Chapter 1
What is a Dressed Photon?

Incipe quidquid agas, pro toto est prima operis pars.
Decimus Magnus Ausonius, *Idyllia*, XII

To start with our description of the dressed photon (DP) and its applications, the present chapter surveys some common concepts that are used throughout this book.

1.1 Comparison with Conventional Light

First, try to answer the following three simple questions.

[Question 1]
After the end of a glass fiber is sharpened to form a nanometer-sized apex, its tapered side surface is coated with an opaque film, leaving the apex of the fiber uncoated to form a nanometer-sized aperture. Such a sharpened glass fiber is called a fiber probe (probe), which has been frequently used in the technical fields to be covered in this book. Now, assume that this probe is placed in a vacuum chamber, as shown in Fig. 1.1. The chamber is filled with a low-pressure gas, whose molecules dissociate by absorbing ultraviolet light. Visible light is injected into the probe from its tail.

Now, the question is: Do the freely moving gas molecules in this chamber dissociate when they arrive at the apex of the probe?

[Question 2]
As an example, consider optical lithography, which is a popular method of forming a fine pattern on the surface of a crystal substrate, such as silicon (Si) (Fig. 1.2). Here, the crystal surface to be patterned is coated with a photo-resist film, whose structure changes due to a photo-induced chemical reaction caused by the absorption of ultraviolet light. A photo-mask with a nanometer-sized aperture is placed on the photoresist film, and the photo-mask surface is irradiated with visible light.

M. Ohtsu, *Dressed Photons*, Nano-Optics and Nanophotonics,
DOI: 10.1007/978-3-642-39569-7_1,

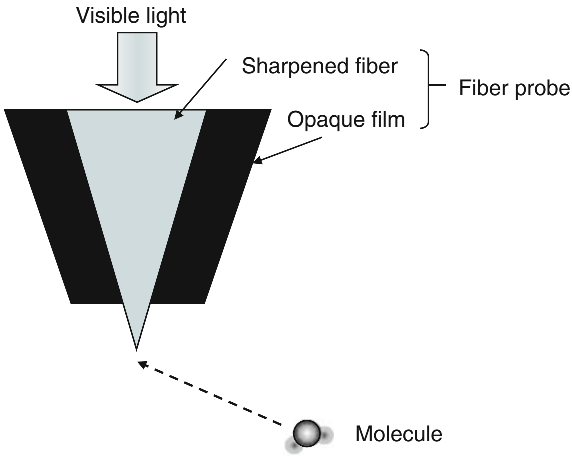

Fig. 1.1 Dissociation of molecules by using visible light and a fiber probe with a nanometer-sized apex

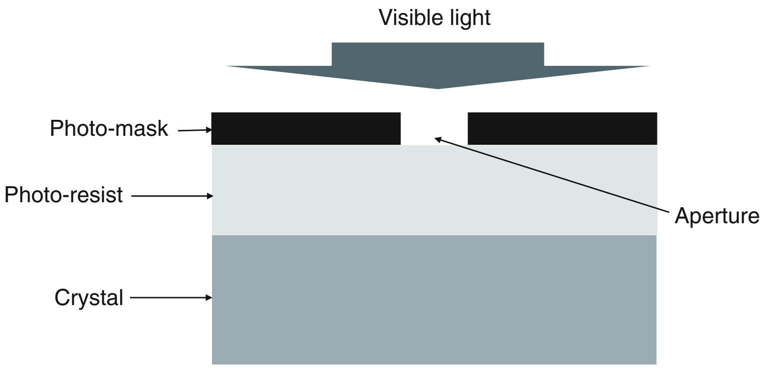

Fig. 1.2 Optical lithography using visible light and a photo-mask with a nanometer-sized aperture

Now, the question is: Is the aperture pattern of the photo-mask transcribed to the surface of the photo-resist film?

[Question 3]
Is it possible to fabricate a light emitting diode by using a bulk Si crystal?

