Novel functions and prominent performance of nanometric optical devices made possible by dressed photons

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Abstract

This paper describes the operation of an optical buffer memory device in order to demonstrate a novel function made possible by dressed photons (DPs). It was shown that output signals repeatedly appeared with a period of 150 ps by applying a readout optical pulse to the device. Next, to demonstrate the prominent performance achievable by DP devices, single-photon operation with a probability as high as 99.3 % was confirmed. Finally, the magnitudes of the dissipated and consumed energies of the DP device were shown to be 10^4 times lower than those of a CMOS logic gate.

1 Introduction

Optical technology developed rapidly with the advent of lasers in the 1960s and matured in the 1990s. Since then, it has become difficult to meet the requirements that are demanded in order to construct infrastructures for future society, namely, the increasing speed/capacity in optical information transmission, the increasing density in optical information storage, and the increasing resolution in optical fabrication.

The principal cause of these difficulties is that propagating light has been used. In other words, the long-wavelength approximation has been used for analyzing light–matter interactions. This approximation involves diffraction of light, which limits miniaturization of devices—a problem known as the diffraction limit. Furthermore, only electric dipole-allowed transitions have been exploited because of the long-wavelength approximation, by dealing with light and matter separately.

On the other hand, the principle of the dressed photon (DP) has given birth to novel optical functions that can break through the diffraction limit. The DP, a novel off-shell quantum field, is created by the interaction between a photon and an electron (or an exciton) in a nanometric space [1]. It should be noted that the DP is incompatible with the on-shell propagating light field. A variety of nanometer-sized optical devices have been developed by using DPs for transmitting or controlling optical signals [2]. These devices, called DP devices, have brought novel functions with prominent performance levels, which can meet the requirements above to construct infrastructures for future society.

Section 2 of this paper describes an optical buffer memory device that demonstrates a typical example of the novel functions of DP devices. As examples of the prominent performance of achievable by DP devices, Section 3 demonstrates that the dissipated and consumed energies of this optical buffer memory device were extremely low. A summary of the paper is given in Section 4.

2 Optical buffer memory device

In order to explore the possibility of realizing an optical buffer memory device, preliminary experiments were carried out by using a nano-optical condenser [3], called an optical nano-fountain, whose structure is schematically explained by Fig. 1(a). Three groups of cubic CuCl nano-materials (NMs) embedded in a NaCl host crystal at a temperature 40 K were used: A large NM (L-NM with the side length l_L) was surrounded by a large number of small NMs (S-NMs with the side lengths l_S). Medium-sized NMs (M-NMs with the side lengths l_M) were placed in the spaces between the L-NM and the S-NMs. The ratio $l_S : l_M$ was adjusted to be $1:\sqrt{2}$ so that the lowest excited energy level of an exciton in an S-NM and the second-lowest excited energy level in the M-NM were resonant with each other. The ratio $l_M : l_L$ was also adjusted to be $1:\sqrt{2}$ to achieve resonance between the M-NMs and the L-NM. For these adjustments, the averages of l_S, l_M, and l_L were set to be approximately 3 nm, 5 nm, and 7 nm, respectively, in the device fabrication process.

