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Off-shell scientific nature of dressed photon energy transfer and dissipation

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Abstract

First, the principles of size-dependent resonance, bi-directional energy transfer, and subsequent energy dissipation are reviewed. Second, experimental results on energy transfer, dissipation, and light emission from multiple three-dimensionally arranged nanometer-sized particles are presented. These results imply that the dressed-photon (DP) energy transfers through a unique path via which the emitted light power takes the maximum value. Third, the results of preliminary numerical calculations carried out by using a random walk model are presented. These results show that there are serious problems originating from the principle of on-shell science assumed in the calculations. In order to solve these problems, a quantum walk is presented as a promising off-shell scientific model. Finally, it is suggested that the unique path above can be found by improving this quantum walk model.

1. Introduction

Extensive experimental studies on dressed photons (DPs) have found a large number of novel phenomena that originate from the unique nature of DP energy transfer and dissipation. They have been applied to realize innovative technologies [1]. These phenomena are totally different from those that have been popularly known in the field of conventional on-shell science. This paper reviews these phenomena and evaluates them from the viewpoint of novel off-shell science that is complimentary to the on-shell science [2]. After a review of experimental results in Sections 2 and 3, Section 4 introduces the result of preliminary numerical calculations for analyzing the experimental results. The results indicate that these calculations have serious problems, and numerical calculations based on an off-shell scientific quantum walk (QW) model are promising to solve these problems. Based on this unique off-shell scientific model, Section 5 presents a DP energy transfer path that can be possibly used to solve them. Section 6 presents a summary.

2. Energy transfer and dissipation of the dressed photon

This section reviews the mechanisms of DP creation, its energy transfer, and subsequent dissipation for measurements.

2.1 Creation and transfer

A DP is created on a microscopic material surface by the interaction between a light field and a microscopic material field. The DP creation process is described by the following three steps [3,4]:

(1) A microscopic material field (a timelike momentum field) interacts with a vector boson field[1)].

(2) In addition to a stable pair of the Majorana fermions (a spacelike momentum field)[1)], an unstable pair consisting of a Majorana particle and anti-particle (timelike momentum fields) is created (pair creation).

(3) Although this unstable pair annihilates within a short time duration (pair annihilation), a novel light field (a timelike momentum field) remains at the microscopic material. This is the DP.

In the case where the spins of the particle and anti-particle in (2) are anti-parallel, an electric DP (with spin 0) is created. When they are parallel, on the other hand, a magnetic DP (with spin 1) is created. The creation of these DPs has been experimentally confirmed [3-5].

A simple example of the microscopic material above is a nanometer-sized particle (NP) (Fig. 1(a)). That is, a DP is created on this NP by light irradiation. More realistic examples are the tip of a fiber probe, a bump on a rough material surface, and an impurity atom in a material.

If the second NP (NP_2) is placed in close proximity to the first NP (NP_1) (Fig. 1(b)), the energy of the DP on NP_1 transfers to NP_2 when the separation between the two NPs is shorter than the size of the NPs (a tunneling effect) because the spatial extent of the DP is equivalent to the size of the NP, as has been formulated by a Yukawa function [3, 4]. This transfer most probably occurs when the sizes of the two NPs are equal, which has been called size-dependent resonance [6]. This resonance can be interpreted as the resonance between the quantized energy levels of excitons in the NPs because the value of the quantized energy of the exciton is inversely proportional to the size of the NP[2)]. Here, it should be noted that this transfer is bi-directional between these NPs, which represents the interaction between the two NPs by exchanging a DP.

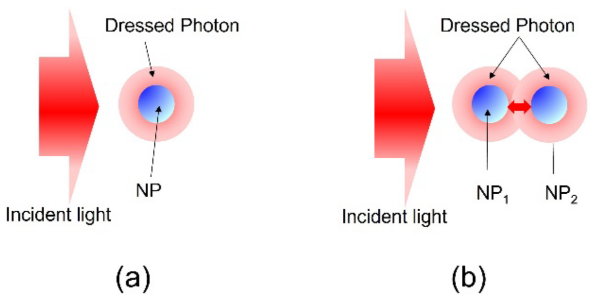


Fig. 1 Creation of DP on a nanometer-sized particle (NP) and its energy transfer.
(a) Creation. (b) Energy transfer.

1) This vector boson field is a spacelike momentum field that is indispensable for representing light–matter interaction. Theoretical studies have proved the existence of this field based on the concept of Clebsch dual representation. These studies have also successfully described that the spacelike momentum field for a classical electromagnetic field is created from condensed boson fields in a microscopic space that is composed of a pair of quantum mechanical Majorana fields (two Majorana fermions). The components of this pair are four-dimensionally orthogonal with each other. For reference, the Clebsch dual representation above uses a pair of scalar parameters (λ, ϕ), that has been introduced to represent the Hamiltonian structure with respect to the isentropic motion of an ideal fluid.

