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# Electronic paramagnetic resonance analysis of point defects in lithium niobate: progress and prospects

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Lithium niobate (LiNbO<sub>3</sub>) crystals, renowned for their exceptional piezoelectric, electro-optic, and nonlinear optical properties, are indispensable in photonic applications such as optical communication, integrated optics, and laser technology. However, the performance of LiNbO<sub>3</sub>-based devices is fundamentally limited by point defects. Consequently, elucidating the mechanisms underlying point defect formation and achieving precise control over defect engineering have emerged as critical research priorities. Although conventional characterization techniques face inherent limitations in directly resolving the microstructures of point defects, electron paramagnetic resonance (EPR) spectroscopy has proven to be a pivotal analytical tool for the non-destructive characterization of paramagnetic defects, driving significant advancements in LiNbO<sub>3</sub> defect research. This article summarizes the intrinsic and impurity defects that significantly affect the optoelectronic properties of LiNbO<sub>3</sub> crystals. Firstly, it elucidates the primary types of point defects, their microstructural characteristics, and their impacts on material properties. Subsequently, it highlights the advancements in EPR technology for studying point defects and provides an in-depth analysis of its advantages in defect analysis. Finally, it proposes the future concerns of studying point defects in LiNbO<sub>3</sub> crystals using EPR technology.

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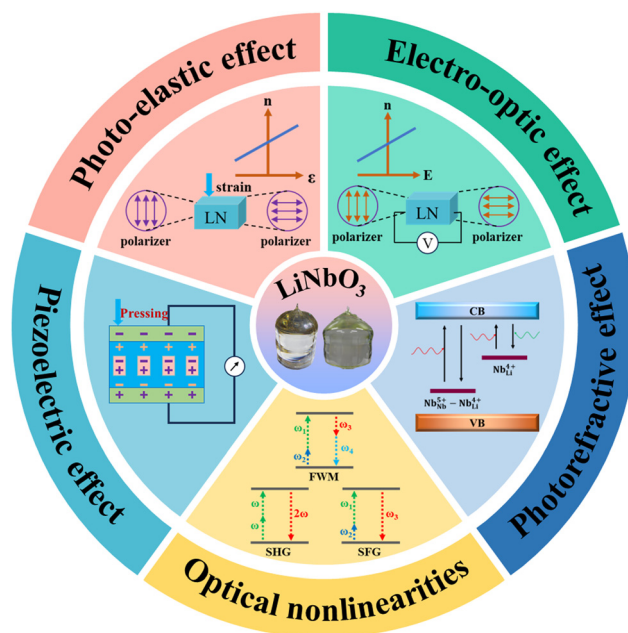
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## 1. Introduction

Lithium niobate (LiNbO<sub>3</sub>) crystals, as a multifunctional crystal material,<sup>1</sup> exhibit the piezoelectric effect, electro-optic effect, nonlinear effect, photorefractive effect, photo-elastic effect, and acousto-optic effect<sup>2</sup> (Fig. 1). Various bulk and thin film devices based on LiNbO<sub>3</sub> crystals are widely used in fields such as optical frequency combs,<sup>3,4</sup> optical communication, integrated optics,<sup>5</sup> and lasers.<sup>6</sup> Owing to its excellent optical-electrical properties, LiNbO<sub>3</sub> is regarded as “optical silicon” in the optics field. Due to the significant advantages of single-crystal thin-film LiNbO<sub>3</sub> in integrated optics, Professor Burrows at Harvard University proposed “Now entering, Lithium Niobate Valley”.

Single-crystal defects can be classified into four categories<sup>7</sup> based on their spatial dimensions: point defects, line defects, planar defects, and bulk defects. In LiNbO<sub>3</sub> crystals, the main types of defects include bulk defects (*e.g.*, inclusions), planar

Fig. 1 Properties of LiNbO<sub>3</sub> crystals.

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defects<sup>8</sup> (twinning boundaries), line defects<sup>9</sup> (dislocations), and point defects<sup>10</sup> (vacancies). Notably, advancements in crystal growth techniques coupled with improved microscopic characterization methodologies have enabled substantial progress in elucidating the formation mechanisms of the first three defect categories, along with effective suppression of their occurrence density. Nevertheless, atomic-scale characterization limitations persist in obscuring the generation dynamics and microstructure of point defects, becoming a critical bottleneck in optimizing the functional performance of LiNbO<sub>3</sub> crystals. As is well known, the performance of LiNbO<sub>3</sub> crystals is closely related to point defects. However, the formation mechanisms and elimination methods of point defects in LiNbO<sub>3</sub> crystals have been scarcely researched.

The investigation of point defects requires the integration of multi-scale characterization techniques, primarily encompassing magnetic resonance spectroscopy (*e.g.*, electron paramagnetic resonance<sup>11</sup> and nuclear magnetic resonance<sup>12</sup>), spectral analysis (photoluminescence<sup>13</sup> and X-ray absorption fine structure<sup>14</sup>), atomic-level microscopy techniques (scanning transmission electron microscopy<sup>15,16</sup>), synchrotron radiation characterization, and computational simulations (density functional theory<sup>17</sup>). Among these, electron paramagnetic resonance (EPR) spectroscopy enables non-destructive acquisition of critical defect information, including local symmetry, coordination environment and charge state through the detection of spin resonance signals from unpaired electrons.<sup>18</sup> This technique is widely recognized as the central methodology for establishing comprehensive point defect models in materials science.<sup>19</sup> Although significant experimental efforts have been devoted to analyzing the point defects in LiNbO<sub>3</sub> crystals by EPR spectroscopy, systematic reviews about point defect characterization in LiNbO<sub>3</sub> crystals remain strikingly limited. Notably, existing review articles<sup>20,21</sup> predominantly focus on the electronic structure and localized environmental analysis of extrinsic defects, while systematic investigation of the EPR spectrum signatures and defect dynamics in intrinsic defect systems remains notably scarce.

Firstly, this review reviews the pivotal advancements facilitated by EPR spectroscopy in characterizing point defects within LiNbO<sub>3</sub> crystals, systematically describing the analysis results of EPR spectroscopy for intrinsic and external defects. Secondly, we also noticed that EPR spectroscopy has more important analytical application in stoichiometric lithium niobate (SLN) crystals. Lastly, the future application of EPR spectroscopy in defects analysis is proposed.

## 2. Point defects in LiNbO<sub>3</sub>

The ideal crystal structure of an LiNbO<sub>3</sub> crystal consists of oxygen octahedra stacked in coplanar arrangements, with their shared planes perpendicular to the trigonal symmetry axis (*i.e.*, polar axis). These different stacked units interconnect through edge-sharing coordination, forming an oxygen-octahedral framework<sup>22,23</sup> (Fig. 2a). As a ferroelectric material with a Curie temperature of approximately 1483 K (1210 °C), it exhibits distinct paraelectric and ferroelectric phase structures. Its ferroelectric phase structure arises from the cooperative displacement of Li<sup>+</sup> ions and Nb<sup>5+</sup> ions along the crystallographic *c*-axis, generating spontaneous polarization through ionic rearrangement (Fig. 2b). At this point, cations in the +*c* direction fill the oxygen octahedron in the form of “–Li Nb–□–Li Nb–□–”, where “□” represents vacancies.<sup>22</sup> This structure would be one of the key factors causing LiNbO<sub>3</sub> crystals to be plagued by defects.