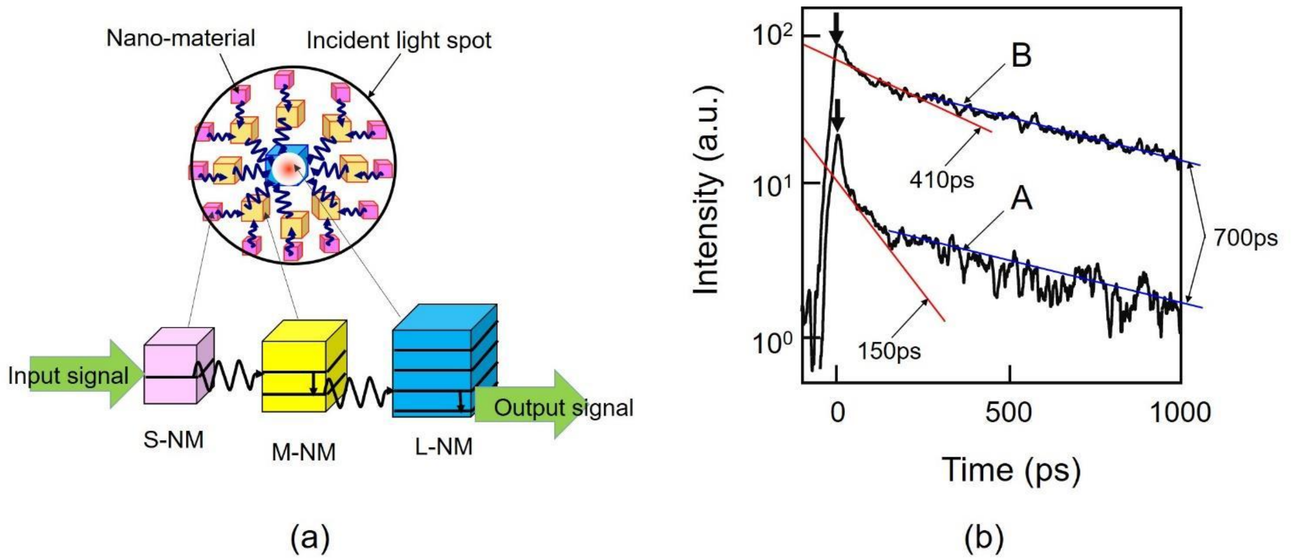


Fig. 1 A nano-optical condenser.

(a) The structure.

(b) Measured temporal variation of the emitted light intensities. Curves A and B represent the intensities, emitted from M-NMs and L-NM, respectively. The peaks at $t=0$, identified by the downward arrows, represent artifacts that originated from the incident optical pulse.

This device used autonomous DP energy transfers from the S-NMs to the M-NMs and subsequently to the L-NM for collecting the incident optical energy at the L-NM. Figure 1(b) shows the measured results of the relation between time (t) and the light intensity emitted from the device after it was illuminated by a short optical pulse of 325 nm-wavelength at $t=0$ [4]. The curve A is the intensity of the light emitted from the M-NMs as a result of the DP energy transfer from the S-NMs to the M-NMs and subsequent relaxation of the excitons from the second-lowest excited energy level to the lowest excited energy level in the M-NMs. The curve B is the intensity of the light emitted from the L-NM as a result of the DP energy transfer from the M-NMs to the L-NM and subsequent relaxation of the exciton in the L-NM. The peaks of these curves at $t=0$, identified by the downward arrows, represent artifacts that originated from the incident optical pulse.

As a result of fitting exponential functions to these curves, the decay time constant of the curves A and B were found to be 150 ps and 410 ps, respectively, in the range $0 \le t \le 300\text{ps}$. These values corresponded to the DP energy transfer times. In the range $t \ge 300\text{ps}$, the two curves decayed with the time constant of 700 ps, which corresponded to the conventional radiation lifetime of the L-NM [5].

Based on the preliminary experimental results above, the novel optical buffer memory was expected to operate within a time shorter than the radiation lifetime of the NM. Figure 2 schematically explains the structure and operation of the optical buffer memory device. For holding the input optical signal in this device, nutation of the DP energy between two NMs of equal side length was used, as is shown in Fig. 2(a). The buffering time corresponds to the cycle time of the nutation. To read out the held signal, a NOT logic gate, whose operation was based on DPs [6], was installed in proximity to the two NMs (Fig.2(b)). Application of a readout optical pulse to the NOT logic gate created output photons that propagated out from the device.

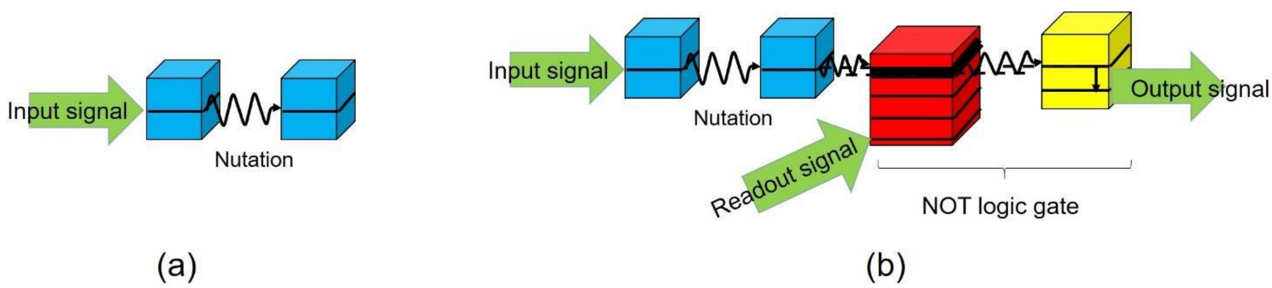


Fig. 2 An optical buffer memory device.