2) Since the DP is a photon–exciton coupled field, this phenomenon should be evaluated by the resonance between the DP on NP_1 and that on NP_2 instead of the resonance between the exciton energies. However, since the quantized energy of the DP is inversely proportional to the size of the NP [3, 4], the present interpretation is valid also for the quantized energy of the DP.

2.2 Dissipation for measurement

The DP energy transfer in Subsection 2.1 cannot be measured in macroscopic space because it occurs only in the microscopic space composed of the two NPs. For measurement, the DP energy must be dissipated from the microscopic to the macroscopic space. Figure 2 shows a method for inducing such dissipation, in which NP_2 in Fig. 1(b) is replaced by a larger NP (NP_L) [7]. In order to utilize the size-dependent resonance, the sizes of the two NPs are adjusted so that the lowest quantized energy E_{S1} of the smaller NP (NP_S) is tuned to the second-lowest quantized energy E_{L2} of NP_L. By this adjustment, annihilation of the exciton with energy E_{S1} in the smaller NP_S creates the DP that efficiently transfers to NP_L, resulting in the efficient creation of an exciton with energy E_{L2} in NP_L. This exciton rapidly relaxes from the second quantized energy level (E_{L2}) to the lowest level (E_{L1}) of NP_L. By this relaxation, a small amount of excess energy $E_{L2} - E_{L1}$ dissipates to the macroscopic heat bath in which these NPs are buried. After this relaxation, the exciton in NP_L rapidly annihilates and emits a photon. That is, the energy E_{L1} dissipates to the macroscopic space in the form of propagating light that can be measured.

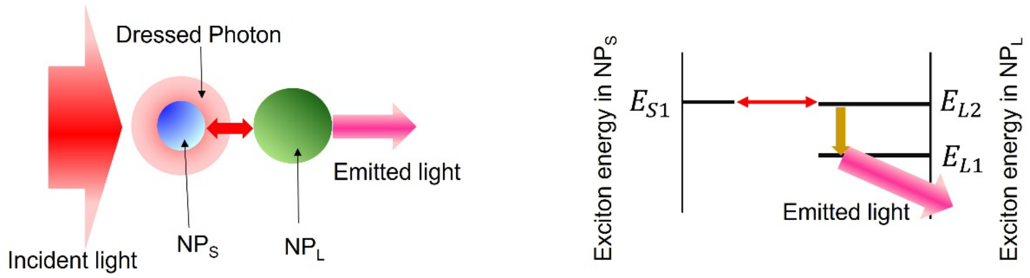


Fig. 2 DP energy dissipation.

NP_S and NP_L are smaller and larger NPs, respectively.

Black squares in Fig. 3 represent the measured values of the temporal variation of the optical power that was emitted from NP_L by pulsed light irradiation. A semiconductor (CuCl) was used as the

NP material. Curve A represents the exponential function $\exp(-t/\tau_{f1})$ (τ_{f1}: decay time constant) fitted to the measured values of the short-time range ($0 \le t \le 2$ ns) immediately after pulsed light irradiation [8]. This short-time variation represents an off-shell scientific fast DP energy transfer that should be described by a quantum walk (QW) model. Curve B represents a slow exponential function $\exp\left(-\sqrt{t/\tau_{f2}}\right)$ (τ_{f2}: decay time constant) fitted to the measured values of the longer-time range. The quantity in this function $\sqrt{t}$ represents an on-shell scientific thermal relaxation phenomenon that can be described by a random walk (RW) model. For reference, similar temporal variation behaviors of CdSe NPs have been also measured [9].

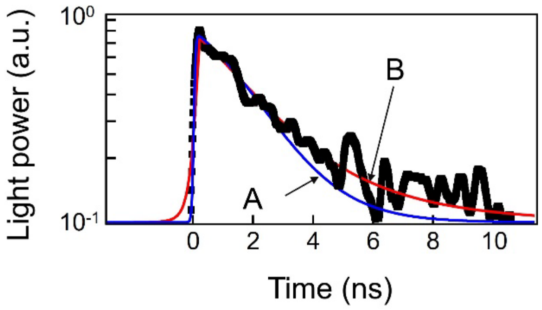


Fig. 3 Temporal variation of the optical power emitted from NP_L by pulsed right irradiation.
A semiconductor (CuCl) was used as the NP material. Curves A and B are the exponential functions $\exp(-t/\tau_{f1})$ and $\exp\left(-\sqrt{t/\tau_{f2}}\right)$, respectively.

