Single-photon level ultrafast all-optical switching

Xiao-Feng Han, Yu-Xiang Weng, Rui Wang, Xi-Hao Chen, Kai-Hong Luo, Ling-An Wu, and Jimin Zhao[a]

Institute of Physics, Chinese Academy of Sciences, and Beijing National Laboratory of Condensed Matter Physics, Beijing 100190, People's Republic of China

We demonstrate an approach to all-optical switching, where a weak beam controls a strong beam, based on three-wave mixing optical parametric amplification in a nonlinear crystal. Ultrafast switching within 400 fs has been achieved with a 130 fs single-photon level switch beam containing, on average, 0.75 photon/pulse, which can turn on/off a signal pulse containing 5.9 $\times 10^8$ photons. The transverse patterns for the on and off states are well defined and the switch has a large bandwidth of up to 10 nm. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2909540]

All-optical switching has profound application potential in communications and data processing due to its ultrafast operation and other superior properties, which are not subject to conventional electronic limitations.[1,2] Recently, low-light-level switching has emerged as an exciting direction of all-optical switching, where a weak light beam switches on/off a strong light beam,[3] a function essential for cascaded classical and quantum computation elements.[4] Single-photon level switching is critical for quantum networks based on photons[5] and has been achieved through electromagnetic induced transparency in atoms.[6–13] Using a weak beam to switch a stronger beam was first reported by Dawes *et al.*,[3] where as few as 2700 photons were observed to switch a 6500 times stronger beam. The underlying mechanism there was four-wave mixing (due to quantum interference) instability pattern formation in a warm atomic gas. Here, we present an approach that is based on three-wave mixing[14] in a nonlinear crystal, where a switch beam containing single photons is capable of switching a signal beam containing up to 5.9 $\times 10^8$ photons. In addition to being easy to implement, our approach facilitates ultrafast operation over a very large bandwidth.

The underlying mechanism is three-wave mixing optical parametric amplification (OPA) with a beta-barium borate (BBO) crystal as the core switching element. Parametric down conversion in a BBO crystal has been used before in quantum information science to produce high-intensity entangled photon pairs,[15] which can be entangled in every degree of freedom.[16] Versatile design of optical switching based on OPA has been implemented to enhance the contrast ratio in ultrashort pulse generation;[17] four-wave mixing optical parametric gain in silica and on a silicon photonic chip has also been demonstrated.[18,19] However, the performance of OPA-based ultrafast low-light-level switching, where a weak beam switches a strong beam, has not been reported so far. For weak light interactions three-wave mixing in a non-linear crystal has the advantage of a relatively large optical nonlinearity compared with that of many four-wave mixing processes. In a similar case using three-wave mixing upconversion in a BBO crystal, we have realized a time-resolved fluorescence spectrometer capable of detecting as few as 15 fluorescence photons.[20] In this work, we show that three-wave mixing OPA can be used to implement single-photon

level ultrafast all-optical switching, where the switch beam is more than 10^8-fold weaker than the signal beam.

