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REVIEW - CONDENSED MATTER

Recent studies on the light-induced phenomena in condensed matter systems and related numerical tools

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Abstract
Recent studies of light–matter interaction reveal that light can significantly manipulate materials' properties. For example, recent experiments demonstrated light-induced phenomena such as light-enhanced superconductivity, ferroelectricity, topological phase transition, and light-driven quantum transport in condensed matter systems. With these experimental observations, various theoretical studies tried to provide possible microscopic mechanisms such as nonlinear phonon interaction, displacive excitation of coherent phonon, and Floquet engineering. These comprehensive experimental and theoretical studies suggested the possibility of light-controlled devices as an application. This review summarizes recently reported light-induced phenomena and related microscopic mechanisms. In addition, the numerical tools for the simulation of light-induced dynamics are introduced.

Keywords Light-matter interaction · Superconductivity · Ferroelectricity · Floquet engineering

1 Introduction

Since Albert Einstein's interpretation of the photoelectric effect [1], the light–matter interaction has been an important research topic in quantum physics, optics, and condensed matter physics in the last century [2–4]. Especially, various information of materials could be extracted from the response against the light on the condensed matter system. For example, the photoelectric effect reveals a work function of the solid system, the energy difference between filled states and vacuum level, through a scattering between electron and photon [1]. The optical conductivity and dielectric response provide the electric properties in the solid, and the X-ray diffraction gives a geometrical structure of the system [5]. In addition, the angle-resolved photoemission spectroscopy makes it possible to investigate the band dispersion of electronic structure [6]. These experimental observations indicate that applying light to the material can provide diverse information about the systems.

Recent studies of the interaction between strong light and condensed matter systems have attracted attention by showing previously obscured phenomena. For example, the light-enhanced superconductivity is experimentally observed in cuprate, alkali-doped C_{60}, and molecular solids [7–9]. Comprehensive experiments and theoretical works reveal that light can induce the ferroelectric transition from the quantum paraelectric phase in $SrTiO_3$ [10–13]. The light-induced topological phase transition is also demonstrated in layered WTe_2 and $ZrTe_5$ [14, 15]. In addition, light-controlled magnetism is observed in piezo-magnetic material and transition metal-dichalcogenides [16, 17]. These reports suggest that the light can be a suitable controller tuning a material's property.

This review summarizes recent studies of light-induced phenomena and related microscopic mechanism in solid-state systems, as shown in Fig. 1. First, the recent experimental and theoretical reports on the light–matter interactions are introduced, such as light-enhanced superconductivity, light-induced ferroelectricity, light-induced magnetism, and light-induced topological phase transition. Second, the possible microscopic mechanisms of the light-induced phenomena are suggested, such as nonlinear phonon interaction, displacive excitation of coherent phonon, and excitation of electronic structure as summarized in Tables 1 and 2. Third,

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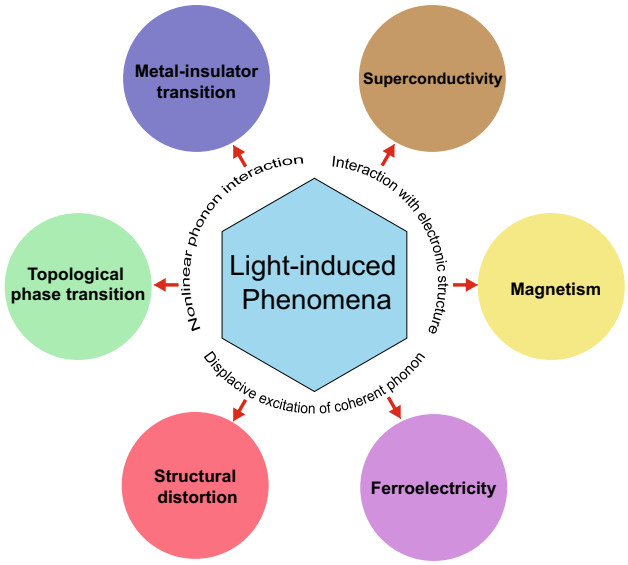

Fig. 1 Schematic diagram of light-induced phenomena and related microscopic mechanism

useful numerical tools for investigating the light–matter interaction are provided.

