Generation Mechanism of Dressed Photon and Unique Features of Converted Propagating Light

M. Ohtsu

Research Origin for Dressed Photon,
3-13-19 Moriya-cho, Kanagawa-ku, Yokohama, Kanagawa 221-0022 Japan

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Abstract

Based on theories from off-shell science, this article explains that a timelike Majorana particle and anti-particle pair pops up at a point-like source due to light–matter interaction in a nanometer-sized space. A dressed photon (DP) is generated by subsequent annihilation of this pair. It also describes the quantization of the DP by using the energy quantum $(\kappa_0)^2$, where the inverse of κ_0 represents the maximum size of the DP and is called the DP constant. The DP, in its high energy level, is spontaneously de-excited, and its energy is converted to propagating light energy. The converted light field behaves like a particle because its spin is zero. It is called DP-cluster light, and its unique features are confirmed by photon statistics experiments. It is a cluster of photons that behaves as if it were a single photon with the accumulated amount of energy. Thus, it is free from diffraction. Experimental results on an optical polarization rotator, the DP constant, and photon breeding are also reviewed by referring to off-shell science theories.

1. Introduction

A dressed photon (DP) is a quantum field that is generated in a complex system composed of photons and electrons (or excitons) in a nanometer-sized material [1]. A variety of unique optical phenomena have been found through experimental studies on the DP [2-5]. However, on-shell science, which is the established base of conventional optical science, has never succeeded in theoretically analyzing these phenomena. This is because on-shell science has never dealt with the light–matter interaction in a nanometer-sized space even though this interaction is indispensable for generating the DP. Fortunately, off-shell science (the complement of on-shell science) has started recently to deal with this interaction and has produced several significant outcomes [6-8].

This article outlines theoretical analyses on the generation mechanism of the DP based on off-shell science theory. Furthermore, this article also reviews unique features of the propagating light generated due to the energy conversion from the DP, which have been analyzed in recent experimental and theoretical off-shell science studies.

2. Generation and quantization of a dressed photon

Based on the classical Clebsch dual field model, off-shell science theory has succeeded in describing the light–matter interaction in a nanometer-sized space, in which the longitudinal components of the electromagnetic field play an essential role [6-8]. As an epoch-making result, it described the generation mechanism of the DP: As a result of the interaction between the spacelike vector field (satisfying the spacelike Klein-Gordon (KG) equation) and a point-like source at the position r =0, a timelike Majorana particle and anti-particle pair pops up at r =0. These particle fields are non-propagating, and the pair annihilates immediately to generate a small light field. This is the DP field.

The generated DP exhibits two distinct natures:

(a) In the case of pair-annihilation involving anti-parallel spins, the resulting spin 0 DP has an electric nature.

(b) In the case of pair-annihilation involving parallel spins, the resulting spin ± 1 DP has a magnetic nature.

The timelike mode of the solution of the KG equation, to be perturbed by the point-like source, has the form $\lambda\left(x^0,r\right)=\exp\left(\pm k_0 x^0\right)R\left(r\right)$. It is regarded as unstable because the value $\lambda\left(x^0,r\right)$ increases or decreases rapidly (exponentially) with the increase of the time x^0. Here, $R\left(r\right)$ satisfies

$$R''+\frac{2}{r}R'-\left(\hat{\kappa}_r\right)^2 R=0, \qquad (\hat{\kappa}_r)^2 \equiv \left(k_0\right)^2-\left(\kappa_0\right)^2>0 \quad . \tag{1}$$

The solution $R\left(r\right)$ is known as the Yukawa potential and has the form

$$R(r)=\exp\left(-\hat{\kappa}_r r\right)/r\,, \tag{2}$$

which decreases rapidly as r increases. It represents the spatial distribution of the DP. $\left(\hat{\kappa}_r\right)^2$ corresponds to the field energy, whose minimum is $\left(\kappa_0\right)^2$.

The DP field can be treated quantum mechanically. That is, the energy $\left(\hat{\kappa}_r\right)^2$ is quantized and is expressed as

$$(\hat{\kappa}_r)^2=n\left(\kappa_0\right)^2, \tag{3}$$

where $n(=1,2,3,---)$ is the energy quantum number that identifies the energy level of the quantized DP. The minimum value $\left(\kappa_0\right)^2$ is an energy quantum. The inverse of κ_0 represents the maximum size of the DP:

$$L_{\max}^{(dp)} = 1/\kappa_0 , \tag{4}$$

and is called the DP constant [8].

3. Conversion to propagating light and its unique features

Off-shell science theory also showed that the DP is converted to propagating light [7,8]. The conversion mechanism, and the unique features of the converted propagating light, are:

[1] Conversion mechanism: For the DP, generated or annihilated at a point-like singularity r=0 in a material, a phonon field (a quantized lattice vibration in the crystalline material) serves as the environment. If the DP stays in its high energy level ($n \geq 2$ in eq. (3)), it is de-excited due to triggering by the fluctuating phonon field. As a result, the DP energy is converted to generate propagating light. This conversion mechanism is similar to that of spontaneous emission that has been studied in conventional on-shell science.

