Study on Photon-Controlled Optical Switching Devices using Surface-Stabilized Ferroelectric Liquid Crystals

Kentaro Yamada, Hiroyuki Okada

E-mail: m24c1497@ems.u-toyama.ac.jp
Graduate School of Science and Engineering, University of Toyama
3190 Gofuku, Toyama 930-8555, Japan

ABSTRACT

We investigated photon-controlled optical switching devices using a surface-stabilized ferroelectric liquid crystals. We measured the voltage versus photon-counting characteristics. As a result, we can evaluate voltage dependent photon number characteristics and analyzed statistics arises from Poisson distribution.

1 Introduction

With the recent advance in quantum information processing and optical quantum communication, precision control technology at the single-photon level is necessary. Conventional optical communication devices have been designed on the precise modulating macroscopic light intensity, however, to achieve operational accuracy at the photon level, new optical control elements are necessary. Among these situations, liquid crystal (LC) devices with lower operational voltage, high transmittance, and large change of retardation are promising compared to conventional optical switching devices. In this situation, we investigated the LC switches with common nematic LCs.[1] To operate shorter s\witching speed, we studied the photon-controlled switching devices using surface-stabilized ferroelectric liquid crystal (SSFLC) [2] and evaluated voltage versus photon number characteristics and statistically analyzed from the Poisson distribution.

2 Foundational Technology of the LC Device

We fabricated the SSFLC device with a cell gap of less than 2 μm. The LC material used was CS-1025 (JNC, spontaneous polarization Ps = -16.4 nC/cm^2, tilt angle θ = 21°, response time 73 μs). Polyimide alignment layers were coated and rubbed on ITO glass substrates, and an anti-parallel alignment cell is fabricated. The LC material was injected at above clearing point and sealed. Then, slowly cooled from 100°C through the Sc* phase sequence using temperature control at a cooling rate of 1°C/min to obtain a stable LC alignment. For investigating basic properties of the SSFLC cell, the voltage vs transmittance (*V-T*) characteristics and response time were measured.[3] To measure the number of photons, the light intensity was reduced with an ND filter (OD = 6), and while alternately switching the applied voltage to the SSFLC with a ±V pulse waveform. The number of photons was measured with gate times of 100 ms and 1 s. A photon counting head (Hamamatsu, H11890-110) was used as the detector. A schematic measurement system is shown in Fig. 1. The birefringence for transmitted light changes, allowing it to function as a phase difference control element or a switching device.[4] Particularly in quantum optical applications, it uses as a polarization modulation or an interferometer element for controlling the number of photons.

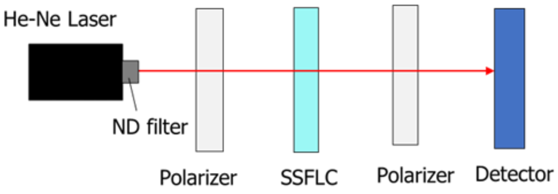

Fig. 1 Measurement system using SSFLC devices.

3 Measurement of Voltage vs. Average Photon Number Characteristics

The device characteristics were measured by varying the pulse voltage ±V and statistically analyzed the number of transmitted photons. Figure 2 shows the photon counting characteristics under a pulse voltage with ±V changing every 10 s and gate time of 100 ms. With increase in the pulse voltage, the number of photon counts exhibited Ferro(+), Ferro(-), and Intermediate states. From the pulse voltage above 0.6 V, the number of photon count was gradually decreased and saturated above 1.2 V. Although it may be a rare case, each measurement point includes at least one point in the Intermediate state. Figure 3 magnifies the change from 0 to 2V. As a result, the change in transmittance from the pulse voltage was reflected in the photon count distribution's shape, altering the average number of transmitted photons as the voltage increased. The Ferro(+) and Ferro(-) states were analyzed assuming a Poisson distribution, as shown in Figures 4 and 5.

