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Past, present, and future studies on the longitudinal electric field components of light

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Abstract

Unlike a planar lightwave, a tightly focused light beam has longitudinal components of the electric field (LCEF) that are polarized along the propagation direction. This article reviews the past and present status of theoretical and experimental studies on the LCEF. By pointing out that the LCEF is an essential constituent element of the dressed photon (DP), the future outlook of these studies for advancing DP science and its applications is discussed.

1. Introduction

Elementary textbooks on optics study planar lightwaves of infinitely large cross-section that propagate through space in a vacuum or in a macroscopic material [1]. In this picture, light has been recognized as a transverse wave composed of transverse electric fields that are polarized in a plane normal to its propagation direction.

In contrast, a typical laser light beam has a finite cross-sectional size. Furthermore, it can be decreased to a size as small as the optical wavelength when it is focused by a lens with a high numerical aperture (NA). In such a tightly focused situation, the light beam around the focal plane is no longer a planar lightwave, and thus, it is not a transverse wave either. Instead, it can have longitudinal components of the electric field (LCEF) that are polarized along the propagation direction.

Studies on the LCEF had already commenced before the advent of lasers. Subsequently, the concept of the LCEF was applied to microscopy, spectroscopy, and material processing technology, bringing about novel experimental results that are impossible to achieve when only the transverse components of the electric field are used. Theoretical analyses of the interaction between the LCEF and matter in a microscopic space are indispensable for understanding these experimental results. However, such analyses have not been actively carried out. In fact, the gauge for the vector potential for describing the LCEF has not yet been adequately determined. Furthermore, even though a high-intensity LCEF is required to acquire experimental results in a reproducible manner, this requirement has not been met because of the technical difficulties involved in fabricating a high-NA lens. A further difficulty was that experimental methods for suppressing the transverse field components have not yet been developed.

Even with these difficulties, theoretical and experimental studies on the generation and application of the LCEF are continuously progressing, and they have given some hints for achieving advances in optical science. To realize these advances, it should be pointed out that off-shell science has elucidated that the LCEF is an essential constituent element of the dressed photon (DP) [2]. The DP is a quantum field created in a complex system composed of photons and electrons (or excitons) in a nanometer-sized space [3]. The fruits of this science have been applied to the development of generic technologies (for example, nanometer-sized optical devices, information processing systems using these devices, nano-fabrication technology, and energy conversion technology) which have realized disruptive innovations.

Section 2 of this article reviews the past and present status of studies on the LCEF. In Section 3, the future outlook of these studies for advancing DP science and its applications is discussed. Section 4 presents concluding remarks.

2. Past and present

Even before the advent of lasers, the behavior of the LCEF had been studied by theoretically analyzing the structure of light near the focus of an aplanatic system [4]. Subsequent studies found that this behavior in the focal plane showed a resemblance to the well-known picture of the lines of force emanated from an oscillating electric dipole [5]. In particular, along the direction of the azimuthal line, $\psi=0$, the transverse electric field was found to be strictly zero, indicating that the electric field was purely longitudinal. This implied the possibility of generating the LCEF while suppressing transverse components. Furthermore, it was expected that an LCEF as high as 10^5 V/cm could be attained by focusing a laser beam, and this could be used for accelerating charged particles.

The exact Maxwellian formulation for the LCEF was developed by using the angular spectrum method in order to derive the Maxwellian stress tensor of the nonlinear force [6]. The results were compared with experimentally acquired data on the energy of electrons emitted from a laser-irradiated tenuous plasma. The results agreed with each other, thus demonstrating the polarization independence of the energy if all components of the Gaussian beam, including the LCEF, are used to constitute the Maxwellian stress tensor. From this demonstration, it was confirmed that the LCEF significantly contributed to the light–matter interaction even though the intensity of the LCEF was low compared with its transverse counterparts. Encouraged by this confirmation, researchers developed interferometric techniques to convert a linearly polarized laser beam into a radially polarized one with uniform azimuthal intensity. As a result, it was demonstrated that the radially polarized focused beam had sufficiently high-intensity LCEF for accelerating charged particles [7].