### 2.1. Intrinsic defects

LiNbO<sub>3</sub> crystal is a typical non-stoichiometric crystal, and its high-quality single crystal is usually grown from a congruent melt (Li : Nb = 48.6 : 51.4) using the Czochralski method, which is called a congruent lithium niobate (CLN) crystal. Due to the absence of Li<sup>+</sup>, intrinsic defects mainly consisting of Li vacancy (V<sub>Li</sub>) and anti-site Nb (Nb<sub>Li</sub>) appear in the lattice. The existence of these intrinsic defects significantly affects the electro-optical



Fig. 2 (a) Ideal structure of LiNbO<sub>3</sub>, (b) ferroelectric phase (left) and paraelectric phase (right) structure of LiNbO<sub>3</sub>.



and nonlinear optical properties of the crystal, thereby limiting their applications in optoelectronic modulators, surface acoustic wave devices, and related fields. Therefore, the regulation of these intrinsic defects and their effects on material performance remains a critical research focus in the field of LiNbO<sub>3</sub> crystals.

Over the past few decades, substantial research efforts have been devoted to developing intrinsic defect structure models in LiNbO<sub>3</sub> crystals. However, due to inherent theoretical limitations and inconsistencies among various defect models, many have been subsequently abandoned. This chapter focuses on four representative defect models that have demonstrated particular significance in understanding the structural properties of LiNbO<sub>3</sub> crystals.

Fay *et al.* (1968) first proposed the oxygen vacancy model,<sup>24</sup> postulating that the absence of Li in crystals generates Li vacancies, while requiring the concomitant formation of oxygen vacancies to maintain charge neutrality. The structural formula of this model is [Li<sub>1-2x</sub>V<sub>2x</sub>][Nb[O<sub>3-x</sub>V<sub>x</sub>]], where V represents a vacancy. Based on this model, a positive correlation between crystal density and Li content would be expected. However, precise experimental results demonstrate that the crystal density decreases with an increase in Li/Nb ratio.<sup>25</sup> This discrepancy between theoretical predictions and experimental observations ultimately led to the rejection of the oxygen vacancy model.

The Nb vacancy model was proposed,<sup>26</sup> wherein excess Nb occupies octahedral vacancies lacking lithium, forming Nb<sub>Li</sub>, with charge compensation achieved by niobium vacancies (V<sub>Nb</sub>) (Fig. 3a). At this time, the crystal chemical structure formula is [Li<sub>1-5x</sub>Nb<sub>5x</sub>][Nb[O<sub>1-4x</sub>V<sub>4x</sub>]]O<sub>3</sub>. However, based on the niobium vacancy model, it was calculated that there are 5.9 mol% Nb<sub>Li</sub> and 4.7 mol% V<sub>Nb</sub> in the CLN crystal with Li/Nb = 0.942. From an energy perspective, these high concentrations of high valence Nb<sub>Li</sub> is unstable. Therefore, the ilmenite structure formed by the partial exchange of Li<sup>+</sup> and Nb<sup>5+</sup> was proposed (Fig. 3b). This localized ilmenite structure can transform high-charged Nb<sub>Li</sub><sup>4+</sup> and V<sub>Nb</sub><sup>3-</sup> into simple V<sub>Li</sub><sup>-</sup>, thereby significantly improving the overall energy stability of defect structures based on the niobium vacancy model.

Based on the differences in density and cell parameters of LiNbO<sub>3</sub> crystals with different Li/Nb ratios, the Li vacancy

model was proposed in 1968. This model suggests that excess Nb in CLN crystals occupies the Li sites to form Nb<sub>Li</sub>, with charge compensation achieved through the formation of Li vacancies (V<sub>Li</sub>), as illustrated in Fig. 3c. The structural formula is [Li<sub>1-5x</sub>V<sub>4x</sub>Nb<sub>x</sub>][NbO<sub>3</sub>]. Both the lithium vacancy model and niobium vacancy model fundamentally exclude oxygen vacancies in the LiNbO<sub>3</sub> crystal, instead proposing the presence of Nb<sub>Li</sub> defects. The concentration of Nb<sub>Li</sub> in the lithium vacancy model is only around 1/5 of that in the niobium vacancy model, resulting in a more energetically favorable and stable defect configuration. In 1992, Iyi<sup>27</sup> measured the lattice parameters, density, and crystal powder diffraction data of LiNbO<sub>3</sub> crystals with different compositions, supporting the lithium vacancy model. Subsequent experimental studies<sup>28-30</sup> have consistently demonstrated that the lithium vacancy model is a more accurate defect structure model, which has gained widespread acceptance in the scientific community. Density functional theory is commonly used to determine the main intrinsic defects in crystals. According to the formation energy of different defect structures ( $E_{V_{Li}} \sim -0.23$  eV,  $E_{V_{Nb}} \sim -1.20$  eV,  $E_{Nb_{Li}+4V_{Li}} \sim -0.25$  eV,  $E_{5Nb_{Li}+4V_{Nb}} \sim -1.12$  eV), Xu *et al.* predicted that the defect cluster composed of four lithium vacancies compensating for anti-site niobium in CLN crystals is the most stable structure.<sup>31</sup> Li *et al.* used a mixed hybrid exchange–correlation functional to improve the computational accuracy and obtained similar conclusions that for most LN crystals, their Fermi level is located in the lower half of the electronic bandgap, and anti-site niobium and Li vacancies coexist (*i.e.* Nb<sub>Li</sub> + 4V<sub>Li</sub>). Nb vacancies may only form under specific conditions.<sup>32</sup>

Table 1 presents a comprehensive comparison of the four major defect models for the LiNbO<sub>3</sub> crystal. Among them, the Nb<sub>Li</sub> defect has emerged as the most widely accepted defect in LiNbO<sub>3</sub> crystals, which means that analyses focusing on Nb<sub>Li</sub> would be the key for defect analysis. Recent studies have further revealed that Nb<sub>Li</sub> defects exert a significant influence on the physical properties of LiNbO<sub>3</sub> crystals, demonstrating predominantly detrimental effects across various crucial material



Fig. 3 Defect models in LiNbO<sub>3</sub> crystals. (a) Nb vacancy model, (b) ilmenite model, and (c) Li vacancy model.