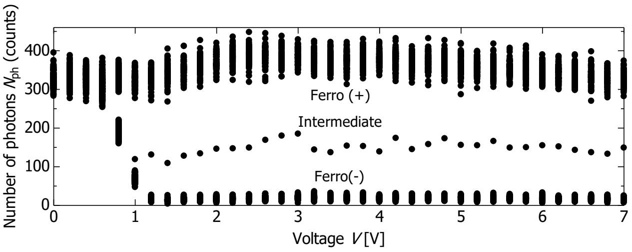

Fig. 2 Photon counting characteristics.

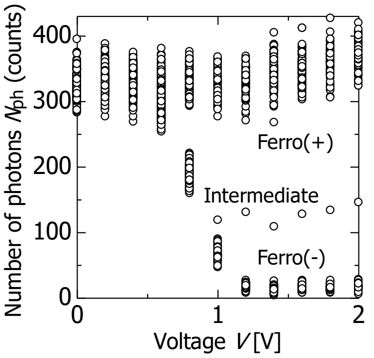

Fig. 3 Photon counting characteristics (0-2V).

The number of photons follows Poisson statistics, given by the probability:

$$P(n) = \frac{\lambda^n}{n!}\exp(-\lambda),$$

where λ is the average number of photons and n is the number of photons. When the λ is much larger, the statistics follows Gaussian distribution given by

$$P(n) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left[-\frac{(n-\lambda)^2}{2\sigma^2}\right],$$

where σ is the standard deviation of the distribution.

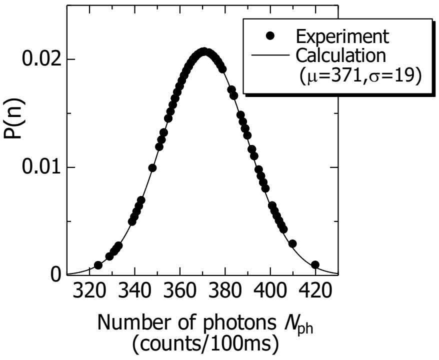

Fig. 4 Photon counting statistics: Ferro(+)

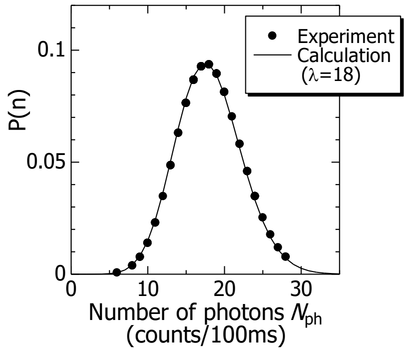

Fig. 5 Photon counting statistics: Ferro(-)

The Ferro(+) state fits a Gaussian distribution with an average of 371 photons, and the Ferro(-) state fits a Poisson distribution with an average of 18 photons. It became clear that the Ferro(+) state, with its wider distribution, is suitable for evaluating switching characteristics. On the other hand, under the Ferro(-) state, the relative ratio of photon number fluctuation was large, and the influence of fluctuation was observed to be more prominent. This demonstrated that LC devices are applicable to quantum-level optical statistics measurement.

Let us discuss these experimental results. The response speed of conventional nematic LCs is in the order of several milliseconds, which limits their application in high-speed optical communications and switching devices. Therefore, new materials and driving methods are required to improve response speed. Furthermore, the inherent light absorption and scattering of LCs can act as noise sources in photon control, making the design of low-loss materials a significant challenge.

In contrast, the SSFLCs enable microsecond-order optical switching and can potentially reduce noise from fluctuations through improved molecular alignment. Thus, with future performance improvements, they are expected to serve as optical switches for quantum communication, elements for measuring photon number distribution by varying incident light intensity, and tools for manipulating photonic qubits by precisely controlling polarization states.

4 Conclusions

In this study, we studied a photon-controlled switching devices using the SSFLC. It was experimentally shown that the photon number distribution can be adjusted by utilizing the refractive index change from pulse voltage application and switching between Gaussian and Poisson distribution characteristics with average photon numbers 371 and 18 was confirmed under Ferro(+) and Ferro(-) states, respectively. This revealed that the LC optical switch is effective for optical applications. In the future, by overcoming the challenges of response speed and noise reduction, its implementation as a practical optical switching device in quantum communication and quantum information processing is anticipated.

References

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