Even when increasing the number of NPs in Fig.1(b) from two to N (Fig. 4), bi-directional transfer of the DP energy in these NPs is also possible. Size-dependent resonance is also used here to maximize the efficiency of the DP energy transfer by using NPs of the same size. Figure 5 shows that a larger NP (NP_L) is placed at the end of the array of NP_Ss, as is the case of Fig. 2. After the DP energy reaches NP_L by repetitive bi-directional energy transfers between the adjacent NP_Ss, the DP energy is dissipated from NP_L to the macroscopic space in the form of propagating light which can be measured.

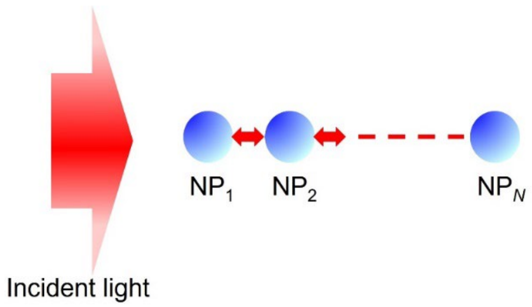


Fig. 4 Bi-directional transfer of the DP energy through linear array of NP_Ss (NP_1–NP_N).

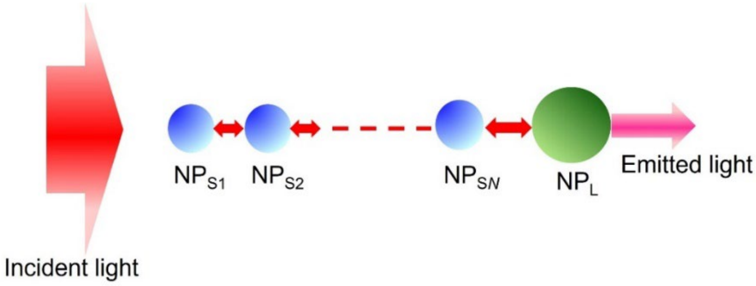


Fig. 5 DP energy dissipation.

NP_{S1}–NP_{SN} correspond to NP_1–NP_N in Fig. 4. NP_L is a larger NP.

By changing the number of NPs and by modifying their spatial layout as in Fig. 5, novel devices such as an optical switch [7], an optical nano-fountain (a super-resolution convex lens) [10], and an amoeba-inspired computing device [11] have been fabricated and their operations have been demonstrated. In the optical nano-fountain, a single NP_L is surrounded by multiple NP_Ss. Experiments on this device have confirmed that the efficiency of the DP energy dissipation from NP_L to the macroscopic space took a maximum when N=3. Preliminary numerical calculations have shown that it took a maximum when N=4, which nearly agreed with the experimental results above [12, 13]. Furthermore, these preliminary calculations have shown that the efficiency of this energy dissipation was higher when several paths of the energy transfer from the multiple NP_Ss to NP_L were cut off [13].

However, it should be pointed out that these preliminary numerical calculations have serious problems: They have dealt only with the uni-directional DP energy transfer by using a random walk (RW) model. That is, they are based on the principles of on-shell science. Furthermore, they required complicated fine adjustments of the values of relevant physical quantities in order to make the calculated results agree with the experimental values.

These problems originated from the nature of on-shell science, which did not deal with the interactions between the NPs mediated by DPs, and thus, neglected the bi-directional DP energy transfer.

3. Experimental results for three-dimensionally arranged nanometer-sized particles

This section discusses the DP energy transfer and dissipation when a large number of small NPs (NP_Ss) are arranged in box-shaped and channel-shaped templates.

3-1 Box-shaped template

Figure 6(a) schematically explains a large number of small NPs (NP_Ss) that were arranged in a box-shaped template. A large NP (NP_L) is arranged on the top of this box [14]. The size-dependent resonance is also used here, as is the case in Fig. 5. Since the CdSe NPs used for the experiments absorb some amount of the light power, the DP energy may decrease by repeating the DP energy transfer between adjacent NPs. Thus, the propagating light power emitted from NP_L may decrease by increasing the number of NP_Ss arranged between the input and output ports (by increasing the direct distance L between these ports). For reference, in on-shell science, the rate of the decrease is formulated as $\exp(-\alpha_{abs} x)$, where α_{abs} is the absorption coefficient and x is the optical path length.