Table 1 Comparison of defect models for LiNbO<sub>3</sub>

| Model        | O vacancy model | Nb vacancy model | Ilmenite model | Li vacancy model |
|--------------|-----------------|------------------|----------------|------------------|
| Li vacancy   | ✓               | —                | —              | ✓                |
| O vacancy    | ✓               | —                | —              | —                |
| Nb vacancy   | —               | ✓                | ✓              | —                |
| Anti-site Nb | —               | ✓                | ✓              | ✓                |

characteristics. For example, Nb<sub>Li</sub> defects act as photorefractive centers<sup>33</sup> between energy levels (Fig. 4a), greatly reducing the optical-damage resistance threshold of the crystal. The electro-optic coefficient,  $\gamma_{61}$ , of the LiNbO<sub>3</sub> crystal decreases with a decrease in Li content from a stoichiometric ratio to the congruent component, which was also assigned to the increase in Nb<sub>Li</sub> defects<sup>34</sup> (Fig. 4b). Furthermore, the pinning effect of Nb<sub>Li</sub> defects hinders domain inversion,<sup>35</sup> substantially increasing the domain inversion voltage in CLN crystals compared to near stoichiometry lithium niobate (NSLN) crystals (Fig. 4c). In addition, Wang *et al.* confirmed that the piezoelectric coefficient,  $d'_{15}$ , and electromechanical coupling coefficient,  $k'_{15}$ , of NLSN crystals are superior to that of CLN crystals at operating temperatures in the range of 0–650 °C, which is also attributed to the contents of Nb<sub>Li</sub> defects<sup>36</sup> (Fig. 4d).

## 2.2. Extrinsic defects

The incorporation of various doping elements significantly enriches the properties and broadens the application prospects

of LiNbO<sub>3</sub> crystals<sup>40–46</sup> (Fig. 5). For instance, hydrogen atoms typically exist in oxide crystals as OH ions,<sup>47,48</sup> and the presence of unexpected H ions can alter the refractive index of LiNbO<sub>3</sub> crystals. Elements such as Mg,<sup>49–51</sup> Zn,<sup>52</sup> In,<sup>53,54</sup> Sc,<sup>55</sup> Sn,<sup>56</sup> Hf<sup>57,58</sup> and Zr,<sup>39,59,60</sup> which possess stable valence states and optical inertness, are employed to enhance the optical damage resistance in LiNbO<sub>3</sub> crystals. Conversely, Cu,<sup>61–63</sup> Mn,<sup>64</sup> Fe,<sup>65,66</sup> Ni and Ce<sup>67,68</sup> were used to enhance the photorefractive effect by introducing the impurity defect energy levels in the crystal bandgap. Additionally, rare earth ions such as Er,<sup>69–71</sup> Nd,<sup>72,73</sup> Yb,<sup>46,74</sup> Tb,<sup>75</sup> Dy,<sup>76</sup> Ho<sup>77,78</sup> and Tm<sup>79</sup> serve as active ions, imparting laser properties to LiNbO<sub>3</sub>.

However, doping engineering also introduced external defects due to the different radii and ionic valence of the dopants. When the doping concentration of Mg exceeds 6 mol%, the optical damage resistance threshold of the Mg:CLN crystal significantly decreases, which is caused by the Mg<sub>Nb</sub> defect formed by Mg occupying the Nb sites. Lanthanide elements such as Nd and Yb have large ionic radii, which cause severe lattice distortion in LiNbO<sub>3</sub> crystals, making them prone to cracking during the growth process. In addition, the segregation effect causes a concentration gradient of doping elements along the crystal axis, which changes the thermal expansion coefficient of the crystal and may lead to cracking during cooling. Obviously, micro defects serve as critical determinants governing the physical properties of LiNbO<sub>3</sub> crystals. Consequently, the application of advanced characterization techniques is essential to systematically investigate the formation



Fig. 4 (a) Nb<sub>Li</sub> acts as a photorefractive center in CLN crystals. (b) Dependence of the electro-optic coefficient,  $\gamma_{61}$ , on the crystal composition in pure LiNbO<sub>3</sub> crystals, where  $X_c$  represents the Li content in the LiNbO<sub>3</sub> crystal.<sup>34</sup> Reproduced from ref. 34 with permission from AIP Publishing, copyright 1998. (c) Ferroelectric hysteresis loop of NSLN measured at room temperature.<sup>37</sup> Reproduced from ref. 37 with permission from Elsevier, copyright 2022. (d) Variations in electromechanical coupling factors and piezoelectric coefficients as a function of temperature for NSLN (red) and CLN (green) crystals.<sup>36</sup> Reproduced from ref. 36 with permission from the American Chemical Society, copyright 2024.





Fig. 5 Application of dopants in the  $\text{LiNbO}_3$  crystal.<sup>38,39</sup> Reproduced from ref. 38 with permission from the Editorial Office of Opto-Electronic Journals Group, Institute of Optics and Electronics, copyright 2022. Reproduced from ref. 39 with permission from the Optical Society of America, copyright 2011.

mechanism of defects and their influence on the physical properties of crystals.

Lithium niobate on insulator (LNOI) is completely changing the lithium niobate industry, with advantages such as higher performance and new equipment and applications.<sup>80,81</sup> It not only maintains the excellent optical properties of bulk crystals, but also enables photonic devices/circuits to be easily scaled down to the sub-micron scale.<sup>82</sup> However, processing methods such as ion implantation, ion beam etching, and ion irradiation can cause lattice damage and introduce new defects.<sup>83</sup> Current research on LNOI primarily focuses on fabrication quality, with the use of high-resolution X-ray diffraction to verify the ordering of single crystals<sup>84</sup> and Raman spectroscopy to evaluate the quality of lattice arrangement.<sup>85</sup> There are few reports on the analysis of defects in LNOI, and aberration corrected electron microscopy can be used to directly observe the atomic occupancy. However, EPR technology has not yet been applied to the analysis of defects in LNOI. The defects or damages have a significant impact on the various physical properties of LN crystals. Post-annealing treatment is an effective method for restoring these damages and defects. Usually, H ion implantation into waveguides requires annealing at a temperature of 200–300 °C to reduce optical absorption and improve the waveguide performance. Ashley *et al.*<sup>86</sup> injected a high dose of Ti into LN to form a planar waveguide, and the ion-implanted region was completely amorphized. After annealing at 1000 °C for 1 h, its electro-optic coefficient,  $\gamma_{33}$ , was measured to be 29 pm V<sup>-1</sup>, which is close to that of bulk crystals. High-temperature annealing helps to restore the electro-optic properties of ion-sliced LN films.<sup>87,88</sup> Moreover, SHG experiments

showed the recovery of the nonlinear coefficient of a LN thin film after annealing at 600 °C.<sup>89</sup>