(a) Holding an optical signal by means of nutation of the DP energy between two NMs.

(b) Acquiring an optical signal by applying a readout optical pulse to the NOT logic gate.

As was the case in Fig. 1, CuCl NMs were used for demonstrating the device operation. Pump-probe spectroscopy was used for acquiring spectral data, where the pump and probe pulses corresponded to the optical input and readout pulses, respectively. Their pulse widths were 2 ps. Figure

3(a) is the spatial distribution of the light intensity emitted by illuminating the NMs with 325 nm-wavelength light. Figure 3(b) represents the spectral profile of the light emitted from NMs located in the area surrounded by a broken circle in Fig. 3(a). The peaks A and B correspond to the input signal (the illuminated light) and the light applied for readout, respectively. The peak C is the output signal, by which the operation of the optical buffer memory was successfully confirmed.

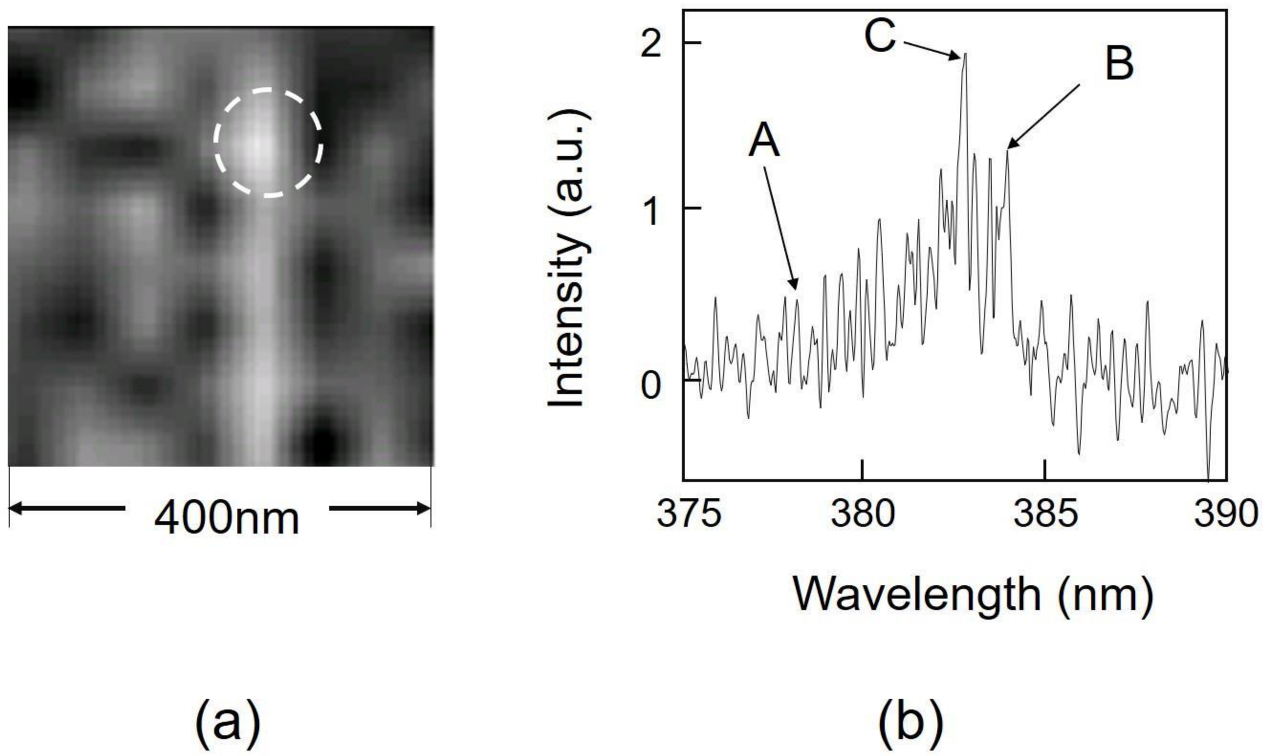


Fig. 3 Result of experiments using CuCl NMs.