The optical configuration of our experimental setup is shown in Fig. 1. A Ti:sapphire regenerative amplifier (Hurricane, Spectra Physics) was used to deliver 258 μJ optical pulses at a repetition rate of 1 kHz. The central wavelength was 800 nm and the pulse width about 130 fs. The output beam was split into two parts with a ratio of 7:3. The stronger beam assumed the role of a pump beam[3] after frequency doubling by a 1-mm-thick BBO crystal (SHG in Fig. 1, denoting second harmonic generation). The weaker beam was attenuated by a neutral density filter and acted as the switch beam. The pulses of both beams, in the working state, were spatially and temporally overlapped in another 2-mm-thick BBO crystal (OPA in Fig. 1), which is the major element of the switch. The focal length of the lens for the pump beam was 22 cm, and 32 cm for the switch beam. The OPA BBO crystal was cut for type I phase matching with the angles $\theta_c=32°$ and $\Phi_c=0°$. Before SHG, we used a telescope system instead of a focusing lens to reduce the beam diameter by just 50% to avoid damaging the first BBO crystal. At 192 mW average power for the 800 nm pump beam, the measured SHG conversion efficiency was 24.5%. The dielectric mirrors (DM in Fig. 1) selectively reflected the 400 nm beam. After a neutral density filter, the 400 nm pump power was measured to be 39 mW. The OPA crystal was placed about 8 mm ahead of the focal point. The angle α between the pump and switch beams was 6° outside and 3.9° inside
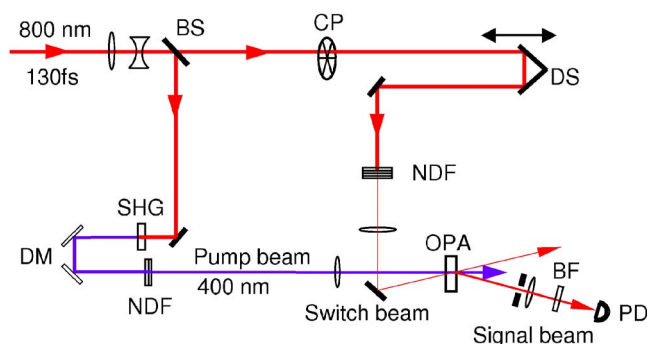

FIG. 1. (Color online) Schematic of the experiment. BS: 70%–30% beam splitter, CP: chopper, DS: delay stage, DM: dielectric mirror, NDF: neutral density filter, BF: band pass filter, and PD: photodetector. The core element of our single-photon level switch is the 2-mm-thick BBO crystal (OPA).

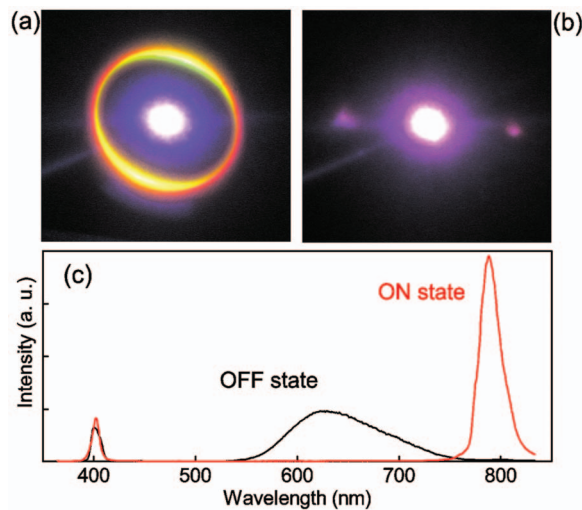[a]Electronic mail: jmzhao@aphy.iphy.ac.cn.

FIG. 2. (Color) The on/off state of the optical switch. (a) off state pattern. (b) on state pattern. (c) Corresponding spectra of the on and off states. The former gives a 10 nm or 5 THz bandwidth of the ultrafast switch. a.u.: arbitrary units.
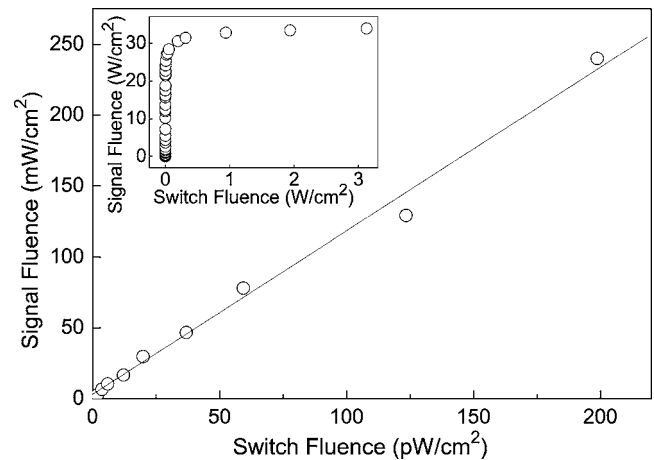

FIG. 3. Linear fluence dependence of the signal beam on the switch beam in the low energy regime. The inset gives the whole range of dependence.

the crystal. When the switch beam was blocked, the crystal position was optimized to achieve the brightest superfluorescence from the parametric down-conversion cone with the pump alone. The switch beam was then allowed in and its direction optimized, such that a 400 nm photon was annihilated to generate two 800 nm photons with the maximum efficiency. The direction of the two output beams is indicated in Fig. 1, where the signal beam is taken to be in the direction symmetric to that of the switch beam.