### 3. Application of EPR in defect characterization

#### 3.1. Introduction of EPR spectroscopy

EPR spectroscopy is sensitive high-resolution spectrum technology for the detection of unpaired spins, which has been widely used in fields such as physics, chemistry, biology, and materials. Briefly, when EPR spectroscopy is used to study unpaired electron spins in solid materials, Hamiltonian parameters can be used to describe various possible interactions, which generally take the following form:

$$H_{\text{spin}} = H_{\text{EZ}} + H_{\text{HF}} + H_{\text{CF}} + H_{\text{Q}} + H_{\text{NZ}}$$

where  $H_{\text{EZ}}$  is the electronic Zeeman interaction, representing the interaction between the effective spin,  $S$ , and the applied magnetic field,  $B$ . As long as there are unpaired electrons, there must be electron Zeeman interactions, which are an essential component of the Hamiltonian parameter.  $H_{\text{EZ}}$  can be represented by a  $g$ -tensor, which can reflect the local point symmetry of defects.  $H_{\text{HF}}$  is a hyperfine interaction, representing the interaction between the magnetic moment of unpaired electrons and the magnetic moment,  $I$ , of nearby atomic nuclei. When  $I > 0$ , hyperfine splitting occurs, dividing the spectral lines into  $(2I + 1)$  lines. Obtaining an effective spin,  $S$ , and magnetic moment,  $I$ , through EPR spectrum analysis can help us quickly determine the types and charge states of impurity



elements. Due to the influence of the electrical crystal field, additional interactions called fine structure interactions ( $H_{CF}$ ) can occur in paramagnetic defects with  $S > 1/2$ , which will result in 2S splitting of the EPR spectrum lines.  $H_Q$  and  $H_{NZ}$  are the nuclear quadrupole interaction and nuclear Zeeman interaction, respectively, which are small compared to the Zeeman energy and not stated here. For more details, readers can refer to textbooks on EPR spectroscopy, as well as the recent article by Rudowicz,<sup>90</sup> in which the current situation in this area is reviewed and discussed.

### 3.2. Application of EPR spectroscopy in defect analysis of $\text{LiNbO}_3$

The formation of defect structures in crystals is fundamentally governed by the charge states of impurity ions occupying lattice sites and their corresponding charge compensation mechanisms. Excessive Nb occupies the Li sites in CLN crystals to form  $\text{Nb}_{\text{Li}}$  defects, whose concentration and structure have not yet been determined. Due to the complexity of the CLN crystal structure and the limitation of experimental equipment resolution, it is usually difficult to directly observe the structural information of  $\text{Nb}_{\text{Li}}$  defects. Furthermore, the substitution mechanisms of doping elements in CLN crystals, particularly concerning site occupancy preferences and charge compensation, remain poorly understood and require further systematic investigation.

Fortunately, these defects in the crystal are originally paramagnetic or after specific treatment, which can be detected by EPR spectroscopy very accurately. EPR spectroscopy exhibits exceptional sensitivity, and different elements with determined nuclear spin numbers and abundances produce characteristic spectral splitting patterns, which can serve as a “fingerprint” for identifying defect identities.<sup>20</sup> Additionally, ENDOR spectroscopy can probe the surrounding environment of defects, providing crucial insights into their charge compensation mechanisms. Therefore, some progress has been made by EPR and ENDOR technology in analyzing defects in  $\text{LiNbO}_3$  crystals over the past few decades.

**3.2.1. EPR spectrum analysis of intrinsic defect.** In  $\text{LiNbO}_3$  crystals, the  $\text{Nb}_{\text{Li}}$  defect has been widely recognized as the most critical intrinsic defect. It was believed that due to the lower content of Li in the CLN crystal, the higher strength of Nb–O bonds compared to Li–O bonds, the small difference in ionic radius between  $\text{Li}^+$  ( $r = 0.76 \text{ \AA}$ ) and  $\text{Nb}^{5+}$  ( $r = 0.69 \text{ \AA}$ ) and their similar spatial environment, Nb tends to occupy the Li sites to form  $\text{Nb}_{\text{Li}}$ .<sup>10</sup> Peterson discovered two types of lattice environments for  $\text{Nb}^{5+}$  in the CLN crystal lattice through  $^{93}\text{Nb}$  nuclear magnetic resonance experiments, which implied the existence of  $\text{Nb}_{\text{Li}}$ .<sup>26</sup> Therefore, extensive research has been conducted using EPR spectroscopy to analyze the structural information of  $\text{Nb}_{\text{Li}}$ .

Schinner<sup>91</sup> firstly obtained a nearly equidistant 10-line EPR spectrum in CLN crystals after laser irradiation (Fig. 6a). This was attributed to the hyperfine interaction between unpaired electrons and  $^{93}\text{Nb}$  nuclei ( $I = 9/2$ ). The relevant Hamiltonian parameters were calculated to be  $g_{\parallel} = 1.90$ ,  $g_{\perp} = 1.72$ ,  $A_{\parallel} = 0.011 \text{ cm}^{-1}$  and  $A_{\perp} = 0.023 \text{ cm}^{-1}$ . Its hyperfine splitting and

$g$ -shift are typical features of  $\text{Nb}^{4+}$  in a distorted oxygen octahedral environment.<sup>92,93</sup> Based on the axial symmetry of the spectrum, they attributed this signal for the first time to the electron self-trapping of the Nb lattice, *i.e.*  $\text{Nb}_{\text{Nb}}^{5+} + e^- \rightarrow \text{Nb}_{\text{Nb}}^{4+}$ . However, Müller *et al.* proposed an alternative interpretation by analyzing the angular dependence of the  $\text{Nb}^{4+}$  signals. Their fitting of the anisotropic  $g$ -tensor and  $A$ -tensor (Fig. 6b) suggested a reduction in local symmetry around the  $\text{Nb}^{4+}$  center.<sup>94</sup> The observed symmetry reduction arises from the formation of a charge compensation structure induced by the excess positive charge of  $\text{Nb}_{\text{Li}}$ . This distortion of the local coordination environment provides compelling evidence that the EPR signals originate from the Nb ions occupying the Li sites. Faust<sup>95</sup> noticed that the intensity of EPR spectrum of  $\text{Nb}_{\text{Nb}}^{4+}$  is lower in thermally reduced CLN crystals doped with 6 mol% MgO (Fig. 6c). The reason for this may be that high concentration Mg doping eliminates the  $\text{Nb}_{\text{Li}}$  defects in CLN crystals, resulting in the disappearance of the EPR spectrum belonging to  $\text{Nb}_{\text{Li}}^{4+}$ . Zheng *et al.*<sup>96</sup> provided the calculated Hamiltonian parameters for  $\text{Nb}_{\text{Li}}$  defects, demonstrating excellent agreement with experimental data. Their analysis further revealed the structural configuration of the defect center, showing that  $\text{Nb}_{\text{Li}}$  is displaced from the ideal Li site by  $\Delta z \approx 0.19 \text{ \AA}$  along the polar axis, while the coordinating oxygen ions in the plane between  $\text{Nb}_{\text{Li}}^{4+}$  and  $\text{Nb}_{\text{Nb}}^{5+}$  exhibit a lateral displacement of  $\Delta x \approx 0.30 \text{ \AA}$  away from the  $C_3$  axis. The reason for the offset is that when  $\text{Nb}_{\text{Li}}^{5+}$  captures electrons to form  $\text{Nb}_{\text{Li}}^{4+}$ , the decrease in electrostatic repulsion causes  $\text{Nb}_{\text{Li}}^{4+}$  to shift towards the center of the oxygen octahedron. Meanwhile, due to the overlap of electron clouds, the oxygen ions between  $\text{Nb}_{\text{Li}}^{4+}$  and  $\text{Nb}_{\text{Nb}}^{5+}$  are far away from the oxygen triangle center. Regrettably, the underlying mechanisms responsible for the enhanced  $\text{Nb}_{\text{Li}}^{4+}$  signal in annealed CLN crystals following Xe lamp irradiation remain unclear. In particular, the local charge compensation structure associated with  $\text{Nb}_{\text{Li}}$  defects has not been fully elucidated.