The answers to these three questions must be "No!", as a natural consequence of the principles of conventional optical and materials sciences. The reasons are as follows:

[Question 1]
There are two reasons: (1) This probe works as a cut-off optical waveguide to visible light because the aperture size is much smaller than its wavelength. Therefore, the molecules in the proximity of the probe apex are not illuminated by the light.

(2) Even if they were illuminated, they would not dissociate because they do not absorb visible light, whose photon energy is much lower than that of ultraviolet light.

[Question 2]
There are two reasons, which are almost equivalent to those of Question 1: (1) The visible light does not transmit through the photo-mask because the size of the aperture is much smaller than its wavelength, meaning that the photo-resist is not illuminated by the light. (2) Even if it were illuminated, no chemical reaction would be induced because the photo-resist film does not absorb visible light, whose photon energy is much lower than that of ultraviolet light.

[Question 3]
Since Si is an indirect transition-type semiconductor: Electrons have to transition from the conduction band to the valence band in order to emit light. However, in the case of an indirect transition-type semiconductor, the wave-numbers (momenta) of the electrons at the bottom of the conduction band and at the top of the valence band are different. Therefore, for electron–hole recombination, a phonon is required in order to satisfy the momentum conservation law. In other words, an electron–phonon interaction is required. However, the probability of this interaction is low, resulting in a low interband transition probability.

In reality, however, the answers to these questions have already turned out to be "Yes!", with the advent of a novel optical science that overturns long-held beliefs in conventional optical and materials sciences. One objective of this book is to describe the reasons why the answers have turned out to be "Yes!".

To answer "Yes!" to Questions 1 and 2, one has to assume that a minute light field is generated on a nanometer-sized material (called a nanomaterial; for example, the probe apex or the photo-mask aperture), and furthermore, that its energy is as high as that of ultraviolet light. To answer "Yes!" to Question 3, one has to assume that this minute light field is generated also in the Si crystal, which assists the electrons in order to satisfy the momentum conservation law. The details of the reasons for the affirmative answers to Questions 1–3 will be described in Sects. 6.1, 6.2, and 7.3, respectively, from which it will be found that this minute light field is nothing more than the dressed photon (DP). By exploiting the interaction between the DP and the nanomaterial, a novel and innovative optical technology, called "dressed-photon technology", has emerged.

Table 1.1 classifies several optical technologies according to the combination of light and material used. Among them, the ones using propagating light are nothing more than conventional optical technology, which is also called photonics. Although some recent optical methods exploit nanomaterials, they still remain in the category of conventional optical technology because propagating light is used. Thus, their answers to Questions 1–3 are still "No!".

The conventional optical technologies in the right column in this table exploit the wave nature of propagating light. One way to distinguish the differences between

Table 1.1 Classification of optical technologies according to the combination of light and materials used

	Nanometric dressed photon	Macroscopic propagating light
Nanometric material	Dressed-photon technology (Nanophotonics)	Plasmonics, metamaterials, and photonic crystals
Macroscopic material	———————	Conventional optical technology

technology that exploits DPs and technology that exploits propagating light is to examine whether the momenta of the particles involved in the light–matter interaction (photons, electrons, and phonons) are conserved or not: The uncertainty relation $\Delta k \cdot \Delta x \geq 1$ holds between the uncertainty Δk of the wave-number k of the light (the photon momentum) and that Δx of its position x. In the case of the DP, since $\Delta x \ll \lambda$ holds because its size is smaller than the optical wavelength λ, one derives $\Delta k \gg k$ from the uncertainty relation . This means that the wave-number and the momentum are uncertain and non-conserved. In other words, the dispersion relation, i.e., the relation between the wave-number (momentum) and the energy, cannot be used for analyzing phenomena in which the DP is involved. Accordingly, the refractive index, representing the phase-delayed feature of the optical response of the material, cannot be the fundamental physical quantity.

On the other hand, in the case of propagating light, since $\Delta k \ll k$ holds because $\Delta x \gg \lambda$, the uncertainties of the wave-number and the momentum are negligible, and these quantities are conserved. Thus, the wave-number, momentum, dispersion relation, and refractive index are allowed to be used to describe phenomena in which propagating light is involved. Although the recently developed areas of plasmonics, metamaterials, and photonic crystals employ sub-wavelength–sized materials, they are unrelated to dressed-photon technology because they use propagating light and rely on the dispersion relation.