Figure 2 shows the output observed. Figure 2(a) is a photograph of the ring-shaped superfluorescence around the central pump spot without any switch input, with a plain IR detection card as a screen. When the switch photons are allowed in and the appropriate phase-matching conditions fulfilled, parametric amplification wins the competing nonlinear optical process (spontaneous parametric down conversion that leads to broadband optical parametric generation) and the superfluorescence ring is suppressed, being replaced by two strongly amplified bright signal spots at 800 nm, as shown in Fig. 2(b). (The distance between the two dots in the on state is slightly larger than the diameter of the visible superfluorescence ring in the off state, due to its longer wavelength). We define the ring pattern of Fig. 2(a) as the off state and the two-dot pattern of Fig. 2(b) as the on state. Switching between the two digital states is determined by the presence of the switch pulse. In other words, the switch beam controls the on and off states of the signal beam. To check the spectrum of the signal beam, we used a silicon photodetector (Thorlabs DET36A) with a band pass filter [800 nm central wavelength, 12 nm full width at half maximum (FWHM), 67% maximum transmission, and <0.5% minimum transmission] to filter out the visible fluorescence light and scattered 400 nm pump photons. Figure 2(c) shows the spectra of the on and off states, which gives the allowed operation bandwidth of the switch and is observed to be on the order of 10 nm or 5 THz.

Figure 3 shows the fluence dependence of the signal pulse on the switch pulse. Before saturation, the signal fluence is linearly dependent on the switch fluence. In the low energy regime, the signal pulse fluence is about 5.9×10^8 times stronger than that of the switch pulse, which clearly

shows that a weak beam controls the on/off state of a strong beam. The complete range of dependence that was measured is shown in the inset of Fig. 3 for completeness. The fluence of the pump pulse at 400 nm was 2762 W/cm^2.

To examine the low energy limit in more detail, we systematically reduced the switch beam intensity using multiple neutral density filters. In the extreme condition, we reduced the intensity so that each pulse contained (on average) an energy of 0.75 photon [for the $1/e^2$ intensity radius of 40.2 μm in our experiment, this corresponds to 1.5×10^{-5} photons/$(\lambda^2/2\pi)$ or 3.7×10^{-24} J/$(\lambda^2/2\pi)$ associated with each pulse[3]]. By scanning the delay stage (DS) (Fig. 1) the time-resolved signal pulse profile was recorded with a lock-in amplifier and a mechanical chopper modulating at 200 Hz. Only one scan with an integration time of 1 s was needed to observe the signal curve in Fig. 4, where the red line is a Gaussian fit. The time domain FWHM of the curve is 189.6 fs, in correspondence with the 130 fs laser pulsewidth. From Fig. 3, it is estimated that the signal pulse used to plot Fig. 4 contained about 5.9×10^8 photons. This is huge compared with available results on low-light-level switching. Our experiment shows that a beam containing, on average, one photon per pulse is capable of switching a beam that contains 5.9×10^8 photons. (However, to verify that every
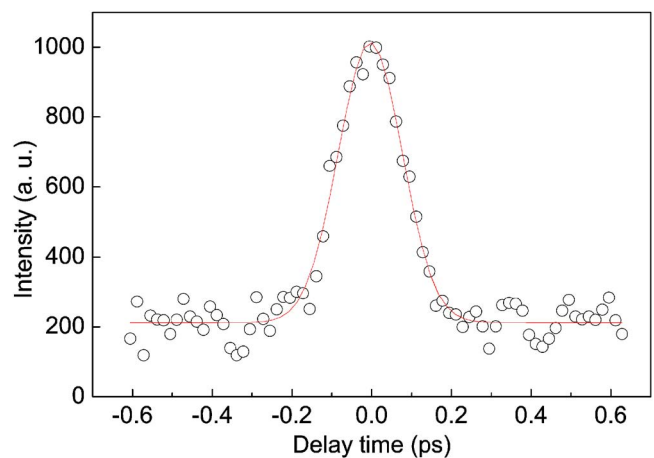

FIG. 4. (Color online) Signal pulse profile in time domain, where the switch pulse energy is, on average, as low as that of a single photon. The switch-on and switch-off operations each take about 200 fs, demonstrating ultrafast operation of the switch. The red line is a Gaussian fit.