$\text{LiNbO}_3$  crystals exhibit darkening when heated to  $500 \text{ }^\circ\text{C}$  under a vacuum, hydrogen, or argon atmosphere, with progressively intensified coloration as the temperature increases.<sup>97</sup> UV-vis absorption spectroscopy shows that annealed samples generate a broad absorption band centered at approximately 500 nm, which shifts to 760 nm after xenon lamp irradiation (optical bleaching).<sup>98,99</sup> The proposed mechanism<sup>98,100</sup> is that the oxygen vacancy introduced during reduction initially traps two electrons to form neutral F-centers, which are responsible for the 500 nm absorption peak. Upon optical bleaching, the F-centers release one electron to become  $\text{F}^+$ -centers. The unpaired electron in the  $\text{F}^+$ -centers interacts through hyperfine coupling with adjacent Nb ions neighboring the oxygen vacancy, manifesting as a 10-line EPR spectrum. Although other intrinsic defects such as lithium and niobium vacancies may exist, they have not yet been experimentally confirmed through spectroscopic characterization.

**3.2.2. EPR spectrum analysis of extrinsic defects.** The deliberate introduction of extrinsic defects by dopants during crystal growth serves as a crucial strategy for tailoring the properties of materials. Thus, to elucidate the impact of doping elements on the physical properties of crystalline materials, a





**Fig. 6** (a) Two-photon-induced ESR at higher microwave power.<sup>91</sup> Reproduced from ref. 91 with permission from AIP Publishing, copyright 1978. (b) Angular dependence of experimental resonance fields with fitted positions for metastable  $\text{Nb}^{4+}$ ,  $T \approx 20$  K,  $\nu \approx 9$  GHz.<sup>94</sup> Reproduced from ref. 94 with permission from Taylor & Francis, copyright 2011. (c) EPR spectrum of  $\text{Nb}^{4+}$ -type centers in undoped (black) and 6 mol% Mg-doped (red) congruent  $\text{LiNbO}_3$  crystals after vacuum reduction for the magnetic field parallel to the crystal  $c$  axis. (d) Defect structure of  $\text{Nb}_{\text{Li}}^{4+}$  center in  $\text{LiNbO}_3$ .<sup>96</sup> Reproduced from ref. 96 with permission from Elsevier, copyright 2008.

comprehensive understanding of their lattice occupancy behavior and chemical states is essential. The paramagnetic nature of most dopant species in the  $\text{LiNbO}_3$  crystal makes EPR spectroscopy particularly advantageous for analyzing these extrinsic defects. Among the various dopants, transition metal ions and rare earth ions represent the primary extrinsic species in  $\text{LiNbO}_3$  crystals, consequently receiving the most extensive attention in EPR-based defect studies.

#### (1) Transition metal ions

Transition metal ions are widely used to enhance the photorefractive ability of  $\text{LiNbO}_3$  crystals. Because their unstable valence states can form defect energy levels in the energy band of  $\text{LiNbO}_3$  crystals, they serve as photorefractive centers. The typical transition metal ions used are Fe, Cu, and Mn, with Fe being the most extensively studied due to its superior ability to improve the photorefractive performance.

For example, five different lattice sites of Fe have been identified in  $\text{LiNbO}_3$  crystals, namely  $\text{Fe}_1$ ,  $\text{Fe}_2$ ,  $\text{Fe}_3$ ,  $\text{Fe}_4$ , and  $\text{Fe}_5$ , respectively. The  $\text{Fe}_1$  center with  $C_3$  symmetry in Fe-doped CLN crystals has been found, and several studies<sup>103–106</sup> have consistently reported a zero-field splitting (ZFS) parameter of  $b_2^0 \approx 0.1680 \text{ cm}^{-1}$  (Fig. 7a). Zhao<sup>107</sup> calculated the ZFS parameters  $D$  and  $a_F$  of  $\text{Fe}^{3+}$  at the Li ( $D = 0.860 \text{ cm}^{-1}$ ,  $a_F = 0.03 \text{ cm}^{-1}$ ) and Nb ( $D = 1.054 \text{ cm}^{-1}$ ,  $a_F = 0.114 \text{ cm}^{-1}$ ) sites in  $\text{Fe}^{3+}:\text{LiNbO}_3$ . The ZFS parameters for  $\text{Fe}^{3+}$  at Nb sites closely

match experimental results<sup>108</sup> ( $D = 1.106 \text{ cm}^{-1}$ ,  $a_F = 0.128 \text{ cm}^{-1}$ ), indicating that the impurity ion  $\text{Fe}^{3+}$  substitutes  $\text{Nb}^{5+}$ , rather than  $\text{Li}^+$  in the  $\text{LiNbO}_3$  lattice.

When the doping concentration of Mg exceeds the threshold, the  $\text{Fe}_2$  center<sup>102</sup> emerges in Fe, Mg co-doped CLN crystals (Fig. 7b). The angle dependence of the EPR spectra indicates that this center exhibits low symmetry.<sup>109</sup> Boker<sup>102</sup> proposed that  $\text{Fe}^{3+}$  preferentially occupies the  $\text{Nb}^{5+}$  sites, forming stable charge compensation structures ( $\text{Mg}_{\text{Li}}^+ - \text{Fe}_{\text{Nb}}^{2-}$ ). The reason for this is that the smaller ZFS parameter  $D$  corresponds to the geometric position of  $\text{Fe}^{3+}$  occupying the Nb sites, making this configuration energetically favorable in heavily doped CLN crystals. The  $\text{Fe}_3$  (Fig. 7c) and  $\text{Fe}_5$  (Fig. 7e) centers are distinguished in stoichiometric lithium niobate crystals (grown with  $\text{K}_2\text{O}$  as the flux, denoted as SLN-K) doped with 0.45 mol% Mg and 0.01 mol% Fe.<sup>101,110</sup> The  $\text{Fe}_4$  center is observed in the SLN-K crystal with 0.001% Fe (Fig. 7d). Due to the smaller crystal field parameter  $b_2^0$ ,  $\text{Fe}_3$ ,  $\text{Fe}_4$ , and  $\text{Fe}_5$  are attributed to Fe occupying the Nb sites. The variation in EPR spectra for Fe centers at Nb sites is closely linked to the concentration of intrinsic and extrinsic defects in the crystal lattice. In Mg:CLN crystals, their charge compensation structure is completed by  $2\text{Mg}_{\text{Li}}^+ - \text{Fe}_{\text{Nb}}^{2-}$ , while in SLN-K crystals, charge compensation is achieved through protons or additional  $\text{Li}^+$ .

Mn:Fe:LN crystals with deep and shallow energy levels can utilize dual color storage to exhibit non-volatile storage properties.