2 Recent studies of light-induced phenomena

The responses of material against applied light could differ depending on the field strength of light or intrinsic properties of a material. For example, light with weak field strength leads to a perturbative interaction, and unusually it gives information about materials such as dielectric function and optical conductivity. With the recent development of the state-of-art laser technique, on the other hand, it is possible to generate a specific frequency laser pulse with high intensity that can drive dynamics in the non-perturbative region. This non-perturbative interaction between light and matter is expected to show unprecedented phenomena. Recent studies report that strong light can induce the structural phase transition and substantially modify the material properties of material [8, 14, 22]. In this section, recent light–matter interaction reports are summarized.

2.1 Light-enhanced superconductivity and light-induced electron–electron pairing

Ever since the first observation by Ohnes, superconductivity has attracted attention by showing unprecedented physics and a possibility of its application. Such MRI, magnetic levitation, and other versatile applications are already exploited or suggested these days. On the other hand, the low-temperature condition for its operation is a significant bottleneck for the application of superconductor [23, 24]. Following the basic BCS theory, however, the upper boundary of the critical temperature of phonon-mediated superconductivity is less than 40 K [25]. For this reason, the material that shows unconventional superconductivity with high temperature is focused. Various materials, including Curate and ion-based superconductors, have been found in the last few decades, but their critical temperature is still lower than room temperature [23, 26]. Even though the general theory is required to understand and predict the high-temperature superconductor, it has not been developed for these unconventional superconductors. In this aspect, various experimental observations are required to find the clue for the high-temperature superconductor.

Recent studies of light–matter interaction reported exciting phenomena in the superconductivity [7, 8]. When a light is applied to the superconductor at a given temperature over its critical temperature in the ground state, the superconducting state is still observed in the measurement of optical conductivity. In the alkali doped C_{60}, for instance, the superconductivity state at 100 K is sustained by applying the THz field pulse [8]. The non-equilibrium state of phonon excited by nonlinear phonon interaction is expected to enhance the paring of electrons and the critical temperature in this light-enhanced superconductivity. Recently, the light-enhanced superconductivity in the molecular solid structure (kappa

Table 2 Microscopic mechanism for light-induced ferroelectricity and magnetism

Microscopic mechanism	Ferroelectricity	Magnetism
Nonlinear phonon interaction	$SrTiO_3$ [10–13]	$ErFeO_3$ [21],CoF_2 [16]
Floquet Engineering		MoS_2 [17]

Table 1 Microscopic mechanism for light-induced superconductivity and topological phase transition

Microscopic mechanism	Superconductivity	Topological phase transition
Nonlinear phonon interaction	$LESCO_{1/8}$ [7], K_3C_{60} [8]	
Displacive excitation of coherent phonon		WTe_2 [14], $ZrTe_5$ [15]
Floquet Engineering		Graphene [18], Dirac [19]
		Quantum well [20]

salt) and Cavity-enhanced superconductivity through the polaritonic condition are also reported [9, 27].

With these experimental observations, several theoretical suggestions exist on this light-induced phenomenon [27–30]. For example, it is suggested that the dynamical squeezing of the density of state near the Fermi level can enhance the paring between electrons [28]. It is reported that light could enhance the electron–phonon coefficients, which leads to an increased critical temperature of superconductivity, through the nonlinear phonon interaction [29]. On the other hand, the direct light-mediated electron paring is also investigated [27, 30]. These theoretical studies provide the possible microscopic mechanism of light-induced superconductivity and paring of electrons.

2.2 Light-induced and light-controlled ferroelectricity

Two recent experiments reveal that the light can induce the ferroelectricity from the paraelectric $SrTiO_3$ [10, 11]. One experiment demonstrated that the near-infra-red laser pulse leads the long-lived ferroelectricity by light-driven strain [10]. Especially, it is observed that the repeat applied laser during the few minutes with nanosecond duration gives the strained domains with few micrometer sizes that show non-zero electric polarization in an hour. The other experiment shows that the single-cycle terahertz (THz) field pulse induces the transient ferroelectricity [11]. The following theoretical study reveals that this THz field-induced ferroelectricity originates from the excitation between ground and first excited lattice wavefunctions of ferroelectric soft mode in quantum paraelectric state [13]. On the other hand, it is also suggested that optical-cavity can modify the quantum paraelectric ground state into a ferroelectric ground state by considering the vacuum fluctuation of photon [12]. These studies reveal that the light can lead to ferroelectricity from the paraelectric $SrTiO_3$.