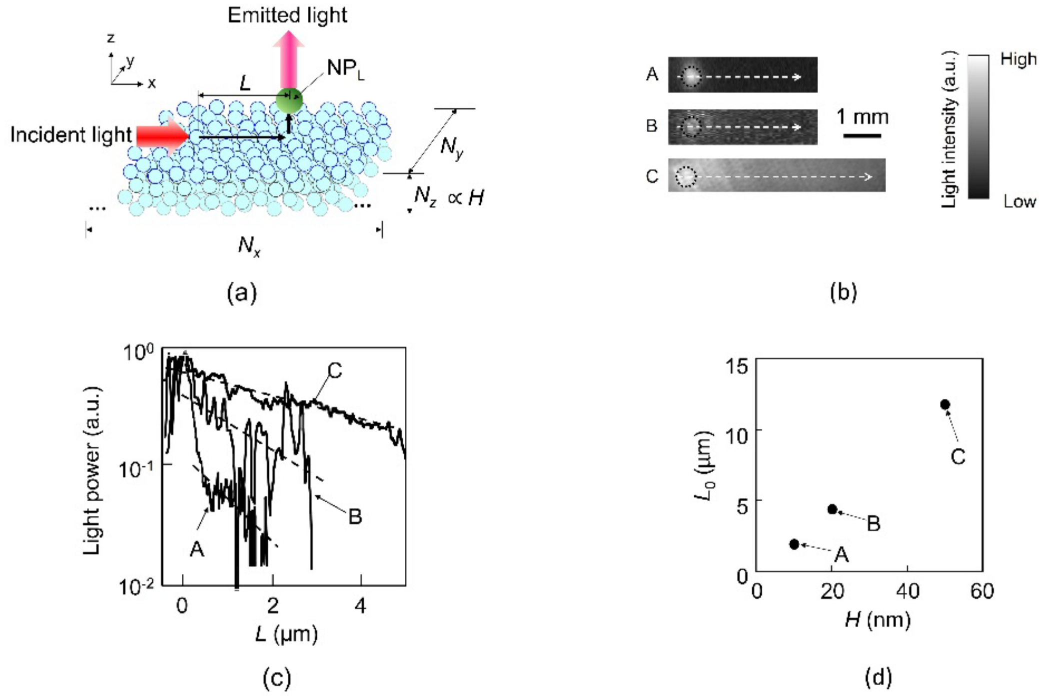


Fig. 6 Bi-directional DP energy transfer and dissipation in a large number of smaller-sized NPs (NP_Ss).

(a) Schematic explanation of the box-shaped arrangement. A semiconductor CuCl was used as the NP material.

(b) Near-field optical microscopic images of the DP energy transfer from NP_Ss to NP_L. The heights H of the three-dimensional arrangements of NP_Ss of the specimens A–C were 10 nm, 20 nm, and 50 nm, respectively.

(c) Measured relation between the direct distance L and the output light power emitted from NP_L for the specimens A–C. Broken lines represent the exponential functions $\exp(-L/L_0)$ fitted to the measured values, where L_0 is the attainable distance.

(d) Relation between H and L_0 for the specimens A–C.

However, the acquired experimental results, shown by Fig. 6(b), show the opposite features, as demonstrated by Fig. 6(c). Figure 6(c) shows the relation between the direct distance L and the output light power emitted from NP_L, where the heights H of the boxes of the specimens A–C were 10 nm, 20 nm, and 50 nm, respectively. They were proportional to the number N_z of NP_Ss that were vertically piled up. Broken lines in this figure represent the exponential functions fitted to the measured values. Since the output light power, normalized to the input power, corresponds to the transmittance

T , this function is expressed as $T = \exp(-L / L_0)$, where L_0 is named the attainable distance. Figure 6(d) shows the relations between H and L_0 for the specimens A–C. They clearly indicate an increase in L_0 with an increase of H, which is opposite to the decreasing feature in the on-shell scientific model described above.

Since the box-shaped arrangements of NP_{SS} enables the formation of a longer path for the DP energy transfer by increasing H, monotonic decreases in the light power are expected by this increase, due to the increase in the amount of optical absorption over the full length of the path. However, the experimental results in Fig. 6(d) are contrary to this expectation. These unexpected results imply the following feature of the off-shell science:

[Feature 1] The DP selects a bi-directional path for maximizing the output light power. In other words, the DP chooses the path to contribute it energy most efficiently to the macroscopic system.

This path is not necessarily the shortest, as is schematically explained by Fig. 7(a). That is, the criterion for the path selection is different from that of the on-shell science in Fig. 7(b).