Fig. 7 EPR  $\text{Fe}^{3+}$  spectra of (a) 0.02% Fe-doped LN crystal.<sup>101</sup> Reproduced from ref. 101 with permission from Taylor & Francis, copyright 2011. (b) 6 mol% Mg, Fe-doped CLN crystal.<sup>102</sup> Reproduced from ref. 102 with permission from IOP Publishing, copyright 1990. (c and e) 0.45% Mg and 0.01% Fe co-doped LN-K crystal.<sup>101</sup> Reproduced from ref. 101 with permission from Taylor & Francis, copyright 2011. (d) 0.001% Fe-doped LN-K crystal.<sup>101</sup> Reproduced from ref. 101 with permission from Taylor & Francis, copyright 2011.

Understanding the substitution mechanism of  $\text{Mn}^{2+}$  in  $\text{LiNbO}_3$  crystals is essential for optimizing their performance. The larger hyperfine splitting constant of  $\text{Mn}^{2+}$  suggests that the Mn–O bond tends to be highly ionic.<sup>111</sup> Peterson<sup>112</sup> proposed that doped ions that do not exhibit a tendency to form covalent bonds, but preferentially substitute at the  $\text{Li}^+$  sites. This conclusion is further supported by ENDOR studies,<sup>113</sup> confirming the Li site as the dominant occupancy site for Mn. However, the zero-field splitting parameter  $b_2^0$  of  $\text{Mn}^{2+}$  decreases with an increase in temperature.<sup>114–116</sup> This trend suggests a reduction in octahedral distortion, consistent with  $\text{Mn}^{2+}$  shifting toward the center of the Nb– $\text{O}_6$  octahedron. This behavior suggests that  $\text{Mn}^{2+}$  substitutes at the Nb<sup>5+</sup> site rather than the Li<sup>+</sup> site, contradicting earlier interpretations based on hyperfine splitting and ENDOR studies.

The above-mentioned results indicate that there is still controversy over the occupancy of Mn in  $\text{LiNbO}_3$  crystals. To resolve this inconsistency, more comprehensive EPR experiments should be designed and performed to unambiguously determine the position of  $\text{Mn}^{2+}$  in the lattice. Some other transition metal ions, such as  $\text{Cr}^{3+}$ ,  $\text{Ti}^{3+}$ ,  $\text{Ni}^{2+}$ , and  $\text{Co}^{2+}$ , in  $\text{LiNbO}_3$  crystals have also been studied using EPR spectroscopy technology.<sup>117–120</sup>

## (2) Rare earth ions

Rare earth (RE) ions are incorporated into  $\text{LiNbO}_3$  crystals as optically active centers, enabling their widespread use in solid-state lasers,<sup>121</sup> optical amplifiers, and wavelength converters. The spectral properties of these dopants are critically dependent on their local crystal field environment, which is closely related to the site location of the doped ions. RE ions in  $\text{LiNbO}_3$  crystals can locate at four cation sites, *i.e.*, three octahedral sites (Li<sup>+</sup> site, Nb<sup>5+</sup> site and a vacant octahedron) or an interstitial

tetrahedral site. However, the actual occupancy situation is much more complex. Spectroscopic studies have shown that even if rare earth ions occupy the same lattice sites in  $\text{LiNbO}_3$  crystals, they exhibit different spectral properties due to being surrounded by different lattice environments. The lanthanide ions with unpaired electrons located in their 4f orbital are usually used in  $\text{LiNbO}_3$  crystals. Emission spectroscopy<sup>21</sup> and EPR spectroscopy<sup>122</sup> have identified multiple non-equivalent centers with different symmetries for these ions, suggesting that the actual incorporation mechanism involves a dynamic interplay between dopant ions and the defect structure of the host lattice.

$\text{Nd}^{3+}$  defect centers ( $g_{\parallel} = 1.42$  and  $g_{\perp} = 2.94$ ) with  $C_3$  symmetry in CLN crystals have been found.<sup>125,126</sup> However, the EPR spectrum of  $\text{Nd}^{3+}$  in CLN crystals displays exceptionally broad lines, making it difficult to resolve contributions from different defect centers or isotopic effects. This explains that why the hyperfine structure was not studied in ref. 110 and 111. The EPR spectrum lines of Nd in NSLN crystals have higher spectral resolution (Fig. 8a). Therefore, eight non-equivalent  $\text{Nd}^{3+}$  centers were identified in NSLN crystals and the  $g$ -tensor values of all the centers were determined. Although all eight centers are the Nd-occupying Li sites,<sup>123</sup> they exhibit different symmetries.  $\text{Nd}_1$  and  $\text{Nd}_8$  exhibit  $C_3$  symmetry, as evidenced by their angle-independent EPR spectra in the  $xy$ -plane (Fig. 8b and c), respectively. The symmetry of the other six defect centers is relatively low, and the reason for the different symmetries is that the defect positions used for charge compensation are different (Table 2).

Earlier studies<sup>126</sup> suggest that the  $\text{Er}^{3+}$  centers with  $g_{\parallel} = 15.1$ – $15.4$  and  $g_{\perp} = 2.1$  in the CLN crystal have  $C_3$  symmetry (Fig. 9a). However, the angular dependence of the EPR spectrum in the





**Fig. 8** (a) EPR spectra of  $\text{Nd}^{3+}$  at  $B||z$  in congruent and nearly stoichiometric  $\text{LiNbO}_3$  crystals doped with 0.06 wt%  $\text{Nd}_2\text{O}_3$  in the melt (thick red line:  $\nu = 9.5$  GHz and  $T = 10$  K and thin blue line:  $\nu = 9.8$  GHz and  $T = 19$  K), as well as in a congruent crystal doped with 1% of Nd (medium green line: X-band,  $T = 20$  K).<sup>123</sup> Reproduced from ref. 123 with permission from AIP Publishing, copyright 2015. (b) Angular dependence of the EPR spectra in nearly stoichiometric  $\text{LN:Nd}^{3+}$ ,  $T = 19$  K,  $\nu = 9.813$  GHz.<sup>124</sup> Reproduced from ref. 124 with permission from John Wiley and Sons, copyright 2006. (c) Angular dependence of the EPR spectra in  $\text{NSLN:Nd}^{3+}$ ,  $T = 19$  K,  $\nu = 9.813$  GHz.<sup>124</sup> Reproduced from ref. 124 with permission from John Wiley and Sons, copyright 2006.