Several theoretical studies also introduced a light-controlled ferroelectric polarization [22, 31]. It is suggested that the THz field pulse can switch the electric polarization of the ferroelectric $PbTiO_3$ [31]. Through the molecular dynamics simulation, they revealed that the train of THz field pulse can shift the electric polarization. Notably, the train of THz field pulse makes it possible to over the barrier of double-well potential for the ferroelectricity with heat dissipation. It is also demonstrated that light can enhance the electric polarization in ferroelectric monolayer SnTe [22]. When the light excites the out-plane IR phonon mode, the nonlinear phonon interaction leads to the lattice distortion along with the in-plane IR phonon mode that is strongly entangled with electric polarization. This property indicates that light can enhance the electronic polarization of ferroelectric monolayer SnTe via the nonlinear phonon interaction between IR phonon modes.

2.3 Light-induced magnetism

Control of magnetism is an important topic in the aspect of saving information in solid. We read the information written in solid by the giant magnetoresistance effect that gives high electronic resistivity depending on the alignment of magnetic momentum in the sandwiched layer structure [32, 33], and we can write the information by switching the magnetic momentum of the system with a strong magnetic field. In addition, light-controlled magnetism has been focused on understanding the ultrafast manipulation of magnetism in the material. Recent light–matter interaction studies demonstrated a possibility of controlling the magnetism through the light [16, 21]. A recent experiment demonstrated that the mid-infrared pulse could induce an effective magnetic field in the antiferromagnetic insulator $ErFeO_3$ [21]. The light-controlled magnetic order is also experimentally observed in piezomagnetic CoF_2 [16]. On the other hand, a theoretical study suggested light-induced Floquet-spin magnetism in the diamagnetic transition metal dichalcogenide system [17]. Light-induced magnetism is expected to be exploited for a new memory device controlled by light.

2.4 Light-induced topological phase transition

The topology of the condensed matter has attracted attention by showing the unique properties such as topologically protected edge and surface states, quantized spin Hall effect, and quantized anomalous Hall effect [34]. Recent light–matter studies reveal that the topological phase transition can be achieved by applying the light to the solid system [14, 15]. For example, it is experimentally demonstrated that THz field pulse leads to the topological phase transition between Weyl semimetal T_d-WTe_2 and trivial semimetal 1T-WTe_2 [14]. In this case, the excited electronic structure by applied THz pulse induces the shear strain in the WTe_2 layers, leading to the geometrical transition between T_d and 1T phases. Bulk $ZrTe_5$, a layered structure, shows light-induced topological phase transition between strong and weak topological insulators [15]. Similar to the case of WTe_2, the excited electronic structure of $ZrTe_5$ by light derives a geometrical distortion by the nonlinear phonon interaction that induces the topological phase transition. The light-induced Hall current in graphene is also observed by light-driven topological states [18]. These studies suggest that light can be an excellent controller for manipulating a topological phase of material.

3 Microscopic mechanism of light-induced phenomena

There are various microscopic mechanisms in these light-induced phenomena. Because material consists of electrons and ions, we can consider three different interactions with light: light–electron, light–phonon, and light–phonon–electron interactions. First, the direct interaction between light electrons can excite the electronic structure or form Floquet band structure [19, 20]. Second, resonant light can excite IR-active phonon modes that lead to the structural phase transition through the nonlinear phonon interaction [29, 35]. Finally, a light-induced modified electronic structure can excite the phonon mode by displacive excitation of coherent phonon mechanism [36]. This section introduces the microscopic mechanism that derives fascinating light-induced phenomena.