1.2 Light–matter Interactions via Dressed Photons

Conventional optical technology has relied on materials science and technology to explore and develop novel materials. By processing these materials, optical devices have been constructed for efficiently emitting, detecting, or modulating propagating light. In other words, conventional optical technology has used propagating light merely as a tool instead of exploring new types of light. In contrast, dressed-photon technology was born as a result of exploring a new type of light, that is, the DP. Since conventional classical and quantum theories of light cannot be directly applied to describe the DP, novel concepts and theoretical bases are required.

In the conventional quantum theory of light, the concept of a photon was established by quantizing the electromagnetic field of light that propagates through macroscopic free space whose size is larger than the wavelength. A photon corresponds to an electromagnetic mode in a virtual cavity defined in free space. Since a photon is massless, it is difficult to express its wave function in a coordinate representation in order to draw a picture of the photon as a spatially localized point particle like an electron. Thus, interactions between photons and electrons in a nanometric space must be carefully investigated. For this investigation, this book always pays attention to whether the light field is nanometric or macroscopic in size, an approach that has never been described in conventional textbooks on light. The main scope of conventional optics textbooks has been a comparison between the classical and quantum features of light.

For describing a light field in a nanometric space, the energy transfer between two nanomaterials and detection of the transferred energy are formulated by assuming that the nanomaterials are arranged in close proximity to each other and illuminated by propagating light (Sect. 2.1). Although the separation between the two nanomaterials is much shorter than the optical wavelength, it is sufficiently long to prevent electron tunneling. As a result, the energy is transferred not by a tunneled electron but by some sorts of optical interactions between the two nanomaterials.

A serious problem, however, is that a virtual cavity cannot be defined in a sub-wavelength–sized nanometric space, unlike the conventional quantum theory of light. In order to solve this problem, an infinite number of electromagnetic modes, with an infinite number of frequencies, polarization states, and energies, must be assumed. In parallel with this assumption, infinite numbers of energy levels must also be assumed for the electrons and holes. As a result of these assumptions, the DP is found to be a that dresses the material energy, i.e., the energy of the electron–hole pair. The interaction between the two nanomaterials can be represented by energy transfer due to the annihilation of a DP from the first nanomaterial and its creation on the second nanomaterial.

The DP field is modulated temporally and spatially. The temporal modulation feature is represented by an infinite number of modulation sidebands, i.e., an infinite series of photon eigen-energies. As a result of the dressing mentioned above, the electron–hole pair also dresses the photon energy, with the result that its eigen-energy exhibits a similar modulation feature. Consequently, a dual relation of the modulation is established between the photon and the electron–hole pair.

The DP has always been named the "optical near field" in the author's early study [1–3]. Although this name appropriately represented the spatial features of the DP, it was not sufficient to represent the detailed interactions with nanomaterials, nor to convey a physical picture of the dressing the energy of the electron–hole pair. Thus, the name "optical near field" has been replaced with "DP" in order to express the detailed interaction explicitly and to provide a clearer physical picture.

Nanophotonics, an innovative optical technology based on the DP, was first proposed by the author and has led to the development of a variety of applications [4–7]. A recent trend in optical technology is the tendency to accept even plasmonics, metamaterials, and photonic crystals (refer to the right column in Table 1.1) into the category of Nanophotonics. However, since they use propagating light and, thus, are unrelated to the DP from the viewpoint of light–matter interactions in nanometric space, the original field of Nanophotonics has now been renamed as "dressed-photon technology" to avoid confusion.

