3-4 Status of Development of Photon Number Resolving Detectors

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Photon number resolving detectors that can count number of photons in the pulses precisely are the important devices for developing universal photonic quantum gates, by combination with non-classical light. This technology will be used to establish quantum decoders that offer a significant upsurge in the capacity of communications channel. We describe our research activities for developing of photon number resolving detectors.

Keywords
Quantum communications, Quantum cryptography, Squeezed light, Quantum state, Photon-number resolving detector

1 Introduction

A photon-number resolving detector is a device that can count the number of photons in the optical pulses. This device is distinguished from a single photon detector, which detects the presence of one or more photons. Simply stated, a photon-number resolving detector must be able to provide an accurate count of the number of photons in even extremely short pulses. Development of a highly sensitive detector that can do so will be welcome news in the fields that require precise spectroscopy, including solid-state physics, astronomy, and biology. Such a device would also be used for applications in the field of quantum information, as described below.

(1) Construction of universal photonic quantum gate in combination with squeezed light and single photon light sources

Please refer to References[1]-[3] for the theoretical demonstration and more detailed information. Realization of this quantum gate will greatly advance technologies to realize optical quantum computers. This component can be applied to diverse technological areas as a quantum information device, and as such will be indispensable in this field.

(2) Improved reliability of quantum cryptography key distribution system

The quantum cryptography key distribution system now being developed for commercialization uses extremely weak coherent light. In order to avoid photon-number splitting attacks and to increase security, we need to reduce the probability of the multiphoton states asymptotically close to zero. Thus, the average photon number used per bit must be attenuated to approximately 0.1, which corresponds to an extremely low probability that a given bit will contain two or more photons. However, the number of photons in coherent light follows a Poisson distribution, such that there is a finite probability that a given bit will contain two or more photons. Even when a single photon light source is used, a photon-number resolving detector can be used to evaluate the reliability of the light source.

As shown in the above examples, photon-number resolving technology is fundamental in the field of optical quantum information. Nevertheless, many technical problems currently remain in the development of this technology. Researchers all over the world are now investigating photon-number resolving detectors using various materials and structures to improve the performance of these devices. Promising candidates have been provided by the groups of Stanford University visible light photon counter (VLPC)[4], and the US National Institute of Standards and Technology (NIST) transit edge sensor[5]. Here, we consider the affinity between optical fiber communications and the visible and near infrared region—now a cutting-edge research topic in quantum optics—and focus on a photon-number resolving detector with sensitivity in the 1.5-μm wavelength band, the so-called telecommunications wavelength. In particular, we describe the high-sensitivity charge integration photon detector (CIPD) now under development by the National Institute of Information and Communications Technology (NICT) with the aim of arriving at the implementation of a photon-number resolving technology.

2 CIPD for telecommunication wavelength

To begin, the charge integration photon detector (CIPD) is a combination of a photodetector and a charge integration readout circuit. The readout circuit used here has previously been applied to devices such as those for precise spectroscopy. Originally, it was not designed as a readout circuit for communications. Generally speaking, this is a readout circuit that improves the signal-to-noise ratio (S/N) by sacrificing readout bandwidth. We will describe the telecommunications wavelength CIPD below.

We used an InGaAs PIN photodiode with high sensitivity in the telecommunications wavelength as the photodetector. An InGaAs PIN photodiode generates an electron-hole pair per photon. If the quantum efficiency is sufficiently high, the number of photons can be resolved by accurately counting the number of charges generated. Figure 1 shows a schematic diagram of the CIPD. We cooled

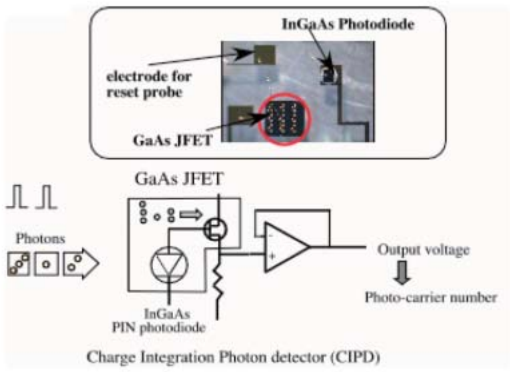

Fig.1 *Schematic diagram of telecommunications wavelength charge integration photon detector (CIPD)*