3.1 Nonlinear phonon interaction

Light-driven structural phase transition can give a change of properties of a material. Among the microscopic mechanisms of light-driven structural phase transition, nonlinear phonon interaction is an effective mechanism. If arbitrary phonon modes are excited by light, the effect of light would be like simple thermal excitation. In simple thermal excitation of phonon, a harmonic approximation can be applied to describe phonon dynamics in materials. On the other hand, if a specific phonon is highly excited by a resonant laser, the effects of anharmonicity and nonlinear interaction with other phonons become significant. In monolayer SnTe, for example, there is nonlinear phonon interaction ($Q_{IR}^{out\,2}Q_{IR}^{in}$) between out-plane IR ($Q_{IR}^{out}$) and in-plane IR phonon (Q_{IR}^{in}) in the monolayer SnTe [22]. If we apply a resonant laser pump on out-plane IR mode, the oscillation of out-plane IR mode is out-of-range of harmonic approximation, and its nonlinear phonon interaction is significant. Through the $Q_{IR}^{out\,2}Q_{IR}^{in}$ coupling, the lattice distortion along with Q_{IR}^{in} could be achieved. Notably, this coupling shifts the potential energy surface of Q_{IR}^{in} regardless of the sign of Q_{IR}^{out} but depends only on the amplitude of Q_{IR}^{out}. As a result, lights can enhance the electric polarization of monolayer SnTe through the nonlinear phonon interaction. A similar scenario can be applied to the strong topological insulator $ZrTe_5$ [15, 37]. In the $ZrTe_5$, the complex nonlinear phonon interaction between A_g modes induces the lattice distortion along with A_{1g} modes. Once this lattice distortion is derived by a resonant light in $ZrTe_5$, its topological phase transition between strong and weak topological insulating states is experimental demonstrated [38]. These results indicate that light can modify material properties through nonlinear phonon interactions.

Nonlinear phonon interaction also can induce the magnetic polarization and enhances the superconductivity through the light [16]. CoF_2 is a piezomagnetic system showing a phase transition between antiferromagnetic (AFM) and ferromagnetic (FM) orderings under pressure. A recent experiment reveals that the THz field pulse derives ferromagnetism in CoF_2 through the nonlinear phonon interaction [16]. In this case, the nonlinear phonon interaction ($|Q_{IR}||Q_{IR'}|Q_R$) between two IR modes and one Raman mode gives a lattice distortion along with the Raman mode. Interestingly, this light-driven lattice distortion shows a ferromagnetic ordering in the CoF_2. As a result, the light-induced ferromagnetism is achieved in CoF_2. On the other hand, La_2CuO_4 is an antiferromagnetic Mott insulator, and it becomes an unconventional superconductor ($La_{2-x}(Ba/Sr)_xCuO_4$) with atomic substitution. It is experimentally demonstrated that light can induce the superconducting $La_{1.675}Eu_{0.2}Sr_{0.125}CuO_4$($LESCO_{1/8}$) from its trivial phase at ground state [7]. In this case, it is found that the mid-infrared pulse excites in-plane Cu–O stretching mode, which induces structural distortion from the low-temperature geometry. This understanding also reveals that light can enhance the superconducting critical temperature through the nonlinear phonon interaction.

3.2 Excitation of coherent phonon and structural distortion by modified electronic structure

An excited electronic structure by light can induce the structural transition or coherently excited phonon modes. When the applied light modifies the charge density of a material, the ion can feel the modified forces from the electron-ion interactions. This interaction leads to lattice distortion that sometimes could involve a phase transition. For example, the layered system T_d-WTe_2 shows THz-field induced topological phase transition through the excitation of electronic structure [14, 39]. At low temperature, the WTe_2 layer is stacked without the inversion symmetry that is called the T_d phase. At high temperatures, this inversion symmetry is restored by thermal fluctuation with layer sliding, and this structure is known as the $1T$ phase. When the light excites the electronic structure near the Fermi level in T_d-WTe_2, the share mode, which is an alternative layer–layer shifting motion, is excited by modified electron charge density. Through these light–electron and electron-share mode interactions, the light-induced structural phase transition between T_d- and $1T$-WTe_2 gives topological phase transition to trivial semimetal from Weyl semimetal. This light-driven structural distortion through the modified electronic structure is explained as displacive excitation of coherent phonon mechanism [36].