The LCEF has been applied to spectroscopy of a single fluorescent molecule [8]. In that study, the molecule was excited by a focused laser beam, and the orientation of the absorption dipole moment was determined by mapping the spatial distribution of the electric field components. As a result, it was found that an annular illumination geometry strongly enhanced the LCEF in the vicinity of a planar dielectric/air interface, where the intensity became as high as those of other components. The method of geometrical optics was used to qualitatively analyze the spatial features of the enhanced LCEF.

The method of vector-wave optics was used for detailed analyses of the spatial features of the light field in an image space for application to fluorescence correlation spectroscopy and single-molecule fluorescence detection with a confocal microscope [9]. Furthermore, the rotational dynamics of a fluorescent single molecule on a material surface were investigated by polarization spectroscopy, which succeeded in evaluating the intensity of the LCEF at the focal plane [10]. With the aim of advancing these applications, radially polarized cylindrical-vector beams were found to be advantageous for generating a high-intensity LCEF near the focal plane [11]. Furthermore, it was found that, as its cross-sectional size decreased, the intensity of the LCEF increased and finally exceeded that of the transverse field.

In order to confirm the contribution of the LCEF to light–matter interactions, spectroscopic measurements on a single trapped $^{40}\mathrm{Ca}^+$ ion were carried out [12]. For triggering the Zeeman-split $^{40}\mathrm{Ca}^+$ quadrupole $S_{1/2}$-$D_{5/2}$ transition, the $^{40}\mathrm{Ca}^+$ ion was illuminated with twisted light having opposite orbital and spin angular momenta. The acquired experimental data were compared with a theoretical model in which the LCEF was taken into account. The results agreed with each other, thus confirming the significant contribution of the LCEF to the light–matter interaction. A chip-scale sensor was recently developed for experimentally analyzing the orbital angular momenta of this type of light [13,14].

The interaction between tightly focused ultrashort optical pulses and transparent media was used to imprint their local polarizations in the focal region [15]. By referring to the experimental results of this imprinting, complex polarization states, including the LCEF, were investigated. As a result, it was confirmed that a small crater on the fused silica surface was formed by the contribution from the LCEF, which demonstrated a novel material ablation mechanism due to the LCEF.

As reviewed above, in conjunction with experimental studies, theoretical studies of tightly focused light beams have demonstrated the importance of taking the LCEF into account for analyzing light–matter interactions. It has also been demonstrated that the LCEF can even dominate the interaction with matter. Following these demonstrations, there is currently substantial interest in structured light, that is, customized light fields generated to suit specific needs in applications of the LCEF [16,17].

It should be pointed out that reports on theoretical and experimental studies of the LCEF have not been found in the field of quantum electrodynamics. Although the LCEF has been briefly described in relevant articles [18,19], the vector potentials and interaction Hamiltonian have been discussed only by using conventional Coulomb and Lorenz gauges.

3. Future outlook

This section presents some comments regarding references [6], [8-10], [12], and [13]. Based on these comments, the future outlook of each of these studies for advancing DP science and its applications is discussed.

<Reference [6]>

[Comments]

From a theoretical basis derived by using the angular spectrum method, reference [6] claimed that the LCEF significantly contributed to the light–matter interaction. It should be noted that this method was based on a concept from on-shell science called linear causality. This reference also claimed that, as a logical consequence derived using Maxwell's equations, the intensity of the LCEF increased with decreasing cross-sectional size of the light. Figure 1 briefly explains the relation between the cross-sectional size and the intensity of the LCEF. This figure shows that the cross-sectional size discussed in this reference (also in [4,5,7-17]) was larger than the wavelength of the light. In other words, it was a discussion of a situation below the diffraction limit, which means that the LCEF was investigated using the conventional on-shell scientific method. This reference did not describe the reason why the nonlinear ponderomotive force induced the polarization-independency of the electron energy even though the intensity of the LCEF was low. Furthermore, this reference did not discuss the light–matter (electron) interaction in a microscopic space.