the part enclosed in the frame in the figure down to 4.2 K to suppress thermal noise and leakage current. As the first-stage amplifier, we adopted a GaAs JFET, and used it in the source follower connection. A GaAs JFET does not generate kinks or hystereses at low temperatures and provides excellent static characteristics. It has also been confirmed that a GaAs JFET produces only low levels of dielectric polarization noise, which is the thermal noise generated in the absence of charge compensation. The charges generated in the PIN photodiode are accumulated in the gate electrode of the GaAs JFET, and the voltage induced by the accumulated charges is reflected in the source electrode. The accumulated charges must be reset before the device exits the linear operation range of the FET. Generally, a FET is also used for this resetting process. However, as the FET increases noise and capacitance, we used a mechanical probe. The probe can maintain a physical distance from the electrodes except at resetting; this distance minimizes the increase in additional capacitance. The output voltage V_{out} is expressed in the following equation.

$$V_{out} = G_M \frac{MQ}{C_{in}} \tag{1}$$

Here, G_M is the source follower gain, M is the number of charges, Q is the elementary charge, and C_{in} is the input capacitance. For simplicity, we assume G_M = 1; the voltage generated when a single charge is accumulated in the gate is then 1.6 μV for an input capacitance of 0.1 pF. If the noise in the readout circuit can be suppressed to this output voltage or below, the photo-carriers (i.e., the charges) can be counted, which consequently allows us to count the number of photons.

Because the amplifier accumulates charges, the amplifier used in this case is referred to as the charge integration amplifier. Circuits generally require a readout method known as "correlation double sampling" (CDS)[6]. In other words, accumulated charge is estimated based on the difference in the output readout before and after the signal is input. In the estimation, the effective noise is determined by the readout rate, the average time of voltage readout, and the system noise spectrum. When a CDS is used, not only output but also noise is integrated over the bandwidth, so the readout rate must be optimized in signal detection. First, we can express the sampling at the time interval T as $g(t) = \delta(\tau + T) - \delta(t)$, and the corresponding Fourier transformation is expressed in the following equation.

$$\begin{aligned} |F(f)| &= \left| \int_{-\infty}^{\infty} g(t) \exp(-2\pi f t) dt \right| \\ &= 2|\sin(\pi f T)| \end{aligned} \tag{2}$$

This equation shows that the CDS effectively works as a comb filter within the given sampling period. The average over the readout time, T_0, is defined as in the following equations.

$$\begin{aligned} h(t) &= \begin{cases} 1 \ldots -T_0/2 < t < T_0/2 \\ 0 \ldots t < -T_0/2, T_0/2 \end{cases} \\ |H(f)| &= \left| \int_{-\infty}^{\infty} h(t) \exp(-2\pi f t) dt \right| \\ &= \left| \frac{\sin(\pi T_0 f)}{\pi f} \right| \end{aligned} \tag{3}$$

As is clear from this equation, the CDS acts as a lowpass filter. Finally, the noise voltage in the CDS is expressed in the following equation.

$$V_{noise.CDS}^2 = \int_0^{\infty} \frac{V_{noise}^2 \left| F(f)^2 H(f)^2 \right|}{1 + \left(f / f_c \right)^2} df \tag{4}$$

Here, V_{noise} is the noise spectrum of the entire system, and f_c is the cutoff frequency of the external lowpass filter.

As shown in Equation (1), the important issues in this circuit are to increase the gain by reducing the input capacitance and to suppress readout noise. To suppress readout noise at or below the output voltage induced by a single charge, we inevitably need to determine the optimum operating conditions for the GaAs JFET. An effective means of reducing the capacitance is to miniaturize the gate size of the JFET. However, miniaturization of the gate is accompanied by an increase in $1/f$ noise and in random telegraph signal noise; gate size must therefore be optimized. Accordingly, we have applied our own unique noise reduction method[7], which we refer to as the "thermal cure", and have optimized the relevant operating conditions. As a result, we succeeded in reducing noise to below 500 nV/Hz$^{1/2}$ at 1 Hz for a sample with a gate width of 5 μm and gate length of 10 μm, and produced a small input capacitance of 0.037 pF for the GaAs JFET.