3.3 Direct manipulation on the electronic structure

Light also can induce a modified electronic structure that gives a topological phase or unique transport properties. When we apply light to the metallic system, excitation of carriers is generally expected. On the other hand, the light could be dealt with as a time-periodic driver under the dipole approximation. For example, the continuous oscillating E-field leads to the new steady state of the material. Lindner *et al*. demonstrated that the trivial insulator could be a topological insulator under the continuous oscillating E-field with the higher light frequency rather than band gap [20]. If a time-periodic potential $V = V_0 cos(\omega t)$ interacts with trivial insulating band structure, the bands near the Fermi level could be inverted by hybridization between Floquet replica bands. It is revealed that a trivial insulator under the oscillating field becomes a topological insulator known as Floquet topological insulator. On the other hand, it is theoretically suggested that the graphene under the circularly polarized light can provide the anomalous Hall effect [40]. When the circularly polarized light is applied to the graphene, the unbalanced carrier at K and K' states by time-reversal-symmetry breaking leads to the anomalous Hall effect. One decade later, this light-driven anomalous Hall effect is experimentally demonstrated [18]. From Floquet analysis, the Dirac band structure under the light is expected to become gaped topological Floquet bands. On the other hand, a follow-up theoretical study insists that this effect originates from the anomalous Hall effect with the excited carrier rather than the Berry curvature formed by Floquet engineering [41].

4 Numerical tools for the light–matter interaction

Various numerical tools could be employed to investigate the light–matter interactions introduced in previous sections. The computational level should be decided considering the time scale of dynamics. For example, the dynamics with nonlinear phonon interaction generally need to be investigated with a few pico- or nanoseconds time scales. In this case, the *ab initio* molecular dynamics simulation or classical Newton equation should be considered. To explore the light-induced lattice distortion through the excited electronic structure, the Ehrenfest dynamics, which describes the time-propagation of electronic states and ionic system simultaneously, can be employed, but the time-propagation over the 1 ps is hard to do by its high computation cost. If a many-body effect is essential in the dynamics, such as competition between on-site Coulomb interaction and electron–electron attraction, the time-propagation with exact diagonalization or non-equilibrium Green's function approach should be considered. In this section, the various numerical tools for the light–matter interaction are introduced.

4.1 Density functional theory and *ab initio* molecular dynamics simulation

Density functional theory calculation provides the ground-state total energy (E_{KS}) and Kohn–Sham states ($\psi_{i,\mathbf{k}}$) through the Kohn–Sham equation, which is given as follows:

$$[\frac{(\mathbf{p}+\mathbf{k})^2}{2m} + V_{ion} + V_{Hxc}[\rho]]\psi_{i,\mathbf{k}} = \epsilon_{i,\mathbf{k}}\psi_{i,\mathbf{k}}, \tag{1}$$

when $\mathbf{p}$, $\mathbf{k}$, V_{ion}, and V_{Hxc} are momentum operator, Bloch vector, ionic potential, and Hartree and exchange-correlation potential, respectively. The ground state total energy from the Kohn–Sham equation is achieved by subtracting the double-counting terms:

$$E_{KS} = \sum_{i,\mathbf{k}}^{occ} \epsilon_{i,\mathbf{k}} + E_{xc}[\mathbf{r},\rho] - \int V_{xc}[\mathbf{r},\rho]\rho(\mathbf{r})d\mathbf{r} \tag{2}$$

With the ground, Kohn–Sham states, the linear response calculation provides optical properties of the material such as dielectric function, exciton binding energy, and GW band structure. On the other hand, the *ab initio* molecular dynamics simulation can be employed to find the nonlinear phonon interaction. For example, the dynamics with initially atomic displacement ($\mathbf{Q}_\tau = \mathbf{Q}^0_\tau + \mathbf{u}^{ph}_\tau$) along with specific phonon direction ($\mathbf{u}^{ph}$) makes it possible to find the nonlinear phonon interaction with other modes. With this initial condition, the effect of highly excited phonon mode on the electronic or phonon structure, such as modification of band structure or nonlinear phonon interaction, can be achieved under the *ab initio* molecular dynamics simulation.

