(Zr_{1-x}Ti_x)O_3$ (PZT), and La-doped PZT (PLZT), also show great potential for further development. In terms of structure, thin-film materials outperform crystals and transparent ceramics, and considering the latter's complex processing challenges and cost-effectiveness, thin-film materials have a broader development prospect. Moreover, as shown in Figure 3, the field of ferroelectricity has become a prominent research area in recent years, with an increasing number of studies dedicated to exploring effects and materials associated with this phenomenon.

Additionally, we also mentioned some emerging binary EO materials, such as HfO_2, ZnO, and AlN, and their electro-optic effects.

Summary and prospect

With the accelerated development of science and technology in the future, there is a need for electro-optic materials with large EO coefficients, excellent light transmittance, and stable physical and chemical properties, as well as electro-optic modulators that can modulate faster, reduce losses, and have smaller form factors. This paper has conducted an in-depth study of inorganic electro-optic materials, based on the fundamental principles of the EO effect and modulation, and has comprehensively reviewed the research work on spatial EO modulation materials and electro-optic thin films. In addition, we have carried out an in-depth analysis of the basic ferroelectric properties and EO effects exhibited by recently discovered CMOS-compatible non-perovskite inorganic ferroelectric materials. The specific research content and conclusions are as follows: At present, modulators based on LNO dominate the high-speed EO modulator market. However, their limited EO coefficients restrict the performance of commercial modulators using bulk lithium niobate, thereby resulting in larger sizes and higher driving voltages. The development of inorganic optical materials for next-generation EO materials, especially those for silicon chip-level integration, is expected to focus on BTO and PZT, which exhibit higher EO coefficients.

Despite the great potential of ferroelectric materials, there is still an order of magnitude difference between the theoretical prediction and experimental values of their electro-optic coefficients (e.g., for BTO, the theoretical value is 45 pm/V vs. the experimental value of 923 pm/V), and the popular materials still have limitations (complex LNO preparation, low second-order electro-optic coefficient of BTO). The ferroelectric EO modulation effect is intricately related to domain structure and polarization regulation, forming a dynamic, cross-scale process that controls the regulation and response of the polarization structure, as shown in Figure 4. We believe that future breakthroughs need to be made in the following directions:

(1) In-depth investigation of ferroelectric mechanisms: Future research on inorganic ferroelectric EO modulation materials should prioritize elucidating the intricate interplay between ferroelectric polarization and the EO effect, with the ultimate goal of optimizing the latter

through a deeper understanding of the underlying mechanisms.

(2) Material-device co-design: First, simulation-based studies are needed to carefully design the parameters of the EO modulator, thereby optimizing the device structure. Second, in-depth research and verification of the optical transmission loss, device insertion loss, and stability characteristics of these inorganic materials are required. Ultimately, our goal is to identify and explore the next-generation inorganic EO materials that are most likely to become viable alternatives to LNO.

(3) Multiscale characterization techniques: To reveal the underlying mechanisms and inform material design, future research must integrate theoretical frameworks, computational methods (such as DFT), molecular dynamics, and phase-field simulations along with material design strategies. Moreover, a comprehensive analysis of the hierarchical structure and coupled behavior of materials helps to gain a deeper understanding of how to synergistically utilize these structures to regulate the arrangement of ferroelectric chains and the refractive index. Ultimately, by harmoniously integrating the polarization direction, electric field direction, optical field direction, and co-design principles, the EO modulation effect can be optimized, thereby guiding the development of advanced devices.

(4) Lead-free material exploration: In the future, environmentally friendly HfO_2-based and ZnO-based materials can be developed to replace the lead-containing PZT system.

References

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Team

This research was jointly completed by the School of Integrated Circuits at Huazhong University of Science and Technology, the Engineering Research Center of Functional Ceramics of the Ministry of Education, and the Wuhan National Laboratory for Optoelectronics. The team has long been committed to the study of ferroelectric electro-optic mechanisms and device integration. In recent years, they have published a series of breakthrough achievements on electro-optic materials and devices in journals such as Light: Science & Applications, Materials Today, Journal of Advanced Ceramics, and Ceramics International. Associate Researcher Dong Wen stated, "By designing and dynamically regulating structures across scales, we expect to double the performance and halve the cost of electro-optic modulators within the next five years. Ferroelectric materials hold great potential."

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