(a) Spatial distribution of the emitted light intensity.

(b) Spectral profile of the emitted light acquired from the area surrounded by a broken circle in (a). Peaks A and B correspond to the illuminated light and the light for readout, respectively. Peak C is the output signal.

Figure 4 is the temporal variation of the output signal intensity plotted as a function of the time delay, i.e. the time difference between the applications of the input and readout pulses to the device. Curves A and B represent the experimental values. Curve C is the theoretical curve fitted to them by using three numerical values. They were (1) a decay time constant of 600 ps, which corresponded to the time required for the DP energy transfer observed at $0 \le t \le 300\text{ps}$, (2) a decay time constant of 1300 ps, which corresponded to the radiative relaxation observed at $t \ge 300\text{ps}$, and (3) a nutation cycle of 155 ps.

The curve C exhibits a pulsating feature, taking a first local maximum immediately after the readout pulse is applied. This corresponded to the first output signal. Subsequently, a series of output signals repeatedly appeared with a period of 150 ps, which corresponded to the nutation cycle above. Even though the device was as small as 29 nm (Fig. 2(b)), such a long period was successfully realized. This novel function, made possible by DPs, has never been seen before in conventional optical devices.

At the end of this section, it should be pointed out that another type of optical buffer memory device has been proposed by using the anti-symmetric state of the exciton due to the DP energy exchange between the two NMs [7].

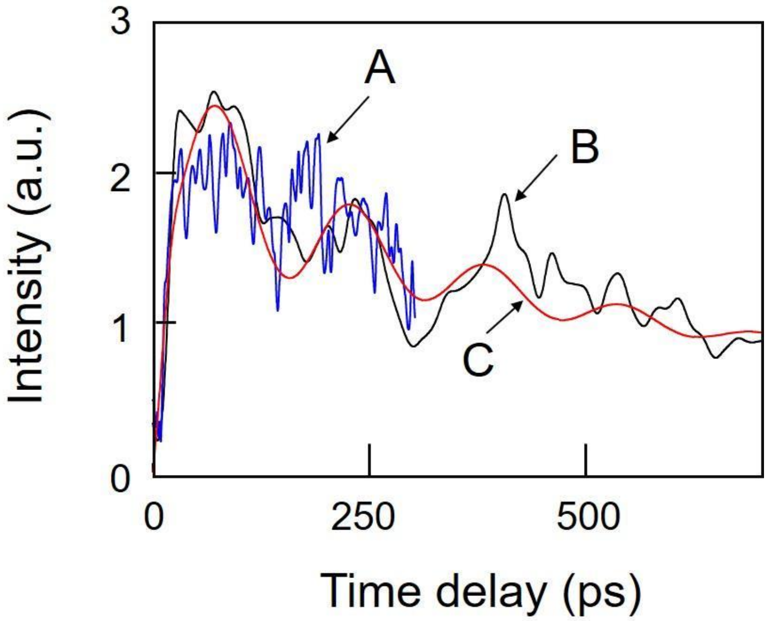
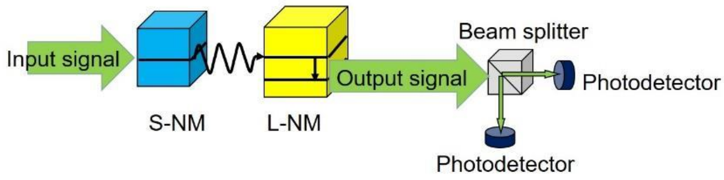


Fig. 4Temporal variation of the output signal intensity as a function of the time delay.
Curves A and B represent the experimental results. Curve C is the theoretical curve fitted to the curves A and B.