Reducing the photosensitive area is an effective means of reducing the capacitance of the remaining component, the InGaAs PIN photodiode. However, when the coupling efficiency with the fiber is taken into consideration, further miniaturization is difficult. On the other hand, a sample with a thick depletion layer can produce low capacitance. Accordingly, we have discovered that commercially available samples with high dopant concentrations simultaneously feature thick photoabsorption layers. Cooling such a sample to an extremely low temperature freezes the carriers and increases the depletion layer; as a result we have reduced capacitance to 0.017 pF.

By arranging the GaAs JFET and the InGaAs PIN photodiode on a CaF_2 board using the hollow mounting method, we have obtained a total input capacitance of 0.054 pF.

The output voltage is 3 μV with the accumulation of a single charge. The noise spectrum indicates a readout rate of approximately 50 Hz when resolving the number of photons with an S/N greater than 2 using the CDS. We conducted a readout test at 40 Hz.

Figure 2-1 shows a histogram for output when light is not input. The standard deviation is 0.26 electrons converted to a number of photo-carriers, so that we can expect an S/N value of approximately 4 with the accumulation of a single charge. However, in an actual application, the S/N will be approximately 2 to 3 due to effects such as those induced by power supply noise.

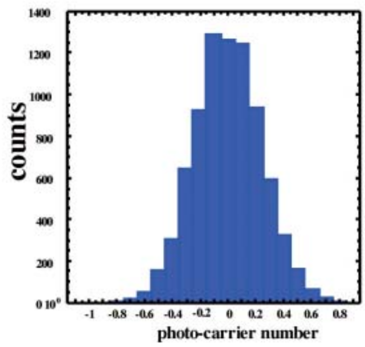

Fig.2-1 *Dark count at readout rate of 40 Hz*

Figure 2-2 shows a histogram with an average photo-carrier number of 1.04–2.85 electrons/pulse[8]. The resolution is 0.1 electrons. The curve in the figure is an approximation with a Poisson distribution and a Gaussian distribution approximating the noise in the readout circuit. The curve is expressed in the following equation.

$$N(x) = \frac{1}{\sqrt{2\pi}\sigma}\sum_{l}^{max} P_n(l)\exp\left\{-(x-l)^2/2\sigma^2\right\} \quad (5)$$

Here, P_n is the Poisson distribution with an average n number of photo-carriers; max is the cutoff number of photo-carriers (here, 20), and σ is the standard deviation of the readout noise of the CIPD.

In Fig. 2-2, multipeak structures can be recognized in up to four photon numbers. This phenomenon occurs as the photoelectrons generate a discrete output voltage. The standard deviation used in the approximation equation indicates that the photo-carrier is counted at approximately S/N = 3. Quantum efficiency is approximately 80%, and coupling efficiency between the fiber and the detector is 80% at maximum. The discrete output distribution indicates that our estimation of the input capacitance is adequate. The low-capacitance measuring technique can also be applied to the assessment of material characteristics in cryogenic device technologies. Further, our CIPD does not perform multiplication in the photodetector, so there is no risk of additional multiplication noise. Thus, the detector is expected to function even with an increase in the number of received photons. We have

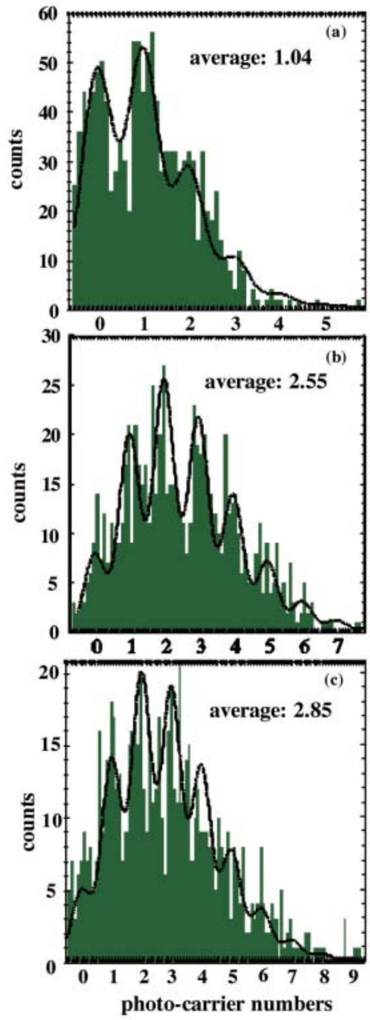

Fig.2-2 *Multipeak structure of photo-carrier distribution*

measured the distribution of coherent light up to an average of approximately 10 photo-carriers.