TABLE I. Probability of obtaining n photons in one pulse for an average photon number of μ.

μ	$n=0$	$n=1$	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$
1	0.368	0.368	0.184	0.061	0.015	0.003	0.0005
0.75	0.472	0.354	0.133	0.033	0.006	0.0009	0.0001
0.4	0.670	0.268	0.054	0.007	0.0007	0.000057	0.0000038

incoming single photon will actuate the switch needs further investigation.) It is well known that the photon number fluctuations of a coherent source of laser light are described by Poissonian statistics, i.e.,

$$P_n = \frac{\mu^n e^{-\mu}}{n!},$$

where P_n is the probability of obtaining n photons when the average photon number is μ. The choice of a small μ value is required to obtain a reasonable approximation to a single-photon source. For example, for a pulsed laser with an average of one photon per pulse, $\mu=1$ so $P_{n=0}=P_{n=1}\approx 0.368$ and $P_{n=2}\approx 0.184$ (see Table I), and the probability of obtaining six or more photons ($P_{n=6}\approx 0.0005$) in a given pulse is less than one out of the 500 pulses per 1 s integration time, and so is negligible for most purposes. The average power of the switch beam in our experiment was 158 μW without the chopper, and the total transmittance of the nine neutral density filters was 1.18×10^{-12}, so the value of μ that was used to plot Fig. 4 was 0.75. The lowest value used to obtain a clear Gaussian signal was 0.4 (not shown), which means that the probability of a switch pulse containing four or more photons in an actuated switching operation was negligible.

The ultrafast operation has a total on and off switching time of less than 400 fs, so the corresponding switching rate is larger than 2.5 THz. A contrast ratio of 1.032:1 was measured for our single-stage setup through chopping the total laser beam before the beam splitter. Higher switching rates can be obtained by employing relatively shorter laser pulses, and improved contrast ratio can be obtained by using better band pass filters and cascading the device.

We would like to emphasize that our demonstration is only proof-of-principle. Our laser has a repetition rate of 1 kHz so there is plenty of time for the OPA crystal to relax to its original state after each operation. The switching action is thus not the accumulated effect of consecutive pulses, unlike what might occur in semiconductor switches. Due to the wide bandwidth, no temperature-sensitive effects have been observed. The switch works at room temperature, which makes it easy to implement, and it is cavity free and cell free, which makes it convenient to operate. It also can be cascaded to achieve higher throughput with possibly a cascade scheme could be similar to that in Ref. 17 where the exact temporal and spectral characteristics of the original switch pulse are preserved if an even number of stages is implemented. Our switch is even more versatile since the signal beam can be along the switch beam direction, so we are not limited to the number of stages. It is interesting that cascading the device can not only achieve higher gain but can also help to remove the background superfluorescence photons and scattered pump photons for single-photon level switching purposes. Background (noise) photons along the same direction as the signal beam in the initial stage will spatially and spectrally separate after the next stage. Therefore, a cascading setup can also function as a noise filter in our experimental approach. Possible switching router properties may be investigated by simultaneously applying another switch beam in a different direction (hence another state on*). How the signal beams would compete with each other (i.e., state on with state on*) requires further investigation.

In summary, we have demonstrated ultrafast all-optical switching where a weak beam switches a strong beam. Through three-wave mixing OPA in a nonlinear optical crystal, a switch pulse at the single-photon level can turn on/off a signal pulse containing 5.9×10^8 photons within 400 fs. In addition, the switch has broad bandwidth and can operate at room temperature. It can be cascaded, and various other improvements and developments may be envisioned.

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