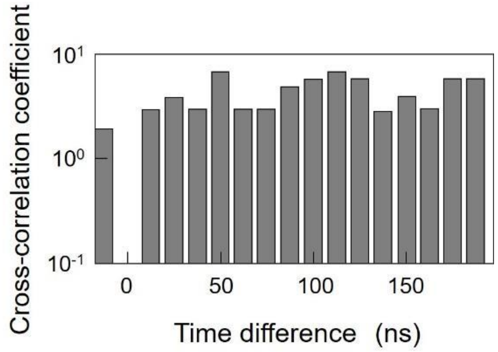
3 Single-photon operation and extremely low-energy consumption

After an exciton is created by injecting a photon to the input terminal NM of the DP device, a photon is created by subsequent DP energy transfer to the output terminal NM and relaxation. Thus, the DP device is expected to be operated by a single photon. This single-photon operation has been confirmed by photon correlation experiments [8]. As shown in Fig. 5 (a), two cubic NMs (S-NM and L-NM) whose side length ratio was adjusted to $1:\sqrt{2}$ were used, as was the case in Fig. 1.

Figure 5(b) shows the experimental results acquired by using cubic CuCl NMs embedded in a NaCl host crystal at a temperature of 15 K [9]. The horizontal and vertical axes represent the time difference between the detections by two photodetectors and the cross-correlation coefficient between the two detected light intensities. When the time difference was zero, the value of the measured cross-correlation coefficient was nearly zero, which meant that the quantum state of the photon was in an anti-bunching state. From these experimental results, the probability of occurrence of the single-photon emission event was estimated to be as high as 99.3%.



(a)



(b)

Fig. 5Experimental results for single-photon operation.

(a) Setup of photon correlation experiment.

(b) Measured dependence of the cross-correlation coefficient on the time difference between the detections by two photodetectors.

Such a high probability of single-photon emission is due to the following blockade mechanisms: If two excitons are created in the S-NM by a single input photon, the exciton energy of the lowest excited level decreases by about 30 meV due to coupling of the two excitons. Thus, this exciton energy is detuned from the input signal energy and also from the exciton energy of the second-lowest excited level in the L-NM. As a result, the creation of two excitons in the S-NM is not allowed, and DP energy transfer from the S-NM to the L-NM is blocked. Due to this blockade mechanism, DP energy transfer to the L-NM is allowed only when one exciton is created in the S-NM. As a result, only a single photon is emitted from the L-NM.

Very low energy dissipation and consumption capabilities are expected due to the single-photon operation of the DP device above. As a first step to confirm these capabilities, the magnitude of the energy dissipation is discussed in comparison with that of conventional electronic devices. For operating an electronic device, electrical wires are required to connect with a power supply and other devices. This means that the magnitude of the energy dissipation is governed not only by the electronic device itself but also by other elements, including wires, and load resistances that consume a large amount of energy. In contrast, since the DP device does not require electrical or optical wires, the energy is dissipated only in the DP device due to relaxation from a higher to a lower energy level in an NM. The rate of this relaxation is about 1×10^{11} s^{-1} in the case of a CuCl NM. Based on this value, the magnitude of the energy dissipated in the DP device was estimated to be extremely low, namely, 10^4 times lower than that of a CMOS logic gate [10]. The energy transfer process in the DP device is similar to that observed in a photosynthetic bacterium [11]. Because of its high energy transfer efficiency, this process is receiving attention as a novel optical function that is inherent to complex systems in nano-scale spaces [12].

As a second step, the magnitude of the energy consumption is discussed by estimating the magnitude of the driving energy and dissipated energy from the viewpoint of transmitting significant information to a receiver [13]. For this estimation, a basic optical information transmission system is considered, as illustrated in Fig. 6. It is composed of an input interface (a nano-optical condenser [3]) to convert the input propagating light to a DP, a NOT logic gate [6], and an output interface. The CuCl NMs in Figs. 1-5 are replaced by InAs NMs for enabling practical room-temperature operation. The output interface is composed of a gold NM to convert the created DP to propagating light [14] that reaches a photodetector. Then, it is converted to an electrical signal.