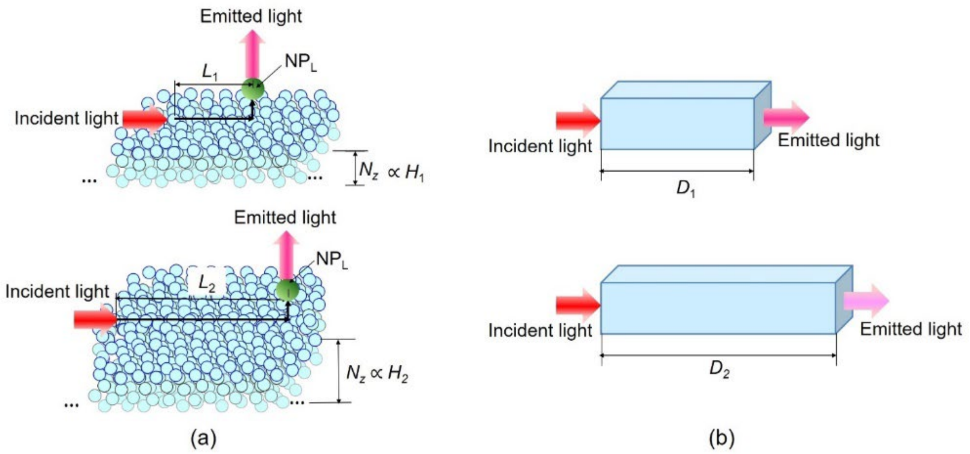


Fig. 7 Comparison between energy transfers of DP and conventional propagating light.

(a) DP energy transfer in a microscopic system (Fig. 6: off-shell science). NPs are smaller than 50 nm (smaller than the optical wavelength of about 1 μm). The size of the volume of the three-dimensionally arranged NPs is smaller than several μm, that is about 1/1,000th the material in (b).

(b) Energy transfer of the propagating light through a macroscopic system (optical wavelength of about 1μm: on-shell science). The optical path lengths D_1 and D_2 through the macroscopic materials are larger than several μm to several mm. In the case where $D_1 > D_2$, the transmittances of these materials satisfy the relation $T_1 > T_2$.

For reference, it should be pointed out that experiments have confirmed that the attainable distance L_0 was insensitive to the fluctuations of the separation between the adjacent NP_{SS} [14]. This implies that accurate separation control is not required, which is advantageous when experimentally arranging a large number of NPs. Such a technical tolerance is also a unique feature of the off-shell science.

3.2 Channel-shaped template

Two pairs of CdSe NPs, consisting of NP_S and NP_L, were used [15]. Figure 8(a) illustrates these pairs, indicated as NP_{S1} and NP_{L1}, and NP_{S2} and NP_{L2}, respectively, for which the size-dependent resonance holds. On the other hand, the size-dependent resonance does not hold between NP_{S1} and NP_{L2}, and also between NP_{S2} and NP_{L1}.

These multiple NPs were arranged in channel-shaped templates, named as C_{S1}, C_{L1}, C_{S2}, and C_{L2} in Fig. 8(a). Figure 8(b) shows an atomic force microscope image of the area surrounded by the red square in Fig. 8(a). By irradiating light to the end of the channel C_{S1}, the DP energy created on NP_{S1}s at this end transfers bi-directionally through this channel and arrives at NP_{L1} in the intersection with the channel C_{L1}. Subsequently, the DP energy transfers through the channel C_{L1} due to the size-dependent resonance. If the DP in channel C_{S1} does not meet NP_{L1} in this intersection, it continues passing through the channel C_{S1}. Figure 8(c) shows a fluorescence microscope image of this transfer. The DP energy transfer from channel C_{S1} to C_{L1} shows two unique features:

[Feature 2]

(2-1) DP energy can transfer even though the channels C_{S1} and C_{L1} cross at right angles.

(2-2) The channels C_{S1} and C_{L2} do not show any crosstalk of DP energy transfer.

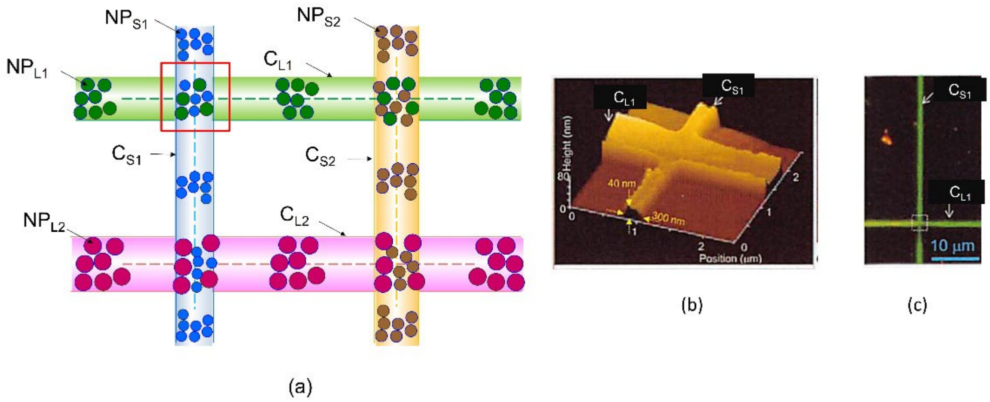


Fig. 8 Two pairs of NPs and their channel-shaped arrangements.