The actual nanomaterials used for dressed-photon technology are buried in or fixed on a crystal substrate and are illuminated by light. That is, the actual nanomaterials are always surrounded by a macroscopic system composed of macroscopic materials and electromagnetic fields. Therefore, the contribution from the macroscopic system must be included in the analysis of the energy transfer between the nanomaterials, which is not straightforward (Sect. 2.2). Furthermore, it is also difficult to define a virtual cavity for a nanometric system surrounded by a macroscopic system. In order to avoid these difficulties, a novel theory was established to describe the "effective interaction" between nanomaterials mediated by the DP. This interaction is also called a "near-field optical interaction", whose energy is expressed by a Yukawa function. Its magnitude rapidly decreases with increasing separation between the two nanomaterials, whose decay length is equivalent to the size of the nanomaterial. The spatially modulated feature of the DP field is represented by this Yukawa function, and a unique spatial feature of the interaction, named "hierarchy", appears due to the size-dependent spatial modulation. This hierarchy has been applied to information security systems (Sects. 8.1–8.3).

1.3 Energy Transfer Between Nanomaterials

Semiconductor nanomaterials, called quantum dots (QDs), have often been used for dressed-photon technology. Novel states of coupling between QDs have been found through study of the interactions between electrons, holes, and excitons in QDs in order to describe the energy transfer mediated by DPs and subsequent relaxation between closely spaced QDs. In the case of DP-mediated interactions, the long-wavelength approximation is invalid because the range of interaction is as short as the size of the QDs. This suggests that an electric dipole transition that has been forbidden in the case of propagating light excitation is allowed in the case of DP excitation. This means that the electric dipole-forbidden energy levels in QDs can be exploited for nanometer-sized photonic devices (DP devices; Chap. 5). The advantage of using these forbidden energy levels is that the contribution of the propagating light to the DP device operation can be excluded in order to avoid malfunction of the device.

In a DP device, DPs mediate the transfers of the energies of the electrons, holes, and excitons in a nanomaterial to an adjacent nanomaterial, and uni-directional energy transfer is realized by the subsequent energy dissipation via interactions with phonons in the heat bath, destroying quantum coherence (Sect. 3.2). As a result, signal transmission becomes possible from one nanomaterial to the other, guaranteeing reliable operation of the DP device.

1.4 Novel Phenomena Arising from Further Coupling

In actual materials, such as semiconductors, the contribution of the crystal lattice also needs to be included in the theoretical model of the DP. By doing so, it has been found that the DP interacts with phonons, i.e., quanta of normal modes of the crystal vibration. As a result of this interaction, a novel quasi-particle is generated on the surface of a nanomaterial (Chap. 4), and the energy of this quasi-particle can transfer to the adjacent nanomaterial, where it induces a novel photo-chemical reaction (Chap. 6). Here, since translational symmetry is broken due to the finite size of the nanomaterial, the momentum (or wave-number) of the quasi-particle has a large uncertainty and is non-conserved, as was the case of the DP itself. Furthermore, in a finite-sized nanomaterial, it is possible to generate multi-mode coherent phonons as a result of the DP–phonon interaction.

The quasi-particle generated by the DP–phonon interaction is called a dressed-photon–phonon (DPP), which is a DP dressing the energy of the multi-mode coherent phonon. As was the case of the DP, the DPP field is temporally and spatially modulated. As a result of the temporal modulation, the DPP gains an infinite number of modulation sidebands. As a dual relation of this modulation, the electron–hole pair dresses the energies of the photon and phonon, which means that the eigen-energy of the electron–hole pair in the nanomaterial is modulated. Furthermore, as a result of spatial modulation, the DPP field leaks out from the nanomaterial surface with a spatial extent as short as the size of the nanomaterial, as was the case of the DP field. Therefore, the DPP can transfer energy from one nanomaterial to another if these two nanomaterials are in close proximity to each other. Since the transferred energy can modulate the electron–hole pair in the second nanomaterial, the quantum state of the second nanomaterial has to be represented by the direct product of the electronic state and phonon state for estimating the magnitude of the transferred energy. The phenomena induced by the DPP have enabled emission and absorption of photons in a material even when their energies are lower than the bandgap energy E_g of electrons in the material. By utilizing these unique phenomena, a novel technology has been developed for up-converting the optical and electrical energies (Chap. 7).