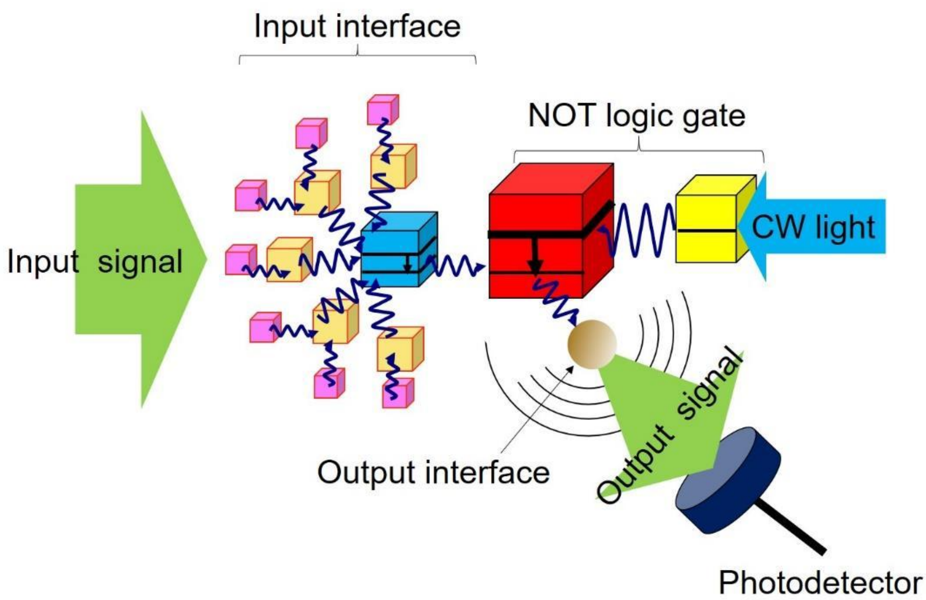


Fig. 6A system composed of an input interface, a NOT logic gate, an output interface, and a photodetector.

The intensity of the propagating light (the output signal) is required to be sufficiently high in order to achieve detection with a sufficiently large signal-to-noise ratio for definitely recognizing the transmitted information. To meet this requirement, it was estimated that the magnitude of energy consumption must be larger than 140 eV, which was approximately equal to the experimentally estimated value (156 eV). In this estimation, the magnitude of the energy consumption at the output interface was found to be the largest. That in the input interface was smaller. It should be emphasized that the magnitude in the NOT logic gate was too small to be neglected. For comparison, the magnitude of the energy consumption of a CMOS logic gate, to which a load impedance is connected, was estimated to be 6.3 MeV [15]. Since the value estimated above (140 eV) is about 10^4 times smaller, it is confirmed that the energy consumption of the system in Fig. 6 is extremely low.

Finally, the signal processing rate of the NOT logic gate in Fig. 6 was estimated by noting that this rate depended on (1) the DP energy transfer time from the input NM to the output NM, (2) the number of photons required to recognize a one-bit signal with a conventional receiver, and (3) the efficiency of the output interface. By using 50 ps [14], 100, and 0.45 for these values, respectively, the signal processing rate was estimated to be as high as 90 Mb/s. If one can utilize the device redundancy of multiple identical devices operating in parallel, the minimum duration for a single information bit can be shortened, allowing further increases in the signal processing rate.

From the estimations described above, it was confirmed that the energy consumed by DP devices was extremely low, which means that a higher degree of integration of these devices can be expected as compared with that of conventional electronic devices. Also, the much higher degree of integration compared with conventional optical devices will enable the construction of novel integrated systems that are not possible as long as conventional electrical or optical devices are used. That is, one can be released from the commonly held view in conventional technology that "light should be used for communication because of its high propagation speed, while electrons should be used for computing because of their small size." A DP computer using DP devices has been proposed as an example of the novel systems that can be constructed when released from this common view [16]. It should be noted that DP computing is completely different from conventional optical computing [17], which carries out digital information processing using several technologies based on spatially parallel processing utilizing the wave optical properties of propagating light, for example, holography. In contrast, DP computing carries out digital processing of time-sequential signals, which has never been possible by using conventional optical devices and propagating light.

4 Summary

First, as an example of the novel functions of DP devices, the operation of an optical buffer memory device was demonstrated. By applying a readout optical pulse to this device, the output signals repeatedly appeared with a period of 150 ps, which corresponded to the cycle of nutation of the DP energy between the two NMs. Second, for demonstrating the prominent performance achievable by DP devices, single-photon operation was confirmed with a probability as high as 99.3 %. Third, the magnitude of the energy dissipated in the DP device was estimated to be 10^4 times lower than that of a CMOS logic gate. Lastly, the magnitude of the energy consumed by the DP device system (composed of an input interface, a NOT logic gate, and an output interface) was estimated to be 10^4 times smaller than that of a CMOS logic gate.

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