Figure 3 shows the results of photo-carrier distribution measurement conducted for an average of 1.58 to 10.18 photo-carriers per pulse with a resolution of 1 electron. The dashed curve is the Poisson distribution. The histogram in the figure agrees well with the Poisson distribution. Figure 3 clearly shows that the detector is capable of measuring the number of photons even when several tens of photons are input, as no multiplication processes are involved. This demonstrates the advantageously large operating range of this telecommunications wavelength CIPD. Based on the present performance of this detector, we can estimate the signal to noise ratio (S/N) and quantum efficiency in the construction of a universal photonic quantum gate. For the S/N, the photon-number resolving detector is required to perform measurement with precision corresponding to the cube root of the number of photons[1] when constructing a

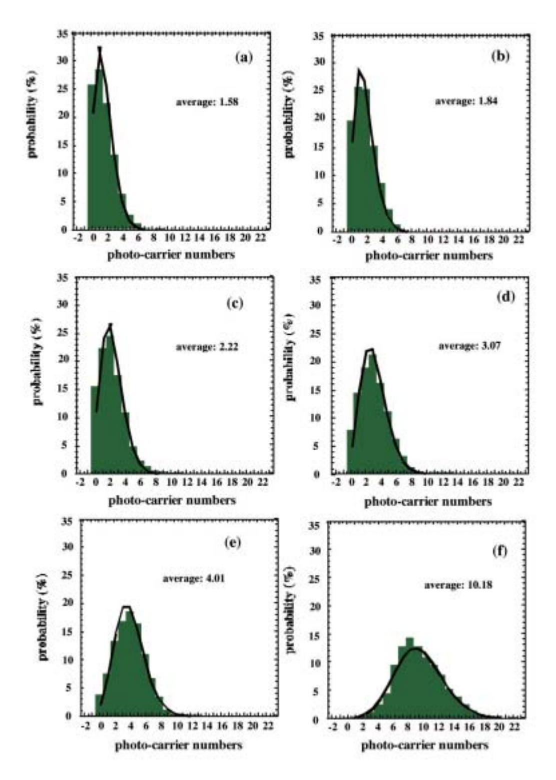

Fig.3 *Photo-carrier distribution measurement at readout rate of 40 Hz*

universal photonic quantum gate. When three photons are used for the signal, the acceptable error is approximately 1.4 photons; when 10 photons are used for the signal, the acceptable error is approximately two photons. Thus, the present performance of the detector is sufficient for application to a universal photonic quantum gate. On the other hand, almost 100% quantum efficiency is required, whereas quantum efficiency is presently at approximately 80%. If coupling loss with the fiber is included, performance is even lower. We need to improve sensitivity by combining optimization of the coating in the photodetector, an increase in the photo-absorption layer, and the high-precision alignment technique. For practical applications, we also need to increase the present operation rate from 40 Hz. The most obvious technique to do so is to reduce the noise in the FET. However, the noise spectrum of the present FET indicates a plateau at or above 1 kHz in an optimistic estimation, and we can easily imagine that a further increase in the rate will increase the integration of noise power, which leads to rapid debasement of the signal-to-noise ratio. We thus need to determine the cause of FET noise and to optimize the structure accordingly. On the other hand, although we do not use a multiplication process in the photodetector at present, in order to increase speed in the future, we should hope to develop an APD for the telecommunications wavelength featuring extremely low multiplication noise. To develop such an APD, we must improve various semiconductor processes; this will include development of a superstructure to control the mobility of electron-hole pairs and improvements in the crystallinity of the compound semiconductor, to suppress leakage current.

3 CIPD for visible and near-infrared

We are also developing a CIPD with sensitivity in the visible and near infrared regions. Today, most cutting-edge demonstrations in the field of quantum information based on photons and squeezed light use free-space optical systems in the visible and near-infrared wavelength region, due to the technological maturity of the relevant light sources and detectors. Thus a CIPD in the visible and near-infrared regions is expected to contribute significantly to these cutting-edge demonstrations. Due to these boundary conditions, the performance requirements for a visible and near-infrared CIPD are summarized as follows.