[2] Unique features of the converted propagating light: It should be pointed out that a light field with spin zero behaves like a particle, as has been described by Wightman's theorem [9]. This theorem claims that only a localizable massless elementary system has spin zero and indicates that the converted propagating light also has spin zero since the DP field has spin zero (refer to **(a)** in Section 1). Thus, this propagating light has a unique bullet-like feature. For reference, the classical Clebsch dual field model in Section 2 has shown that such a peculiar propagating light field has the same energy-momentum tensor as that of a free fluid particle.

4. Experimental evaluations of the unique features

Photon statistics experiments have been carried out recently and have revealed two features of the light emitted from multiple small emission sources in a silicon light-emitting diode (Si-LED) fabricated by DP-assisted annealing: One feature is that the value of the second-order cross-correlation coefficient (CC) is smaller than unity. This indicates an anti-bunching feature. The other feature is that the CC takes a small but nonzero value at the time difference τ=0 [10]. This indicates that a cluster of "photons" is emitted from the multiple small emission sources in the Si-LED.

These two features confirmed that a cluster of "photons" is emitted from the Si-LED and behaves as if it were a single photon that originated from the DP. This cluster of photons is called DP-cluster light [11].

Further experiments were carried out to investigate the generation of the DP-cluster light: They demonstrated that the propagating light generated from a waveguide-structured Si-LED travels in this waveguide with a low transmission loss. This indicated that this light is free from diffraction.

The features of the DP-cluster light are closely related to the localizable property of a spin zero particle (refer to the Wightman's theorem in **[2]**, Section 3). Namely, if the positions of spin zero quantum particles are sufficiently close to each other, a cluster of these particles behaves as if it were a single quantum particle with the accumulated amount of energy. As a result, a light beam consisting of such a light field behaves like a bullet, and thus, it is free from diffraction.

5. Further unique phenomena found by previous experiments

In addition to the recent experimental results in Section 4, further unique phenomena have been found by previous experiments:

[1] For confirming the nature **(b)** in Section 2, an optical polarization rotator has been fabricated by using a SiC crystal. In spite of the fact that this crystal is an indirect transition-type semiconductor, the device exhibited a large magneto-optical effect after the DP-assisted annealing was completed [12].

[2] The value of the DP constant in eq. (4) has been estimated to be 50–70 nm by experiments involving chemical vapor deposition (CVD) and smoothing of a material surface using DPs [4]. This is because, in the case of CVD, the maximum size of the materials deposited on a substrate was 50–70 nm. In the case of smoothing of a material surface, the maximum size of the bumps on the material surface, selectively removed by the DPs, was also 50–70 nm.

[3] The conversion mechanism described in **[1]** of Section 3 was similar to that of spontaneous emission in conventional on-shell science. On the other hand, the mechanism of photon breeding is similar to that of stimulated emission: In the case of fabricating a Si-LED by DP-assisted annealing, the light irradiated onto the Si crystal plays a role of triggering stimulated emission. Here, it should be pointed out that the propagating light is emitted not immediately after this irradiation but by injecting the current after the DP-assisted annealing is completed. However, since the unique spatial profile of the B-atom pairs in the Si crystal, which is formed by the DP-assisted annealing, is governed by the spectral properties of the irradiated light, the emitted light can be regarded as a replica of the irradiated light, as is the case of conventional stimulated emission. The photon breeding is exactly this replicated phenomenon [2]. Replications of the emission wavelength and polarization, due to the photon breeding, have been experimentally confirmed [2]. It is expected that a replica of the light propagation direction will also be produced in the future. The photon breeding with respect to these three parameters (wavelength, polarization, and propagation direction) indicates that all the members of the constituent elements of the photon quantum field (energy, spin, and momentum) can be replicated.

6 Summary

This article reviewed that the DP field was generated by pair-annihilation of the Majorana particle and anti-particle pair that pops up at a point-like source due to light–matter interaction in a nanometer-sized space. It also outlined the quantization of the DP by using the energy quantum $(\kappa_0)^2$, where the inverse of κ_0 represents the maximum size of the DP and is called the DP constant.

When the DP field is in its high energy level, it is spontaneously de-excited and is converted to propagating light. The spin of the converted light field is zero, as is that of the DP field, and thus, this light behaves like a particle. It is called DP-cluster light, and its unique features were confirmed by photon statistics experiments. It is a cluster of photons that behaves as if it were a single photon with the accumulated amount of energy. A light beam consisting of such a light field behaves like a bullet and thus, it is free from diffraction.

In addition to the DP-cluster light, experimental results on an optical polarization rotator, the DP constant, and photon breeding were reviewed by referring to off-shell science theories.

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