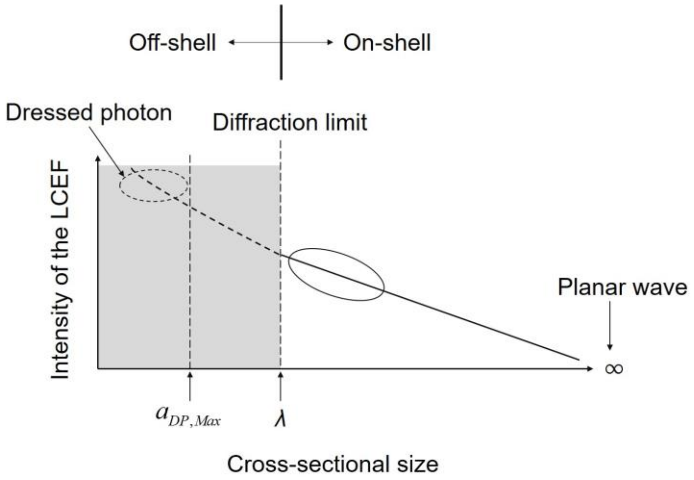

Fig.1 Relation between the cross-sectional size of light and the intensity of the LCEF.

λ is the wavelength of light. $a_{DP,Max}$ is the maximum size (50-70 nm) of the DP [2,3]. The solid ellipse represents the area of the relation that was dealt with in references [4-17]. The broken ellipse is for the DP.

[Outlook]

Figure 1 clearly shows that this reference did not deal with the DP because its maximum size, $a_{DP,Max}$ (=50–70 nm), was much smaller than the wavelength of the light [2,3]. Off-shell science is required to deal with the LCEF in the DP. It is expected that the magnitude of the light–matter interaction originating from the DP increases due to its small cross-sectional size. Off-shell science is also required to describe such a large magnitude.

<References [8-10]>

[Comments]

References [8-10] described that the LCEF generated in the near-field regions at the surfaces of high-NA lenses were applied to microscopy and spectroscopy. Thus, these applications may be called near field optics. However, even though their resolutions were improved, they were still limited by the diffraction of light. That is, these applications still stayed within the region of on-shell science.

[Outlook]

Even though the behaviors of the LCEF discussed in these references were governed by diffraction, the results gave some hints for achieving advances in off-shell science. Progress in off-shell science is expected by taking advantage of these hints.

<Reference [12]>

[Comments]

Reference [12] used the vector potential to describe the light–matter interaction. However, it was based on the Lorenz gauge, which is commonly used for the transverse wave. Furthermore, this reference claimed that the quadrupole transition matrix elements vanished at first order in the coordinates. However, this claim is true only when the long-wavelength approximation is valid. This reference also discussed the interaction between twisted light and a single trapped ion (a simple specimen for spectroscopy) by using the orbital and spin angular momenta. It should be noted that these discussions were based on on-shell science because they relied on these definitely identified momenta.

[Outlook]

In the case where the DP is involved in a light–matter interaction in microscopic space, the long-wavelength approximation turns out to be invalid due to the small size of the DP, beyond the diffraction limit. Thus, the quadrupole transition matrix elements can have non-zero values [2,3]. Progress in off-shell science is required to investigate the novel phenomena occurring under this invalid condition. Furthermore, in the case where the DP is involved in the interaction above, the momenta cannot be defined due to the small size of the DP, beyond the diffraction limit. Under such undefined conditions, violation of the selection rules and allowance of the electric dipole forbidden transition can be observed [2,3]. Off-shell science is required also for describing the phenomena occurring under these conditions.

<Reference [13]>

[Comments]

Reference [13] used light with a wavelength shorter than the absorption-edge wavelength of the relevant matter. This is a method popularly used in on-shell science.

[Outlook]

In the case where the DP is used for imprinting, a technical advantage is that longer-wavelength light can also be used as a source for creating the DP [2,3]. Off-shell science is required to describe the physical processes in such DP-imprinting.

4. Concluding remarks

Even though the mechanism of generating the LCEF and the contribution of the LCEF to the light–matter interactions have been elucidated by modern optical science, the claim that “light is a transverse wave” continues to be seen even now. It is seen even in advanced textbooks on optics. A plausible reason for such a claim is that studies on the microscopic nature of light–matter interactions have not yet been fully developed. Further progress of optical science is required to advance these studies. By noting that the LCEF is an essential constituent element of the DP and that the magnitude of the DP–electron interaction can be very large in a nanometer-size space, off-shell scientific studies on the DP may open a new route to elucidate the intrinsic nature of the LCEF.

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