4.2 Classical equation of motion

The equation of motion for ions under the classical limit can be employed to investigate the nonlinear phonon interactions involving the direct excitation of IR mode by light. For example, the equation of motion for two phonon modes (Q_{IR} and Q_R) and their nonlinear phonon interaction ($Q^2_{IR}Q_R$) can be written as follows:

$$\begin{aligned} \ddot{Q}_{IR} + \Omega^2_{IR}Q_{IR} &= -2k_{nl}Q_{IR}Q_R + Z^*_{IR}E(t), \\ \ddot{Q}_R + \Omega^2_R Q_R &= -k_{nl}Q^2_{IR}, \end{aligned} \tag{3}$$

when Ω, k_{nl}, Z^*_{IR}, and $E(t)$ are frequency of phonon, nonlinear coupling coefficient, mode effective charge of IR mode and external field, respectively. For the precise simulation, the coupling coefficients, mode effective charge, and frequency of phonon could be achieved from density functional theory calculation. From density functional perturbation theory

calculation, diagonalization of dynamical matrix (D) provide the phonon frequency (Ω) and its eigenvector (ϵ):

$$\sum_{j\alpha j'\beta} \epsilon_\alpha(j', q\nu) D_{\alpha\beta}(jj', q)\epsilon_\beta(j\, q\nu') = [\Omega(q\nu)]^2 \delta_{\nu\nu'} \tag{4}$$

The normalized atomic displacement (u) at $q = 0$ is defined in terms of eigenvector (ϵ) and atomic mass (m_τ) as follows:

$$u_\alpha(\tau) = \frac{1}{m_\tau^{1/2}} \epsilon_\alpha(\tau). \tag{5}$$

The potential energy surface of phonons $E[Q_{IR}, Q_R]$ can be evaluated by the density functional theory calculation. Notably, this calculated potential energy surface can provide the nonlinear phonon interaction such as $Q_{IR}^2 Q_R$ and higher terms by fitting.

4.3 Real-time time-dependent density functional theory

Real-time time-dependent density functional theory (rt-TDDFT) makes it possible to investigate the non-equilibrium dynamics of electronic structure and ions in materials under the first-principle approach. On the other hand, the rt-TDDFT proceeds the time-propagation of Kohn–Sham states and consequent ionic dynamics. For the time-propagation of electronic structure, the time-dependent Kohn–Sham equation is solved as follows:

$$i\hbar \frac{\partial}{\partial t} \psi_{i,\mathbf{k}}(t) = [\frac{(\mathbf{p}+\mathbf{k})^2}{2m} + V_{ion}(t) + V_{Hxc}[\rho(t)]]\psi_{i,\mathbf{k}}(t). \tag{6}$$

In practice, various approximations are employed, such as Suzuki–Trotter type split exponential operator, Crank–Nicholson methods, explicit time-reversal symmetric operator, and so on [42]. For example, the wavefunction in next time step ($\psi_{i,\mathbf{k}}(t+dt)$) can be achieved by solving the linear equation in Crank–Nicolson method as follows:

$$[1 + iH(t)\hbar dt/2]\psi_{i,\mathbf{k}}(t+dt) = [1 - iH(t)\hbar dt/2]\psi_{i,\mathbf{k}}(t). \tag{7}$$

Once the wavefunctions $\psi_{i,\mathbf{k}}(t+dt)$ are evaluated, the charge density in next time step ($\rho(\mathbf{r}, t+dt) = \sum_{i,\mathbf{k}}^{occ} |\psi_{i,\mathbf{k}}(t+dt)(\mathbf{r})|^2$) should be updated for Hamiltonian in next time step. On the other hand, the forces on the ion at a given time t can be derived from the Hellman–Feynman theorem ($\mathbf{F}(t)_\tau = dE_{tot}(t)/d\mathbf{R}_\tau$). This process makes it possible to simulate the Ehrenfest dynamics that describe the ionic and electric dynamics at the same time. When we apply the Gaussian-like laser pulse with frequency ω through the vector-potential term ($\mathbf{p}^2/2m \rightarrow (\mathbf{p} + \mathbf{A}(\mathbf{t}))^2/2m$, and $A(t) = A_0 e^{-t^2/\sigma^2} cos(\omega t)$), for example, the electronic structure will be excited by this pulse and the modified charge density can gives modified force on the ions. As a result, the excitation of coherent phonon and structural distortion by modified electronic structure can be investigated under the Ehrenfest dynamics [17].