(a) Two pairs [NP_{S1} and NP_{L1}] and [NP_{S2} and NP_{L2}] and their channels C_{S1}, C_{L1}, C_{S2}, and C_{L2}.

(b) and (c) are atomic force microscope and fluorescence microscope images in the red square in (a), respectively.

Feature **(2-2)** indicates that the DP energy in channel C_{S1} does not transfer to NP_{L2} at the intersection with C_{L2}. This is because of the absence of size-dependent resonance between NP_{S1} and NP_{L2}. Channels C_{S2} and C_{L1} do not show any crosstalk either. The two features **(2-1)** and **(2-2)** above are schematically explained by Fig. 9(a), which imply the unique nature of the off-shell science. The DP energy transfer from C_{S2} to C_{L2} also has **[Feature 2]**. For comparison, in the case of the on-shell science in Fig. 9(b), the propagating light is scattered at the bends of a macroscopic optical waveguide or an optical fiber. No more stable propagation is expected downstream in the channel. Furthermore, light leaks from one waveguide to the adjacent one when the separation between their linearly aligned sections is short, which results in large crosstalk.

Based on the off-shell scientific features above, an optical switch has been proposed which has a slightly different structure from the one presented at the end of Section 2 [16]. This device has been used to assemble a system for solving a multi-armed bandit problem [17].

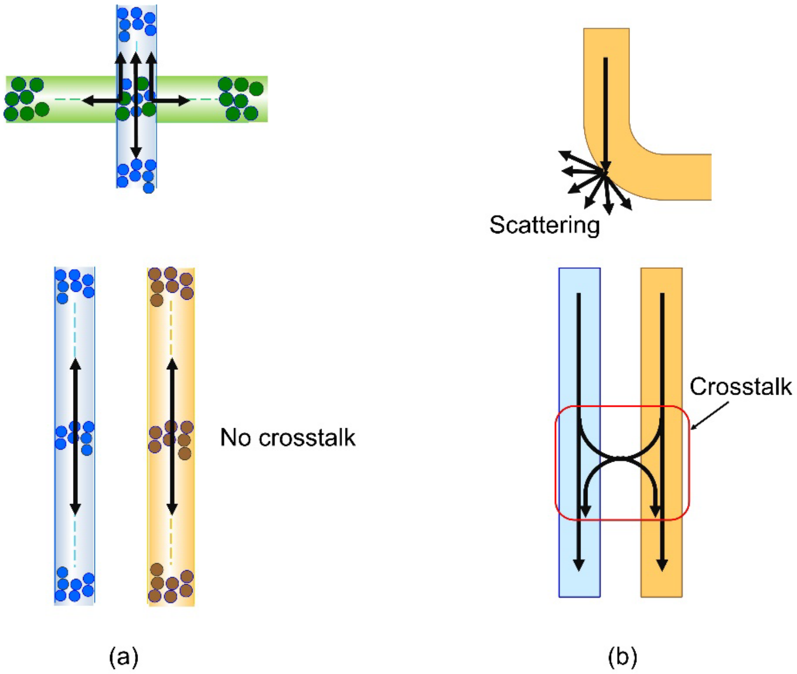


Fig. 9 Comparison between energy transfers of DP and conventional propagating light.

(a) DP energy transfer (double-pointed arrows) in a microscopic system (Fig. 8: off-shell science). NPs are smaller than 50 nm (smaller than the optical wavelength of about 1μm). The size of the volume of the channels for NPs is smaller than several μm, that is about 1/1,000th the devices in (b).

(b) Energy transfer of the propagating light (single-pointed arrows) through a macroscopic optical waveguide or an optical fiber (larger than the optical wavelength of about 1 μm: on-shell science).

4. Present status of numerical calculations and their problems

Preliminary numerical calculations have been carried out for the DP energy transfer among multiple NPs, as described in Subsection 3.1. The dependence of the attainable distance L_0 on the number N of NPs (Fig. 6(d)) has been analyzed by using the on-shell scientific method [18]. A random walk (RW) model was used by assuming that the DP energy transfer time was inversely proportional to the Yukawa function.

Although these calculations have derived the shortest percolation path [18], they had at least the two serious problems:

(1) The calculated quantity was not the creation probability of the DP but that of the exciton only.
(2) The calculation assumed a uni-directional exciton transfer ("excitation transfer" in ref. [18]), not bi-directional.

These problems originated from the principle of the on-shell science. That is, the on-shell science cannot derive the DP creation probability because it does not deal with the interaction. In order to solve these problems, the off-shell science is indispensable because it deals with the interaction, the creation probability of the DP, and its bi-directional transfer. Furthermore, it is expected that the off-shell science properly describes **[Feature 1]** and **[Feature 2]** in Subsections 3.1 and 3.2.