In the conventional interaction between propagating light and a material, the quantum state represented by the above-mentioned direct product was not required because only the electric dipole-allowed transitions have been involved. As a result, in contrast to the interaction mediated by the DPP, the phenomena originating from this interaction are induced only when the photon energy of the propagating light is larger than E_g. In other words, light with a photon energy smaller than E_g (i.e., with a wavelength longer than the cut-off wavelength $\lambda_c = E_g/hc$) is not emitted or absorbed by the material.

Conventional optical technologies, i.e., photonics, in the right column of Table 1.1, have used a variety of materials to construct devices that emit or absorb propagating light. Nanotechnology has rapidly progressed in recent years, producing several nanomaterials such as carbon nanotubes (CNTs) and QDs. When they are used in a laser, for example, a large number of CNTs or QDs are provided in the laser cavity to be used as light emitting media. Although they contribute to improving some aspects of the laser oscillation performance as compared with using a conventional macroscopic material, these devices are nothing more than one class of laser. That is, since this technology improves some aspects of the optical device performance, the innovation brought about by this technology is regarded merely as a “quantitative innovation”.

Photonics developed rapidly after the advent of lasers in the 1960s and matured in the 1990s. However, it has become difficult to meet the requirements of increasing speed/capacity in optical information transmission, increasing density in optical information storage, and increasing resolution in optical fabrication, that are demanded in order to construct infrastructures for future society. Furthermore, since rare or toxic materials have been used for optical devices, it is difficult to solve the problems related to resource conservation and environmental protection.

The principal cause of these problems is that propagating light has been used. Stated another way, spatial averaging–the so-called long-wavelength approximation–has been used for light–matter interactions. This averaging, or approximation, involves diffraction of light, which limits miniaturization of devices, acting as a barrier to increasing the optical storage density, increasing the resolution of optical fabrication, and so on–a problem known as the diffraction limit. Furthermore, only the electric dipole-allowed transitions have been exploited because of the long-wavelength approximation. That is, only materials compatible with these types of transitions have been explored and used to construct optical devices. In other words, conventional optical technology has been based on the principle of wave optics, where light and matter are dealt with separately. On the other hand, since dressed-photon technology uses DPs, i.e., virtual photons dressing material energy, it can be called “light–matter fusion technology”, which fuses light and matter instead of dealing with them separately and independently. The principle of the DP has given birth to novel optical functions that break through these technical limits, including the diffraction limit. An essential innovation brought about by such breakthroughs is called a “qualitative innovation”.

In order to answer the questions “What is the dressed photon?” and “What is its contribution to optical science and technology?”, this book reviews theoretical bases established by combining the concepts of optical science, quantum field theory, and condensed matter physics. On these bases, all of the answers to Questions 1–3 in Sect. 1.1 turn out to be “Yes!”. Furthermore, these principles have been already applied to a variety of technologies, including optical devices, optical fabrication, energy conversion, and optical information security systems, allowing us to break through the limits faced by conventional optical technology and realize qualitative innovations. As a by-product, quantitative innovations have also been realized. dressed-photon technology is now progressing rapidly, establishing new bases of optical technology.

Table 1.2 Annihilation operators used in this book*

Symbol for operator (equation number in which these operators appear for the first time)	Quasi-particle
$\hat{a}$ (2.1)	Photon
$\tilde{a}$ (2.20)	Dressed photon
$\hat{b}$ (2.1)	Electron–hole pair (Exciton)
$\hat{c}$ (4.16)	Phonon
$\hat{e}$ (2.3)	Electron
$\hat{h}$ (2.3)	Hole
$\hat{\alpha}$ (4.30a)	Dressed-photon–phonon
$\hat{\xi}$ (2.27)	Exciton polariton

*The corresponding creation operator, i.e., the Hermitian conjugate of the annihilation operator, is expressed by adding the superscript † to each symbol in this table

1.5 Symbols for Quantum Operators

For the readers' convenience, Table 1.2 summaries the annihilation operators of photons and other relevant particles, which will appear in the following chapters.

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http://www.springer.com/978-3-642-39568-0

Dressed Photons
Concepts of Light–Matter Fusion Technology
Ohtsu, M.
2014, X, 324 p. 156 illus., 26 illus. in color., Hardcover
ISBN: 978-3-642-39568-0