(1) Extremely high quantum efficiency (90% or greater) in the visible and near-infrared regions

(2) Superior coupling efficiency (approximately 100%) with free-space optical systems

In terms of the feasibility of achieving high quantum efficiency, VLPC based on Si have obtained approximately 100% quantum efficiency, therefore we have a strong chance of achieving the required high efficiency in the future by optimizing the thickness of the photoabsorption layer of the Si-based photodetector. On the other hand, in order to obtain superior coupling efficiency, we need not only to optimize the optical system for signal light input but also to avoid using cryogenic cryostats and to select large photosensitive areas. Avoiding operations at extremely low temperatures and using detectors with large photosensitive areas will increase the leakage current and the dielectric polarization noise generated in the detector, which in turn will make it difficult to count photoelectrons. Thus, we have adopted a Si avalanche photodiode (Si APD), which features a multiplication function for the photoelectrons. We assume operation at 77 K, which is relatively easy to implement, and have adopted a Si JFET for the first-stage amplifier of the readout circuit, as this component features low noise at this operating temperature. It has been reported that dielectric polarization noise is dominant at 77 K[9]. This dielectric polarization noise is proportional to capacitance, therefore low-capacitance mounting leads directly to low noise.

Figure 4 shows the CIPD circuit in use.

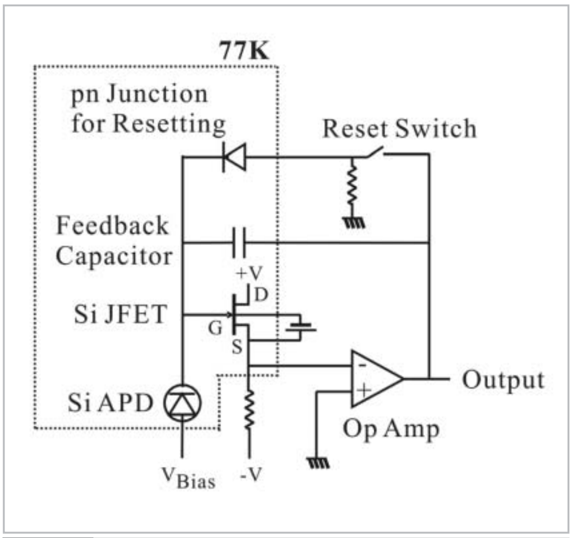

Fig.4 *Schematic diagram of visible and near-infrared CIPD. Operating temperature is 77 K with the exception of the operational amplifier*

The components with the exception of the detector form the so-called capacitive trans-impedance amplifier (CTIA), which is widely used in readout circuits for astronomical observations. The n electrons generated in the light receiving element are accumulated in the feedback capacitance C_f and are converted into voltage. The output voltage from the operational amplifier is expressed in the following equation.

$$V_{out} = \frac{nQ}{C_f} \tag{6}$$

Using a feedback circuit makes it possible to stabilize bias at the accumulation of charge and expands the operational range. We do not use a standard reset FET for the reset mechanism. Instead, we extract the charges by operating a diode with an extremely small capacitance in forward bias for resetting, in order to reduce dielectric polarization noise. The first-stage amplifier, the Si JFET, has high input impedance, low leakage current, and low noise at this operating temperature relative to other transistors. An effective means of reducing noise in the readout circuit is to reduce dielectric polarization noise. To this end, we must reduce the capacitance of each element. The dielectric polarization noise is expressed in the following equation with the complex dielectric constant C" of the dielectric material.

$$I_n^2 = 4kT\omega C'' \\ V_n^2 = I_n^2 / (\omega C_f)^2 \quad (7)$$

Here, k is the Boltzmann´s constant, T is the operating temperature, and ω is the angular frequency. The dielectric polarization noise significantly depends on the crystallinity of the material. By selecting a material with high crystallinity, we can suppress noise. We have selected a Si semiconductor with superior crystallinity to construct a visible and near-infrared CIPD in order to reduce capacitance, and consequently noise, further. Table 1 summarizes the results of reduced capacitance for various elements.