Furthermore, it is expected that the off-shell science can find a variety of natural phenomena that are similar to those in Section 3. It has preliminarily described these phenomena by using the terms such as autonomy and hierarchy [19]. With further progress, it is expected that a universal off-shell science will be established to analyze a variety of natural phenomena, including biological ones.

The interactions above have been dealt with by using an off-shell scientific quantum walk (QW) model that followed the suggestion given by the curve A in Fig. 3. It should be pointed out that the principles of the QW model and the nature of the DP have at least two common features:
(A) Nonreciprocity: Mathematical formulation of the QW uses nonreciprocal algebra composed of vectors and matrices. On the other hand, the DP is a field that mediates the interaction between NPs. Since the interaction is a typical nonreciprocal physical process, the QW and DP have a common feature, represented by nonreciprocity. This allows the QW model to describe the interaction and the bi-directional transfer of the DP energy.
(B) Site: The QW deals with the phenomenon of the energy transfer from one site to its neighbor. On the other hand, since the DP is spatially localized[3)], its quantum mechanical position operator can be defined. Thus, in the case where the site of the QW is the NP on which the DP is created, the position of the DP is equivalent to that of the site of the QW.

Based on these common features, the QW model has been used for numerical calculations of the following two subjects **(a)** and **(b)**:
(a) Energy transfer of DPP[4)] through a fiber probe [21]: Multiple atoms in the fiber probe and the atom at its apex corresponded to NP_{S}s and NP_L in Fig. 5, respectively. Numerical calculations have successfully analyzed the dependence of the DPP creation probability at the apex on the profile of the fiber profile and on the magnitude of the DPP reflection at the slanted face of the fiber probe.
(b) DPP creation probability at a boron (B) atom-pair in a silicon (Si) crystal [22-24]: Multiple Si atoms and a few B atom-pairs corresponded to NP_{S}s and NP_L, respectively. The DPP energy dissipates from the B atom-pair to emit photons to the outer macroscopic space. Numerical calculations have successfully analyzed the dependences of the DPP creation probability on the length and orientation of the B atom-pair. Furthermore, the photon breeding nature has also been successfully analyzed.

It has been confirmed that the results of the numerical calculations in **(a)** and **(b)** agreed with experimental results, which implies that the QW model can be used as a powerful tool for analyzing the nature of off-shell science[5)].

3) The theory of DP creation teaches that the spin of the electric DP is zero [3,4], which has also been experimentally confirmed. Such a zero-spin field is spatially localized, as indicated by Wightman's theorem [20].

4) DPP is a dressed-photon--phonon that is created by the coupling between a DP and a phonon.

5) It should be pointed out that such agreement has never been obtained by the on-shell scientific RW model or a wave-optical model.

5. Off-shell scientific path of DP energy transfer

A two-dimensional QW model for the DPP energy transfer has been built by referring to the two-dimensional lattice in Fig. 10 [25].

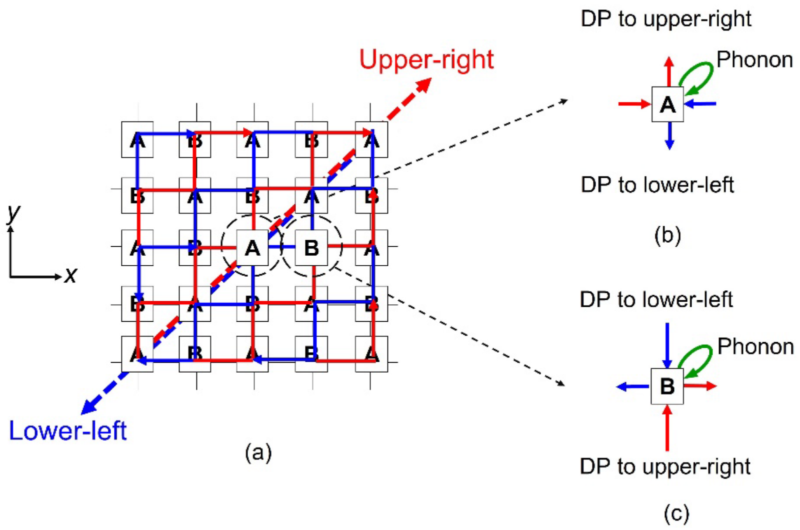


Fig. 10 Two-dimensional lattice.

(a) DPs travel to the upper-right and lower-left (red and blue broken arrows, respectively). The bent red and blue arrows represent the DP hopping from one lattice site to its neighbor, which repeats for these travels. The areas around the lattice sites A and B in (a) are magnified and shown in (b) and (c), respectively. The green loop represents a phonon.