**Table 2** Cartesian components of  $g$ -tensors for  $\text{Nd}^{3+}$  centers in crystallographic axes of  $\text{LiNbO}_3$ .<sup>123</sup> Reproduced from ref. 123 with permission from AIP Publishing, copyright 2015

| Center        | $g_{xx}$ | $g_{yy}$ | $g_{zz}$ | $g_{zy}$ | $\pm g_{zx}$ | $\pm g_{xy}$ |
|---------------|----------|----------|----------|----------|--------------|--------------|
| $\text{Nd}_1$ | 2.995    | 2.995    | 1.448    | 0        | 0            | 0            |
| $\text{Nd}_2$ | 3.090    | 2.920    | 1.345    | -0.040   | 0.015        | 0.240        |
| $\text{Nd}_3$ | 3.277    | 2.750    | 1.419    | 0.024    | 0.109        | 0.030        |
| $\text{Nd}_4$ | 3.430    | 2.700    | 1.421    | 0.035    | 0.100        | 0.220        |
| $\text{Nd}_5$ | 3.43     | 2.60     | 1.43     | -0.13    | 0.18         | 0.20         |
| $\text{Nd}_6$ | 2.915    | 3.06     | 1.454    | 0.008    | 0.043        | 0.025        |
| $\text{Nd}_7$ | 3.14     | 3.04     | 1.488    | 0.044    | 0.062        | 0.030        |
| $\text{Nd}_8$ | 2.970    | 2.970    | 1.563    | 0        | 0            | 0            |

$xy$ -plane (Fig. 9b) confirms that the  $\text{Er}^{3+}$  center ( $g_{xx} = 0.546 \pm 0.110$ ,  $g_{yy} = 1.356 \pm 0.024$ , and  $g_{zz} = 15.093 \pm 0.074$ ) in the CLN crystal has  $C_1$  symmetry.<sup>127–129</sup> The relatively large anisotropy of the  $g$ -factor indicates that the  $\text{Er}^{3+}$  defect center may be located in the distorted Li–O octahedron, *i.e.*  $\text{Er}^{3+}$  occupies the Li site. Th. Nolte<sup>130</sup> proposed that this symmetry reduction ( $C_3 \rightarrow C_1$ ) arises from the random distributions of the charge compensation structure  $\text{Er}^{3+}\text{-V}_{\text{Li}}$ , as illustrated in Fig. 9c. A new  $\text{Er}^{3+}$  defect center with  $g_{\parallel} = 4.26 \pm 0.05$  and  $g_{\perp} = 7.8 \pm 0.1$  was identified in Mg, Er:CLN crystals. The mean  $g$  value,  $(g_{\parallel} + 2g_{\perp})/3 = 6.6$ , is characteristic of the  $\text{Er}^{3+}$  center and closely matches that of the previously reported center.<sup>126</sup> The relatively small  $g$ -tensor anisotropy in this case suggests that the  $\text{Er}^{3+}$  ions are located at the Nb site compare to the previous one.

The tremendous narrowing of EPR spectrum in Yb (0.04 wt%):NSLN crystal (Fig. 10a) compared to Yb:CLN crystal, enabled the resolution of nine non-equivalent  $\text{Yb}^{3+}$  centers.<sup>132</sup> Among them, the spectral features of the  $\text{Yb}_1$ ,  $\text{Yb}_6$ , and  $\text{Yb}_9$  centers remained invariant under rotation of the magnetic field within the  $xy$ -plane, confirming their  $C_3$  symmetry, while the other centers exhibited lower  $C_1$  symmetry. The  $\text{Yb}_1$  center with  $g_{\perp} = 2.706 \pm 0.005$  and  $g_{\parallel} = 4.46 \pm 0.01$  closely resembles the previously reported  $\text{Yb}^{3+}$  center in CLN crystals.<sup>133</sup> The ENDOR

experimental spectrum<sup>132</sup> (Fig. 10b) reveals the hyperfine interaction between the unpaired electrons of  $\text{Yb}_1$  and Nb nuclei, directly indicating that Nb is the nearest neighbor nuclei (Fig. 10c). Therefore, it is reasonable to conclude that  $\text{Yb}_1$  is the  $\text{Yb}^{3+}$  ion substituting for  $\text{Li}^+$ . Due to the similarity between the characteristics of the  $\text{Yb}_2$ ,  $\text{Yb}_3$ ,  $\text{Yb}_4$ ,  $\text{Yb}_7$ , and  $\text{Yb}_8$  centers (Table 3) and the  $\text{Yb}_1$  center, Malovichko<sup>90</sup> proposed that all these defect centers can be attributed to the substitution of  $\text{Li}^+$  by  $\text{Yb}^{3+}$ . This change in symmetry may be caused by the different configurations of Li vacancies around  $\text{Yb}^{3+}$  or the different positions of  $\text{Yb}^{3+}$  in the lattice.

## 4. Summary and prospective

In summary, EPR spectroscopy stands out as a powerful tool for the characterization of defects in  $\text{LiNbO}_3$  crystals, providing unique insights into the formation and local structure of point defects. Through the comprehensive analysis of EPR spectra and determination of Hamiltonian parameters, this technology enables the precise identification of defect types, quantification of defect concentrations, localization of defect sites, and characterization of structural modifications in the surrounding environment. The structural information derived from Zeeman interactions and zero-field splitting parameters, combined with the analysis of quadrupole interactions and hyperfine couplings between impurity electrons and their host/nuclear environments, provides a robust foundation for structural modeling. These critical insights are crucial to explore the impact of defects on the properties of crystals and how to precisely control defects to improve the performance of crystal devices.

Over recent decades, EPR spectroscopy has undergone remarkable progress in characterizing point defects in  $\text{LiNbO}_3$  crystals. The evolution of high-sensitivity EPR systems, combined with improved control over crystal stoichiometry and the





Fig. 9 (a) EPR spectrum of  $\text{Er}^{3+}$  in  $\text{LiNbO}_3$ , measured at  $T = 5$  K and  $\nu_{\text{EPR}} = 25$  GHz.<sup>130</sup> Reproduced from ref. 130 with permission from Elsevier, copyright 1997. (b) Angular dependence of the EPR spectra of the  $\text{LN}:\text{Er}^{3+}$  crystal measured at 8 K in all three perpendicular planes.<sup>128</sup> Reproduced from ref. 128 with permission from John Wiley and Sons, copyright 2008. (c) Possible models of low-symmetry  $\text{Er}^{3+}$  centers.<sup>131</sup> Reproduced from ref. 131 with permission from Materials Research Society, copyright 2009.



Fig. 10 (a) Assignment of lines of different nonequivalent centers and hyperfine structures of  $\text{Yb}^{3+}$ .<sup>131</sup> Reproduced from ref. 131 with permission from Materials Research Society, copyright 2009. (b) ENDOR spectrum for the  $\text{Yb}_1$  center in  $\text{SLN}:\text{Yb}^{3+}$  at  $B||z$ .<sup>132</sup> Reproduced from ref. 132 with permission from John Wiley and Sons, copyright 2008. (c) Model of the  $\text{Yb}_1$  center.<sup>132</sup> Reproduced from ref. 132 with permission from John Wiley and Sons, copyright 2008.

integration of advanced characterization tools, is expected to provide unprecedented new insights into defect structures and their interactions with the host lattice. These developments are paving the way for the establishment of more sophisticated defect models, thereby establishing a robust foundation for the growth of high-quality crystals and the fabrication of high-performance devices. Looking ahead, future research may focus on the following aspects.