Table 1 Example of capacitance of various elements

devices	Si APD (Hamamatsu photonics S8890)	Si PIN PD (Hamamatsu photonics S7911)	Feedback capacitor (fused silica)	Si JFET (MOXTEK, MX30)
capacitance (pF)	0.52	0.23	0.074	0.33

We measured the noise for a CIPD fabricated based on these elements. The integration time for the output signal was 40 msec, which corresponds to a readout rate of 25 Hz. Figure 5 shows the noise distribution with frequency of occurrence as the vertical axis and the counts (converted to number of charges) as the horizontal axis. We obtained a standard deviation of 4.3 electrons by Gaussian fitting the measurement results. Compared to a past readout circuit[10], we were able to reduce noise by 40%.

While the noise in the readout circuit corresponds to 4.3 electrons, the amplification in the Si APD required to resolve the number of photons is more than 10 times larger.

On the other hand, it is known that a Si APD generates excess noise in multiplication. Traditionally, it was believed impossible to resolve photon numbers with a Si APD, as multiplication noise becomes dominant. However, we have found a region within the operating conditions of low temperature and a low multiplication factor in which it is considered possible to resolve photon numbers. For a Si APD with sensitivity to visible light, we arrived at low multiplication noise with an excess noise factor of 1.07 at a multiplication factor of 10.8 and an operating temperature of 77 K[11]. Figure 6 shows the rate of electron generation after multiplication with an average of 1, 3, 7, and 10 generated photo-carriers. As the system readout noise here is 7 electrons/pulse, the system does not resolve the number of photons. However, we concluded that this system reads out a single photon with a signal-to-noise ratio (S/N) of approximately 1. In the future, we plan to perform photon-number resolving experiments at the wavelength of 860 nm, for which a high-quality squeezed light source is now available,

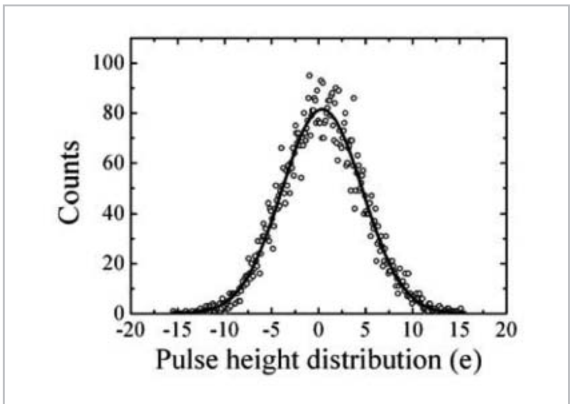

Fig.5 Charge-converted noise distribution of visible and near-infrared CIPD circuit

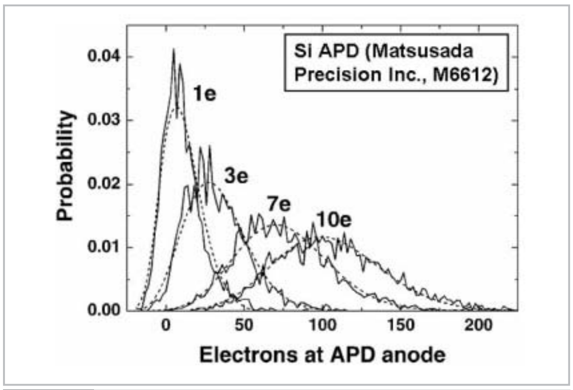

Fig.6 Rate of electron generation after multiplication with Si APD for visible light with average numbers of generated photo-carriers of 1, 3, 7, and 10

combining our exploration for an APD structure suitable for the near-infrared regions with a low-noise readout circuit.

4 Conclusions

This article mainly reports on research conducted at the National Institute of Information and Communications Technology (NICT) in the context of activities to develop photon-number resolving detectors. Of course, other methods are possible. However, although many research institutions all over the world have made various attempts at developing such detectors, not one of these attempts has yielded sufficient performance. The impact of photon-number resolving technology may well be unlimited in quantum optics or quantum information technologies. This technology is also viewed as offering a promising contribution to the development of any optical measurement techniques. Again, the impact is potentially limitless. We believe that the technological development of this device represents an urgent, important challenge. Activities in the development of photodetectors currently undertaken by the relevant manufacturers are limited mainly to efforts at improving speed in the telecommunications wavelength. We believe that NICT, as a national research institution, should take the lead in the development of photodetectors to be used in cutting-edge measurement in support of future fundamental research.

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