For the following discussions, the magnitude and the direction of the input signal to the lattice are represented by a two-dimensional vector $\vec{K}_{\mathrm{in}}$. Those of the output signal are represented by a vector $\vec{K}_{\mathrm{out}}$, which is emitted from the site (sink) as the result of energy dissipation. Furthermore, those of the DPP energy transfer from site i to its neighbor site in the lattice are represented by a vector $\vec{k}_i$.

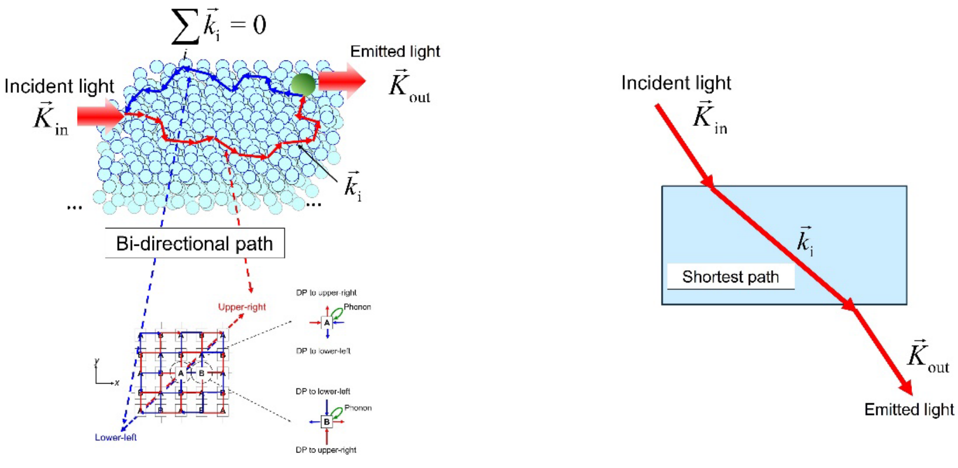
The energy conservation law requires the relation

$$\vec{K}_{\text{in}} + \sum_i \vec{k}_i = \vec{K}_{\text{out}}, \tag{1}$$

to hold, where $\sum_i \vec{k}_i$ represents the sum of the transferred DPP energy at all the sites in the lattice and is composed of the energies transferred toward the upper-right and lower-left directions in Fig. 10. These two directions correspond to the bi-directional energy transfer of the DPP that originates from the interaction, described in **(A)** in Section 4.

As a representative off-shell scientific experimental phenomenon, photon breeding generates the output signal $\vec{K}_{\text{out}}$ that is equal to the input signal $\vec{K}_{\text{in}}$ [22-24]. This means that photon breeding realizes a transmittance T as high as 100 %, which indicates **[Feature 1]** in Subsection 3.1. This can be realized if $\sum_i \vec{k}_i = 0$ in eq. (1) holds, which is possible by optimally adding the paths of bi-directional transfer towards the upper-right and lower-left directions above. That is, the optimal vectorial sum of the red and blue arrows in Fig. 10 can form a closed loop to realize $\sum_i \vec{k}_i = 0$. It should be pointed out that such perfect transmission corresponds to the QW nature of comfortability [26].

Since the number of paths is finite in an actual two-dimensional lattice due to its finite number of sites, a path with $\sum_i \vec{k}_i = 0$ may not exist. However, by increasing the number of sites, it is expected that the value of $\sum_i \vec{k}_i$ can gradually decrease and, finally, converge to zero. The possibility of this convergence has been indicated by the experimental results of Fig. 6(d), which demonstrated the increase in the attainable distance L_0 with the increase in the height H. In short, the DPP may transfer through the path with $\sum_i \vec{k}_i = 0$, as is schematically explained by Fig. 11(a), not through the shortest path given by the on-shell scientific model of Fig. 11(b).



(a) (b)

Fig. 11 Comparison between the paths of energy transfers of a DP and conventional propagating light.
(a) Energy transfers of the DP in the systems in Fig. 7(a). (b) Energy transfer of the propagating light through the macroscopic systems in Figs. 7(b).

6. Summary

The first part of this paper reviewed the principles of size-dependent resonance, bi-directional energy transfer, and subsequent energy dissipation. The second part presented experimental results on energy transfer, dissipation, and light emission from multiple three-dimensionally arranged NPs. These results implied that the DP energy transferred not through the shortest path but through a unique path via which the emitted light power took the maximum value. The third part reviewed the results of preliminary numerical calculations by using a random walk model. The calculations had serious problems that originated from the principle of the on-shell science used in the model. In order to solve these problems, it was pointed out that numerical calculations using a quantum walk model based on the principle of off-shell science was promising. Finally, it was suggested that the unique path above can be found by further improvements of this quantum walk model.

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