4.4 Time-propagation with exact diagonalization in Hubbard model

The Hubbard model has been employed to describe the many-body effect of electrons in lattice [43]. In the Hubbard Hamiltonian, the hopping (t) and on-site Coulomb interaction (U) are considered as follows:

$$H_{Hub} = -t \sum_{<ij>} \hat{c}_i^\dagger \hat{c}_j + U \sum_i \hat{n}_{i\uparrow}^\dagger \hat{n}_{i\downarrow}, \tag{8}$$

when $\hat{c}_i^\dagger$, $\hat{c}_i$, and $\hat{n}_{i\sigma}$ are creation, annihilation and number operator for ith state (with σ spin state), respectively. Depending on the system size, various approaches are employed to solve the Hubbard model, such as exact diagonalization and quantum Monte Carlo simulations [44, 45]. For example, the number of basis sets (N) of the half-filled Hubbard model for the exact diagonalization increases exponentially ($N = 2^L$) depending on the number of sites (L) by considering all occupation configurations. The ground state solution of the Hubbard model provides an understanding of the correlated system.

The time propagation with exact diagonalization makes it possible to investigate the real-time dynamics of correlated states. For example, a recent study suggests that the oscillating field can lead to pairing electrons in the Hubbard model [30]. To describe the time-dependent oscillating field ($A(t)$), the Peierls substitution is employed as follows:

$$t \rightarrow te^{iA(t)} \tag{9}$$

With the time-dependent Hamiltonian ($H(t)$), the adiabatic states ($\phi_0(t)$) at each time t is evaluated to construct the time-propagation as follows:

$$H(t)\phi_l^0(t) = \epsilon(t)\phi_l^0(t) \tag{10}$$

The time-propagation of states can be achieved by applying the time-evolution operator that consists of adiabatic states ($\phi_0(t)$) as follows:

$$\begin{aligned} |\Psi(t+dt)> &\sim e^{i\hat{H}(t)dt}|\Psi(t)> \\ &\sim e^{i\epsilon_l^0(t)dt}|\phi_l^0(t)><\phi_l^0(t)|\Psi(t)> \end{aligned} \tag{11}$$

With this time-propagating state ($|Psi(t)>$), the real-space pair correlation can be evaluated as follows:

$$P(j,t) = \frac{1}{N_j} \sum_{i=1}^{N_j} <\Psi(t)|(\hat{\Delta}_{i+j}^\dagger \hat{\delta}_i + H.c.)|\Psi(t)>, \tag{12}$$

where $\hat{\Delta}_i = \hat{c}_{i,\uparrow}\hat{c}_{i,\downarrow}$ and N_j are on-site singlet pair correlation operator and number of site with j distance separation. With this evaluation of time-profile of pair correlation, the light-induced paring can be investigated [27, 30].

5 Outlook

This review introduced the various light-induced phenomena and related microscopic mechanisms. Recent experimental and theoretical studies demonstrated that light could lead to superconductivity, ferroelectric transition, magnetic momentum, and topological phase transition. In these light-induced phenomena, several possible microscopic mechanisms are suggested. The three microscopic mechanisms were categorized in this review. The first mechanism is light-induced phenomena through the direct excitation of phonon modes. For example, the IR mode excited by light can induce the geometry distortion that leads to modification of material property through the nonlinear phonon interaction. The second mechanism is light-driven electron–phonon dynamics. It is introduced that the electronic structure excited by light can derive the specific phonon motion through the displacive excitation of coherent phonon. The third mechanism is the direct modification of electronic structure by applying light to the material. For instance, the direct modification of electronic structure by light also can modify the topological state of material through Floquet engineering. The numerical tools are also introduced in this review that can be used as a powerful tool for investigating light-induced phenomena. As possible tools, the *ab initio* molecular dynamics, classical equation of motion, time-dependent density functional theory, and time-propagation with exact-diagonalization were suggested. Beyond these light-induced phenomena and numerical tools, I expect new fascinating phenomena and useful numerical tools to be reported in the future. For example, the optical cavity-induced phenomena with condensed matter system are also recently suggested [12, 46].

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