#### 4.1. Anti-site defects need to be clarified

As the most important intrinsic defects in  $\text{LiNbO}_3$  crystals, there are still doubts about the concentration, structure, and charge compensation mechanism of  $\text{Nb}_{\text{Li}}$  defects. Although some studies suggest that the 10-line EPR characteristic spectrum produced by xenon lamp irradiation of annealed CLN crystals originate from  $\text{Nb}_{\text{Li}}$ , there is still a lack of direct experimental evidence. Meanwhile, due to the lack of detailed



**Table 3** Cartesian components of  $g$ -tensors for centers in  $\text{LiNbO}_3:\text{Yb}^{3+}$ . The sign  $\pm$  reflects the presence of mirror conjugated centers with  $g_{xy}(L) = -g_{xy}(R)$ ,  $g_{zx}(L) = -g_{zx}(R)$ .<sup>132</sup> Reproduced from ref. 132 with permission from John Wiley and Sons, copyright 2008

| Center        | $g_{xx}$ | $g_{yy}$ | $g_{zz}$ | $g_{zy}$ | $\pm g_{zx}$ | $\pm g_{xy}$ |
|---------------|----------|----------|----------|----------|--------------|--------------|
| $\text{Yb}_1$ | 2.706    | 2.706    | 4.46     | —        | —            | —            |
| $\text{Yb}_2$ | 2.84     | 2.48     | 4.56     | 0.22     | 0.45         | 0.02         |
| $\text{Yb}_3$ | 2.63     | 2.67     | 4.35     | -0.15    | 0.10         | 0.17         |
| $\text{Yb}_4$ | 2.65     | 2.44     | 4.56     | 0.21     | 0.38         | 0.08         |
| $\text{Yb}_6$ | 2.68     | 2.68     | 4.44     | —        | —            | —            |
| $\text{Yb}_7$ | 2.64     | 2.44     | 4.56     | 0.21     | 0.39         | 0.024        |
| $\text{Yb}_8$ | 2.71     | 2.765    | 4.36     | 0.11     | 0.14         | -0.07        |

information about the anti-site defect structure, it is impossible to construct an appropriate intrinsic defect model; therefore, it is essential to conduct more systematic and in-depth research. Firstly, anti-site Nb exhibits a positive charge state due to charge imbalance and has a stronger attraction to free electrons compared to Nb in the normal lattice position. It is necessary to find a suitable testing temperature that allows electrons at the  $\text{Nb}_{\text{Nb}}$  site to escape, while electrons at the  $\text{Nb}_{\text{Li}}$  site remain bound. At this point,  $\text{Nb}_{\text{Nb}}^{5+}$  exhibits an EPR-silent state, and the characteristic spectrum of  $\text{Nb}^{4+}$  belongs to  $\text{Nb}_{\text{Li}}^{4+}$ . Secondly,  $\text{LiNbO}_3$  crystals with different compositions were subjected to the same treatment and their EPR spectra were detected. It can be expected that with an increase in Li/Nb, the characteristic spectral intensity of  $\text{Nb}_{\text{Li}}^{4+}$  decreases and that of  $\text{Nb}_{\text{Nb}}^{5+}$  increases, which will become favorable evidence for the existence of  $\text{Nb}_{\text{Li}}$  defects.

In addition, the thermal stability and dynamic evolution of defects were studied by first-principal theory calculation. However, the theoretical analysis could not draw a clear map of the defect evolution. The thermal activation energy of different defects varies, and at a specific annealing temperature, defects undergo migration-recombination-annihilation, resulting in a decrease in EPR intensity. By drawing the curve of EPR signal intensity and annealing temperature change through an isothermal annealing experiment, different types of point defects can be identified, their migration energy can be measured, and their interactions and evolution paths can be studied.

#### 4.2. In depth analysis of high-resolution EPR spectrum-assisted point defects in NSLN crystals

Although the EPR signals of  $\text{Nb}^{4+}$  have been detected in CLN crystals, there is currently a lack of sufficient evidence to determine whether the signals originate from  $\text{Nb}_{\text{Li}}$  or  $\text{Nb}_{\text{Nb}}$ . Moreover, there are differences in the Hamiltonian parameters due to spectral broadening and insufficient resolution. When the angle between the microwave direction and the crystallographic  $c$ -axis is too large, the intensity of the split signal will decrease, thus being masked by noise. As a result, clear spectral signals can only be observed on the axis. The same problem also arises in the analysis process of doped ion defect centers. It is difficult to comprehensively detect multiple non-equivalent defect centers of doped ions in the crystal and construct suitable defect models. EPR spectrum simulations have indicated that the

linewidth, asymmetry, and intensity of forbidden transitions in the spectrum are closely associated with inherent defects in non-stoichiometric crystals. This is confirmed by the EPR spectrum of SLN-K crystals, which exhibits narrower and more symmetrical features compared to that of CLN crystals.

Moreover, many new EPR signals have been reported in NSLN crystals doped with lanthanide ions. The results are consistent with multiple non-equivalent defect centers shown in the emission spectra, providing theoretical guidance for the occupancy mechanism of doped ions. Doping a small amount of elements in NSLN crystals can significantly improve certain physical properties, such as the improvement of the optical damage resistance of 1 mol% Mg-doped NSLN crystals,<sup>134</sup> which is similar to that of 4.6 mol% Mg-doped CLN crystals. This low concentration doping helps to explore the mechanism of ion doping and achieve precise control of functional crystals. In addition, NSLN crystals may serve as an ideal system for verifying first principles calculations due to their low defect density and perfect lattice structure. Therefore, using EPR spectrum to analyze the defect structure of NSLN crystals has important research value.

#### 4.3. Advancing high-temperature and time-resolved EPR with AI integration

At present, most EPR spectroscopy research is focused on low-temperature conditions, and future research can be devoted to developing high-temperature EPR spectroscopy for defect analysis under conditions closer to practical applications. This technique will help to understand the defect behavior and corresponding physical property changes in materials at high temperatures, providing guidance for the preparation of high-temperature piezoelectric/electro-optic devices using LN crystals. Time-resolved EPR combined with photoexcitation can directly track the carrier trapping dynamics (hole/electron capture rates of defects), photo-induced defect kinetics (formation/annihilation paths of oxygen vacancies under UV irradiation) and spin-dependent charge transfer (inter-defect interactions governing photorefractive response). These results will provide important information for understanding how materials respond to environmental changes in practical applications. These insights are vital for optimizing the carrier lifetimes in electro-optic modulators and suppressing optical damage in high-power lasers. The significant advancement of AI spectroscopy can help researchers process large amounts of complex data more quickly and efficiently, combining machine learning and data science technology to automatically identify and classify defect features using EPR experimental data. This will improve the efficiency and accuracy of data analysis and promote the intelligent development of defect research.

### Author contributions

Liu H and Sang Y provided the overall concept for this review and designed the review framework; Qin H wrote the original draft and revised and edited the manuscript; all authors contributed to the general discussion.



## Conflicts of interest

There are no conflicts to declare.

## Data availability

No primary research results, software or code has been included and no new data were generated or analyzed as part of this review.

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